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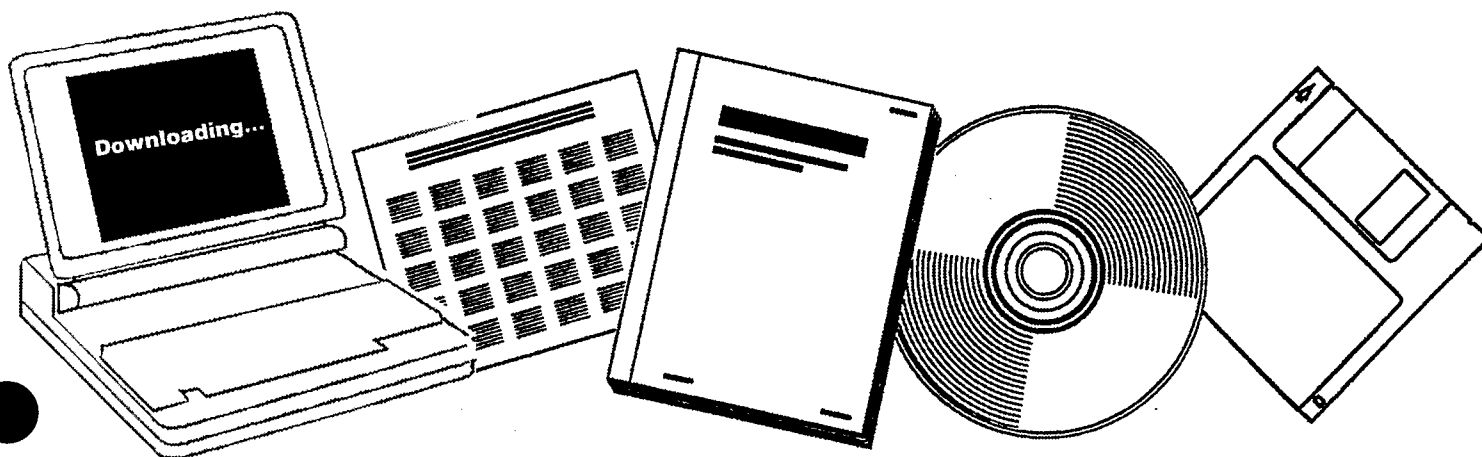
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## ENERGY FACT BOOK-1977

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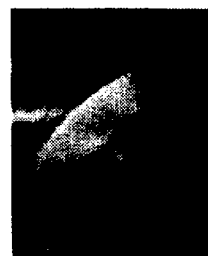
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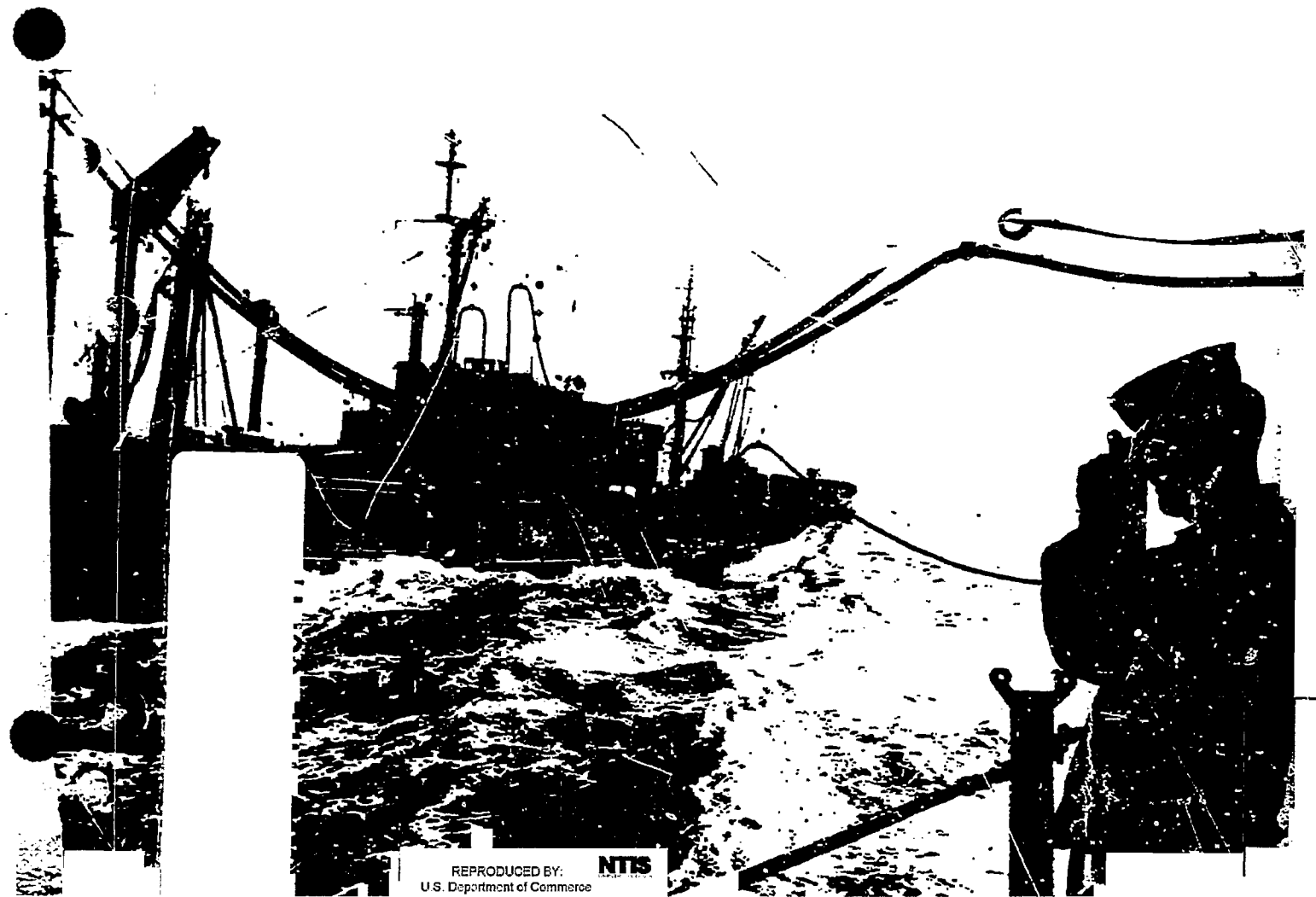
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# ENERGY

## FACT BOOK 1977



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***ENERGY FACT BOOK – 1977***

PREPARED UNDER THE DIRECTION OF THE DIRECTOR, NAVY ENERGY  
AND NATURAL RESOURCES RESEARCH AND DEVELOPMENT OFFICE

TETRA TECH, INC.  
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)  The Energy Fact Book-1977 summarizes the present U.S. Energy situation; Energy R&D Legislation; Federal Government Energy R&D; and International Energy R&D. It includes a brief description of the various processes and developments related to hydrocarbon fuels, synthetic fuels, non-hydrocarbon energy sources and energy conservation.		

## FOREWORD

This edition of the *Energy Fact Book* updates the information published in 1975 and 1976 for the Navy Energy and Natural Resources Research and Development Office.

The fact book contains a comprehensive summary of energy research and development and data on energy production and consumption. Also included are descriptions of progress in developing the technology for transforming coal into a more versatile form of energy, for making oil shale and tar sands practical and economical energy sources, and for utilizing solar energy, wind energy, fuel cells,

biomass conversion, and ocean energy.

Since significant changes are being made in the federal government's role in energy, those chapters covering legislation and government programs are subject to continuous review. A revision of these chapters is planned as soon as the new information becomes available.

A section on the International System of Units (SI)—a modernized version of the metric system established by international agreement—is included. Useful energy-related conversion tables appear in that section.

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## CONVERSION TABLES

### The Modernized Metric System (SI)

The International System of Units (SI)<sup>1</sup> is a modernized version of the metric system established by international agreement. It provides a logical and interconnected framework for all measurements in science, industry and commerce. Officially abbreviated SI, the system is built upon a foundation of seven base units plus two supplementary units, which are listed in Table 1.

Table 1

SI BASE UNITS

Quantity	Name	Symbol
Length	metre <sup>a</sup>	m
Mass <sup>b</sup>	kilogram	kg
Time	second	s
Electric current	ampere	A
Thermodynamic temperature	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd
SI supplementary units		
Plane angle	radian	rad
Solid angle	steradian	sr

<sup>a</sup>The spelling metre is used in a hope of securing worldwide uniformity in the spelling of the name of the base unit of the international system.

<sup>b</sup>"Weight" is a commonly used term for "mass."

### Base Units

**Metre (m)** The metre is the length equal to 1,650,763.73 wavelengths in vacuum of the radiation corresponding to the transition between the levels  $2p_{1/2}$  and  $5d_{5/2}$  of the krypton-86 atom.

**Kilogram (kg)** The standard for unit of mass, the kilogram, is a cylinder of platinum-iridium alloy kept by the International Bureau of Weights and Measures at Paris. A duplicate in the custody of the National Bureau of Standards is used as the mass standard for the United States.

**Second (s)** The second is defined as the duration of 9,192,631,770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom.

**Ampere (A)** The ampere is that constant current that would produce a force equal to  $2 \times 10^{-7}$  newton per metre of length between two straight parallel conductors that are of infinite length (a long wire) and negligible circular cross section, and are placed 1 metre apart in vacuum.

The newton (a derived SI unit) is a unit of force defined as metre-kilogram per second:  $\text{m} \cdot \text{kg} \cdot \text{s}^{-1}$  in terms of SI base units.

**Kelvin (K)** The kelvin, the unit of thermodynamic temperature, is the fraction  $1/273.16$  of the thermodynamic temperature of the triple point of water.

In addition to thermodynamic temperature (symbol T), expressed in kelvins, use is also made of Celsius temperature (symbol t) defined by

$$t = T - T_0$$

where  $T_0 = 273.15\text{K}$  (by definition). Water freezes at  $273.15\text{K}$ . The Celsius temperature is expressed in degrees Celsius (symbol  $^{\circ}\text{C}$ ). The unit *degree Celsius* is thus equal to the unit *kelvin*, and an interval or difference of Celsius temperature may also be expressed in degrees Celsius.

**Mole (mol)** The mole is the amount of substance of a system that contains as many elementary entities as there are atoms in 0.012 kilogram of carbon-12.

When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

**Candela (cd)** The candela is the luminous intensity, in the perpendicular direction, of a surface of  $1/600,000$  square metre of a black body at the temperature of freezing platinum under a pressure of 101,325 newtons per square metre.

### Supplementary Units

**Radian (rad)** The radian is the plane angle between two radii of a circle that cut off on the circumference an arc equal in length to the radius.

**Steradian (sr)** The steradian is the solid angle that, having its vertex in the center of a sphere, cuts off an area of the surface of the sphere equal to that of a square with sides of length equal to the radius of the sphere.

<sup>1</sup>Taken from the French "Le Systeme International d'Unités."

## Derived Units

Derived units are expressed in terms of base units by means of the symbols for multiplication and division. Several derived units have been given special names and symbols that may themselves be used to express other derived units in a simpler way than in terms of the base units. Supplementary units are also used to derive other SI units.

Tables 2, 3, 4, and 5 show examples of SI-derived units expressed in terms of base units, units with special names, units expressed by means of special names, and units formed by using supplementary units.

## SI Prefixes

Each basic unit can be expressed in a factor of 10. The exponential factor, prefix, and symbol are shown in Table 6.

Table 2

### EXAMPLES OF SI-DERIVED UNITS EXPRESSED IN TERMS OF BASE UNITS

Quantity	SI Unit	Unit Symbol
Area	Square metre	m <sup>2</sup>
Volume	Cubic metre	m <sup>3</sup>
Speed, velocity	Metre per second	m/s
Acceleration	Metre per second squared	m/s <sup>2</sup>
Wave number	1 per metre	m <sup>-1</sup>
Density, mass density	Kilogram per cubic metre	kg/m <sup>3</sup>
Current density	Ampere per square metre	A/m <sup>2</sup>
Magnetic field strength	Ampere per metre	A/m
Concentration (of amount of substance)	Mole per cubic metre	mol/m <sup>3</sup>
Specific volume	Cubic metre per kilogram	m <sup>3</sup> /kg
Luminance	Candela per square metre	cd/m <sup>2</sup>

Table 3

### SI-DERIVED UNITS WITH SPECIAL NAMES

Quantity	SI Unit			
	Name	Symbol	Expression in Terms of Other Units	Expression in Terms of SI Base Units
Frequency	hertz	Hz		s <sup>-1</sup>
Force	newton	N		m·kg·s <sup>-2</sup>
Pressure, stress	pascal	Pa	N/m <sup>2</sup>	m <sup>-1</sup> ·kg·s <sup>-2</sup>
Energy, work, quantity of heat	joule	J	N·m	m <sup>2</sup> ·kg·s <sup>-2</sup>
Power, radiant flux	watt	W	J/s	m <sup>2</sup> ·kg·s <sup>-3</sup>
Quantity of electricity, electric charge	coulomb	C	A·s	s·A
Electric potential, potential difference, electromotive force	volt	V	W/A	m <sup>2</sup> ·kg·s <sup>-3</sup> ·A <sup>-1</sup>
Capacitance	farad	F	C/V	m <sup>-2</sup> ·kg <sup>-1</sup> ·s <sup>4</sup> ·A <sup>2</sup>
Electric resistance	ohm	Ω	V/A	m <sup>2</sup> ·kg·s <sup>-3</sup> ·A <sup>-2</sup>
Conductance	siemens	S	A/V	m <sup>-2</sup> ·kg <sup>-1</sup> ·s <sup>3</sup> ·A <sup>2</sup>
Magnetic flux	weber	Wb	V·s	m <sup>2</sup> ·kg·s <sup>-2</sup> ·A <sup>-1</sup>
Magnetic flux density	tesla	T	Wb/m <sup>2</sup>	kg·s <sup>-2</sup> ·A <sup>-1</sup>
Inductance	henry	H	Wb/A	m <sup>2</sup> ·kg·s <sup>-2</sup> ·A <sup>-2</sup>
Luminous flux	lumen	lm		cd·sr <sup>2</sup>
Illuminance	lux	lx	lm/m <sup>2</sup>	m <sup>-2</sup> ·cd·sr <sup>2</sup>
Activity (radioactive)	becquerel	Bq		s <sup>-1</sup>
Absorbed dose	gray	Gy	J/kg	m <sup>2</sup> ·s <sup>-2</sup>

<sup>a</sup> In this expression the steradian (sr) is treated as a base unit.

Table 4

**EXAMPLES OF SI-DERIVED UNITS  
EXPRESSED BY MEANS OF SPECIAL NAMES**

Quantity	SI Units		
	Name	Symbol	Expression in Terms of SI Base Units
Dynamic viscosity	pascal second	Pa·s	$\text{m}^{-1} \cdot \text{kg} \cdot \text{s}^{-1}$
Moment of force	newton metre	N·m	$\text{m}^2 \cdot \text{kg} \cdot \text{s}^{-2}$
Surface tension	newton per metre	N/m	$\text{kg} \cdot \text{s}^{-2}$
Heat flux density, irradiance	watt per square metre	W/m <sup>2</sup>	$\text{kg} \cdot \text{s}^{-3}$
Heat capacity, entropy	joule per kelvin	J/K	$\text{m}^2 \cdot \text{kg} \cdot \text{s}^{-2} \cdot \text{K}^{-1}$
Specific heat capacity, specific entropy	joule per kilogram kelvin	J/(kg·K)	$\text{m}^2 \cdot \text{s}^{-2} \cdot \text{K}^{-1}$
Specific energy	joule per kilogram	J/kg	$\text{m}^2 \cdot \text{s}^{-2}$
Thermal conductivity	watt per metre kelvin	W/(m·K)	$\text{m} \cdot \text{kg} \cdot \text{s}^{-3} \cdot \text{K}^{-1}$
Energy density	joule per cubic metre	J/m <sup>3</sup>	$\text{m}^{-1} \cdot \text{kg} \cdot \text{s}^{-2}$
Electric field strength	volt per metre	V/m	$\text{m} \cdot \text{kg} \cdot \text{s}^{-3} \cdot \text{A}^{-1}$
Electric charge density	coulomb per cubic metre	C/m <sup>3</sup>	$\text{m}^{-3} \cdot \text{s} \cdot \text{A}$
Electric flux density	coulomb per square metre	C/m <sup>2</sup>	$\text{m}^{-2} \cdot \text{s} \cdot \text{A}$
Permittivity	farad per metre	F/m	$\text{m}^{-3} \cdot \text{kg}^{-1} \cdot \text{s}^4 \cdot \text{A}^2$
Permeability	henry per metre	H/m	$\text{m} \cdot \text{kg} \cdot \text{s}^{-2} \cdot \text{A}^{-2}$
Molar energy	joule per mole	J/mol	$\text{m}^2 \cdot \text{kg} \cdot \text{s}^{-2} \cdot \text{mol}^{-1}$
Molar entropy, molar heat capacity	joule per mole kelvin	J/(mol·K)	$\text{m}^2 \cdot \text{kg} \cdot \text{s}^{-2} \cdot \text{K}^{-1} \cdot \text{mol}^{-1}$

Table 5

**EXAMPLES OF SI-DERIVED UNITS FORMED  
BY USING SUPPLEMENTARY UNITS**

Quantity	SI Unit	
	Name	Symbol
Angular velocity	radian per second	rad/s
Angular acceleration	radian per second squared	rad/s <sup>2</sup>
Radiant intensity	watt per steradian	W/sr
Radiance	watt per square metre steradian	W·m <sup>-2</sup> ·sr <sup>-1</sup>

Table 6

**SI PREFIXES**

Factor	Prefix	Symbol	Factor	Prefix	Symbol
10 <sup>18</sup>	exa	E	10 <sup>-1</sup>	deci	d
10 <sup>15</sup>	peta	P	10 <sup>-2</sup>	centi	c
10 <sup>12</sup>	tera	T	10 <sup>-3</sup>	milli	m
10 <sup>9</sup>	giga	G	10 <sup>-6</sup>	micro	μ
10 <sup>6</sup>	mega	M	10 <sup>-9</sup>	nano	n
10 <sup>3</sup>	kilo	k	10 <sup>-12</sup>	pico	p
10 <sup>2</sup>	hecto	h	10 <sup>-15</sup>	femto	f
10 <sup>1</sup>	deka	da	10 <sup>-18</sup>	atto	a

## CONVERSION TABLES

The conversion tables presented here can be used to convert customary units to metric or SI units and vice versa. The conversion of base units and some of the derived units such as length, mass, area, volume, pressure, energy (heat, work, and energy), and power are presented in tabular form. The conversion of temperature and

energy density of various solid, liquid, and gaseous materials are shown on vertical lines for comparison.

The other derived units, such as flow rate, force, heat capacity, radioactivity, thermal conductivity, and viscosity, can be easily derived or converted from these base units and so are not presented here.

# LENGTH

	Millimetres (mm)	Centimetres (cm)	Metres <sup>a</sup> (m)	Kilometres (km)	Inches (in)	Feet (ft)	Yards (yd)	Miles (mi)
Millimetres (mm)	1	$1.0000 \times 10^{-1}$	$1.0000 \times 10^{-3}$	$1.0000 \times 10^{-6}$	$3.9370 \times 10^{-2}$	$3.2808 \times 10^{-3}$	$1.0936 \times 10^{-3}$	$6.2137 \times 10^{-7}$
Centimetres (cm)	$1.0000 \times 10^1$	1	$1.0000 \times 10^{-2}$	$1.0000 \times 10^{-5}$	$3.9370 \times 10^{-1}$	$3.2808 \times 10^{-2}$	$1.0936 \times 10^{-2}$	$6.2137 \times 10^{-6}$
Metres <sup>a</sup> (m)	$1.0000 \times 10^3$	$1.0000 \times 10^2$	1	$1.0000 \times 10^{-3}$	$3.9370 \times 10^1$	3.2808	1.0936	$6.2137 \times 10^{-4}$
Kilometres (km)	$1.0000 \times 10^6$	$1.0000 \times 10^5$	$1.0000 \times 10^3$	1	$3.9370 \times 10^4$	$3.2808 \times 10^3$	$1.0936 \times 10^3$	$6.2137 \times 10^{-1}$
Inches (in)	$2.5400 \times 10^1$	2.54	$2.5400 \times 10^{-2}$	$2.5400 \times 10^{-5}$	1	$8.3333 \times 10^{-2}$	$2.7778 \times 10^{-2}$	$1.5783 \times 10^{-5}$
Feet (ft)	$3.048 \times 10^2$	$3.048 \times 10^1$	$3.048 \times 10^{-1}$	$3.048 \times 10^{-4}$	$1.2000 \times 10^1$	1	$3.3333 \times 10^{-1}$	$1.8939 \times 10^{-4}$
Yards (yd)	$9.1440 \times 10^2$	$9.1440 \times 10^1$	$9.1440 \times 10^{-1}$	$9.1440 \times 10^{-4}$	$3.6000 \times 10^1$	3.0	1	$5.6818 \times 10^{-4}$
Miles (mi)	$1.6093 \times 10^6$	$1.6093 \times 10^5$	$1.6093 \times 10^3$	1.6093	$6.3360 \times 10^4$	$5.2000 \times 10^3$	$1.7600 \times 10^3$	1

Other linear measures not used as frequently:

1 rod <sup>b</sup>	=	5.5 yards	=	5.0292 metres
1 fathom	=	6 feet	=	1.8288 metres
1 cable length	=	120 fathoms	=	$2.1946 \times 10^2$ metres
1 nautical mile	=	6076.10 feet	=	$1.8520 \times 10^3$ metres
1 mil	=	0.001 inch	=	$2.54 \times 10^{-5}$ metres
1 furlong	=	0.125 miles	=	$2.0116 \times 10^{-2}$ miles

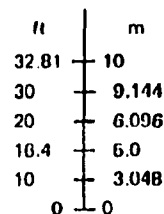
<sup>a</sup>Metre is the base unit of SI system.

<sup>b</sup>It is also known as pole or perch.

Linear measures in metric system:

1 micrometre ( $\mu$ m)	=	0.000001 micron	=	$10^{-12}$ m
1 Angstrom unit (Å)	=	0.0001 micron	=	$10^{-10}$ m
1 millimetre (mm)	=	0.001 micron ( $\mu$ )	=	$10^{-9}$ m
1 micron ( $\mu$ )	=	0.001 millimetre (mm)	=	$10^{-6}$ m
10 millimetres (mm)	=	1 centimetre (cm)	=	$10^{-2}$ m
10 centimetres (cm)	=	1 decimetre (dm)	=	$10^{-1}$ m
10 decimetres (dm)	=	1 metre (m)	=	39.37 inches
100 centimetres (cm)	=	1 metre (m)	=	$10^1$ m
1 dekametre (dkm)	=	10 metres (m)	=	$10^2$ m
1 hectometre (hm)	=	100 metres (m)	=	$10^3$ m
1 kilometre (km)	=	1,000 metres (m)	=	$10^4$ m
1 myriametre	=	10,000 metres (m)	=	$10^6$ m
1 megametre	=	1,000,000 metres (m)	=	$10^9$ m

## LENGTH



Comparison of Conventional Units in Engineering Practice



# AREA

	Square Centi- metres (cm <sup>2</sup> )	Square Metres (m <sup>2</sup> )	Square Kilo- metres (km <sup>2</sup> )	Hectares (ha)	Square Inches (in <sup>2</sup> )	Square Feet (ft <sup>2</sup> )	Square Yards (yd <sup>2</sup> )	Square Miles (mi <sup>2</sup> )	Acre
Square centimetres (cm <sup>2</sup> )	1	$1.0000 \times 10^{-4}$	$1.0000 \times 10^{-10}$	$1.0000 \times 10^{-8}$	$1.5500 \times 10^{-1}$	$1.0764 \times 10^{-3}$	$1.1960 \times 10^{-4}$	$3.8610 \times 10^{-11}$	$2.4700 \times 10^{-8}$
Square metres <sup>a</sup> (m <sup>2</sup> )	$1.0000 \times 10^4$	1	$1.0000 \times 10^6$	$1.0000 \times 10^{-4}$	$1.5500 \times 10^3$	$1.0764 \times 10^1$	1.1960	$3.8610 \times 10^{-7}$	$2.4700 \times 10^{-4}$
Square kilometres (km <sup>2</sup> )	$1.0000 \times 10^{10}$	$1.0000 \times 10^6$	1	$1.0000 \times 10^2$	$1.5500 \times 10^9$	$1.0764 \times 10^7$	$1.1960 \times 10^6$	$3.8610 \times 10^{-1}$	$2.4700 \times 10^2$
Hectares (ha)	$1.0000 \times 10^8$	$1.0000 \times 10^4$	$1.0000 \times 10^{-2}$	1	$1.5500 \times 10^7$	$1.0764 \times 10^5$	$1.1960 \times 10^4$	$3.8610 \times 10^3$	2.4700
Square inches (in <sup>2</sup> )	6.4516	$6.4516 \times 10^{-4}$	$6.4516 \times 10^{-10}$	$6.4516 \times 10^{-8}$	1	$6.9444 \times 10^{-3}$	$7.7160 \times 10^{-4}$	$2.4910 \times 10^{-10}$	$1.5940 \times 10^{-7}$
Square feet (ft <sup>2</sup> )	$0.2903 \times 10^2$	$0.2903 \times 10^{-2}$	$0.2903 \times 10^{-8}$	$0.2903 \times 10^{-6}$	$1.4400 \times 10^2$	1	$1.1111 \times 10^{-1}$	$3.5868 \times 10^{-8}$	$2.2957 \times 10^{-6}$
Square yards (yd <sup>2</sup> )	$0.3613 \times 10^3$	$0.3613 \times 10^{-1}$	$0.3613 \times 10^{-7}$	$0.3613 \times 10^{-5}$	$1.2960 \times 10^3$	0.0000	1	$3.2283 \times 10^{-7}$	$2.0680 \times 10^{-4}$
Square miles (mi <sup>2</sup> )	$2.5889 \times 10^{10}$	$2.5889 \times 10^6$	2.5889	$2.5889 \times 10^2$	$4.0148 \times 10^9$	$2.7878 \times 10^7$	$3.0976 \times 10^6$	1	$6.3996 \times 10^2$
Acres	$4.0486 \times 10^7$	$4.0486 \times 10^3$	$4.0486 \times 10^{-6}$	$4.0486 \times 10^{-1}$	$6.2735 \times 10^6$	$4.3660 \times 10^4$	$4.8400 \times 10^3$	$1.5026 \times 10^{-3}$	1

Other square measures not used as frequently:

1 square rod, pole or perch = 30.25 square yards =  $2.5293 \times 10^1$  m<sup>2</sup>  
1 square chain = 1.0 x 10<sup>-1</sup> acre =  $4.0469 \times 10^3$  m<sup>2</sup>

<sup>a</sup>Square metre is the SI unit for area measurement.

## MASS

	Ounces (oz)	Pounds (lb)	Short Tons (tons)	Grams (gm)	Kilograms <sup>a</sup> (kg)	Tonnes (t)
Ounces (oz)	1	$6.2500 \times 10^{-2}$	$3.1250 \times 10^{-5}$	$2.8350 \times 10^1$	$2.8350 \times 10^{-2}$	$2.8350 \times 10^{-5}$
Pounds (lb)	$1.6000 \times 10^1$	1	$5.0000 \times 10^{-4}$	$4.5359 \times 10^2$	$4.5359 \times 10^{-1}$	$4.5359 \times 10^{-4}$
Short tons (tons)	$3.2000 \times 10^4$	$2.000 \times 10^3$	1	$9.0718 \times 10^5$	$9.0718 \times 10^2$	$9.0718 \times 10^{-1}$
Grams (gm)	$3.5264 \times 10^{-2}$	$2.2046 \times 10^{-3}$	$1.1023 \times 10^{-6}$	1	$1.0000 \times 10^{-3}$	$1.0000 \times 10^{-6}$
Kilograms (kg)	$3.5264 \times 10^1$	2.2046	$1.1023 \times 10^{-3}$	$1.0000 \times 10^3$	1	$1.0000 \times 10^{-3}$
Tonnes (t)	$3.5264 \times 10^4$	$2.2046 \times 10^3$	1.1023	$1.0000 \times 10^6$	$1.0000 \times 10^3$	1

Other mass measures not used frequently:

1 long ton = 2240 pounds	= $1.10646 \times 10^3$ kg	1 dram (troy or apothecary)	= $3.887934 \times 10^{-3}$ kg
1 carat = 0.2 gram	= $2.0000 \times 10^{-4}$ kg	1 grain	= $6.4599 \times 10^{-5}$ kg
1 slug = 32.17 pounds	= $1.45939 \times 10^1$ kg	1 scruple (apothecary)	= $1.295978 \times 10^{-3}$ kg
1 dram (avoirdupois)	= $1.771845 \times 10^{-3}$ kg	1 pennyweight	= $1.5552 \times 10^{-3}$ kg

Other metric measures of mass such as microgram, milligram, centigram, decigram, dekagram, hectogram, etc., are 10 multiple factors of kilogram, and their names imply same multiple factors as those in linear measures.

<sup>a</sup>Kilogram is the base unit of mass in SI system.

Notes: (1) Avoirdupois measures are used in this table. In troy and apothecary measures 1 lb = 12 ounces; in avoirdupois measure 1 lb = 16 ounces; in avoirdupois measure, 1 lb = 0.4530 kg; whereas in troy or apothecary measures, 1 lb = 0.3732 kg.

(2) Tonnes is also referred to as metric tons.

(3) Tons is also referred to sometimes as volumetric measure tons (U.S. shipping) =  $40 \text{ ft}^3$  and tons (British shipping) =  $42 \text{ ft}^3$ . Tons is also referred to as a power unit in refrigeration, where 1 ton = 12,000 Btu/hr.

# VOLUME

	Fluid Ounces (fl. oz)	Pints (pt)	Quarts (qt)	Gallons (gal)	Barrels (bbl)	Cubic Feet (ft <sup>3</sup> )	Cubic Yards (yd <sup>3</sup> )	Cubic Centi- metres (cm <sup>3</sup> )	Liters (l)	Cubic Metres <sup>a</sup> (m <sup>3</sup> )
Fluid ounces (fl. oz)	1	$0.2500 \times 10^{-2}$	$3.125 \times 10^{-2}$	$1.0125 \times 10^{-3}$	$1.6601 \times 10^{-4}$	$1.0414 \times 10^{-3}$	$3.0605 \times 10^{-6}$	$3.0230 \times 10^1$	$3.0220 \times 10^{-2}$	$3.0229 \times 10^{-5}$
Pints (pt)	$1.6000 \times 10^1$	1	$5.0000 \times 10^{-1}$	$1.2500 \times 10^{-1}$	$2.9762 \times 10^{-3}$	$1.6710 \times 10^{-2}$	$6.1889 \times 10^{-4}$	$4.7313 \times 10^2$	$4.7313 \times 10^{-1}$	$4.7313 \times 10^{-4}$
Quarts (qt)	$3.2000 \times 10^1$	2.0000	1	$2.500 \times 10^{-1}$	$5.9524 \times 10^{-3}$	$3.3420 \times 10^{-3}$	$1.2370 \times 10^{-3}$	$9.4625 \times 10^2$	$9.4625 \times 10^{-1}$	$9.4625 \times 10^{-4}$
Gallons (gal)	$1.2800 \times 10^2$	8.0000	4.0000	1	$2.3810 \times 10^{-2}$	$1.3368 \times 10^{-1}$	$4.9511 \times 10^{-3}$	$7.7850 \times 10^3$	3.7850	$3.7859 \times 10^{-3}$
Barrels of oil (bbl)	$5.3760 \times 10^3$	$3.3600 \times 10^2$	$1.6800 \times 10^2$	$4.2000 \times 10^1$	1	6.0145	$2.0798 \times 10^{-1}$	$1.5898 \times 10^6$	$1.5897 \times 10^2$	$1.5898 \times 10^1$
Cubic feet (ft <sup>3</sup> )	$9.5750 \times 10^2$	$5.9844 \times 10^1$	$2.9922 \times 10^1$	7.4805	$1.7011 \times 10^{-1}$	1	$3.7037 \times 10^{-2}$	$2.8313 \times 10^4$	$2.8313 \times 10^1$	$2.8313 \times 10^2$
Cubic yards (yd <sup>3</sup> )	$2.5850 \times 10^4$	$1.6158 \times 10^3$	$8.0790 \times 10^2$	$2.0197 \times 10^2$	4.8087	$2.7000 \times 10^1$	1	$7.6444 \times 10^5$	$7.6444 \times 10^2$	$7.6444 \times 10^{-1}$
Cubic centimetres (cm <sup>3</sup> )	$3.308 \times 10^{-2}$	$2.1136 \times 10^{-3}$	$1.0568 \times 10^{-3}$	$2.6420 \times 10^{-4}$	$6.2900 \times 10^{-6}$	$3.5320 \times 10^{-6}$	$1.3080 \times 10^{-6}$	1	$9.9997 \times 10^{-4}$ $\approx 1.0 \times 10^{-3}$	$1.0000 \times 10^{-6}$
Liters (l)	$3.3081 \times 10^1$	2.1156	1.0568	$2.6420 \times 10^{-1}$	$6.2900 \times 10^{-3}$	$5.5320 \times 10^{-2}$	$1.3080 \times 10^{-3}$	$1.0000 \times 10^3$	1	$1.0000 \times 10^{-3}$
Cubic metres <sup>a</sup> (m <sup>3</sup> )	$3.3080 \times 10^4$	$2.1136 \times 10^3$	$1.0568 \times 10^3$	$2.6420 \times 10^2$	6.2900	$3.5320 \times 10^1$	1.3080	$1.0000 \times 10^6$	$9.9997 \times 10^2$ $\approx 1000.00$	1

Other units for volume not frequently used:

1 acre foot = 1613.33 cubic yards = 1234 m<sup>3</sup>  
 1 bushel (U.S. dry) = 1.2444 cubic feet = 0.03523 m<sup>3</sup>  
 1 bushel (U.S.) = 9.3092 (U.S. gallons) = 0.03523 m<sup>3</sup>

Notes: (1) 1 milliliter (ml) = 1.000027 cm<sup>3</sup>, so, for practical purposes 1 ml = 1 cm<sup>3</sup>.

(2) 1 barrel of oil is 42 gallons while 1 barrel of U.S. liquid is 31.5 gallons = 0.11924 m<sup>3</sup>; in this conversion table, 1 bbl = 42 gallons. 1 barrel of cement is 376 pounds, i.e., 1 barrel of cement is  $1.7055 \times 10^2$  kg.

<sup>a</sup>Cubic metre is the SI unit for volume

# PRESSURE

	Feet of Water (ft of H <sub>2</sub> O)	Inches of Mercury (in of Hg)	Pounds per Square Inch (psi)	Atmospheric (atm)	Barometric (bar)	Millimetres of Mercury (mm of Hg)	Kilograms per Square Centi- metre (kg/cm <sup>2</sup> )	Newtons per Square Metre <sup>a</sup> (N/m <sup>2</sup> )
Feet of water (ft of H <sub>2</sub> O)	1	$8.8263 \times 10^{-1}$	$4.3350 \times 10^{-1}$	$2.9500 \times 10^{-2}$	$2.9891 \times 10^{-2}$	$2.2420 \times 10^1$	$3.0479 \times 10^{-2}$	$2.9890 \times 10^3$
Inches of mercury (in of Hg)	1.1329	1	$4.9120 \times 10^{-1}$	$3.3400 \times 10^{-2}$	$3.3864 \times 10^{-2}$	$2.5400 \times 10^1$	$3.4533 \times 10^{-2}$	$3.3865 \times 10^3$
Pounds per square inch (psi)	2.3007	2.036	1	$6.8048 \times 10^{-2}$	$6.8948 \times 10^{-2}$	$5.1715 \times 10^1$	$7.0308 \times 10^{-2}$	$6.8949 \times 10^3$
Atmospheric (atm)	$3.3900 \times 10^1$	$2.9921 \times 10^1$	$1.4696 \times 10^1$	1	1.0132	$7.6000 \times 10^2$	1.0312	$1.0132 \times 10^6$
Barometric (bar)	$3.3455 \times 10^1$	$2.9530 \times 10^1$	$1.4504 \times 10^1$	$9.8694 \times 10^{-1}$	1	$7.5009 \times 10^2$	1.0108	$1.0000 \times 10^6$
Millimetres of mercury (mm of Hg)	$4.4800 \times 10^{-2}$	$3.9400 \times 10^{-2}$	$1.9337 \times 10^{-2}$	$1.3158 \times 10^{-3}$	$1.3332 \times 10^{-3}$	1	$1.3595 \times 10^{-3}$	$1.3332 \times 10^2$
Kilograms per square centimetre (kg/cm <sup>2</sup> )	$3.2809 \times 10^1$	$2.0968 \times 10^1$	$1.4723 \times 10^{-1}$	$9.6787 \times 10^{-1}$	$9.8060 \times 10^{-1}$	$7.3557 \times 10^2$	1	$9.8067 \times 10^4$
Newtons per square metre (N/m <sup>2</sup> )	$3.3455 \times 10^{-4}$	$2.9529 \times 10^{-4}$	$1.4504 \times 10^{-4}$	$9.8695 \times 10^{-6}$	$1.0000 \times 10^{-6}$	$7.5007 \times 10^{-3}$	$1.0179 \times 10^{-5}$	1

Other units for pressure not frequently used:

lb/ft<sup>2</sup> (lbs/inch<sup>2</sup> = 144 lb/ft<sup>2</sup>)

Torr (1 atm = 760 Torr; 1 Torr = 1 mm of Hg)

1 Torr =  $1.3332 \times 10^2$  H/m<sup>2</sup>

gm/cm<sup>2</sup> (1 atm = 1033.3 gm/cm<sup>2</sup>; 1 kg/cm<sup>2</sup> = 1000 gm/cm<sup>2</sup>)

cm of Hg (1 cm of Hg = 10 mm of Hg)

in of H<sub>2</sub>O (1 in of H<sub>2</sub>O = 1/12 ft of H<sub>2</sub>O)

<sup>a</sup>Newtons per square metre is the SI unit for pressure.

Note: PSI is pounds per square inch; in industry psig, i.e., pressure at gauge is measured 1 psig = 1 psi + 14.696.

## ENERGY, HEAT, WORK

	Joules <sup>a</sup> (J)	Metro Kilogram- Force (m-kg)	Calories <sup>b</sup> (Cal <sub>IT</sub> )	Kilowatt-Hour (kwhr)	British Thermal Unit (Btu)	Foot-Pound Force (ft-lb)	Cubic Foot- Atmosphere (ft <sup>3</sup> -atm)	Horsepower- Hour (hp-hr)	Litre-Atmo- sphere (l-atm)
Joules (J)	1	$1.0197 \times 10^{-1}$	$2.3886 \times 10^{-1}$	$2.7778 \times 10^{-7}$	$9.4781 \times 10^{-4}$	$7.3756 \times 10^{-1}$	$3.4863 \times 10^{-4}$	$3.7251 \times 10^{-7}$	$9.8690 \times 10^{-3}$
Metro-kilogram force (m-kg)	9.80665	1	2.3422	$2.7240 \times 10^{-6}$	$9.2049 \times 10^{-3}$	7.2330	$3.4177 \times 10^{-3}$	$3.6529 \times 10^{-6}$	$9.6776 \times 10^{-2}$
Calories (Cal <sub>IT</sub> )	4.1868	$4.2694 \times 10^{-1}$	1	$1.1628 \times 10^{-6}$	$3.9684 \times 10^{-3}$	3.0881	$1.4692 \times 10^{-3}$	$1.5597 \times 10^{-6}$	$4.1319 \times 10^{-2}$
Kilowatt-hour (kwhr)	$3.6000 \times 10^2$	$3.0111 \times 10^6$	$8.6000 \times 10^6$	1	$3.4127 \times 10^3$	$2.6557 \times 10^6$	$1.2540 \times 10^3$	1.3413	$3.5634 \times 10^4$
British Thermal Unit (Btu)	$1.0551 \times 10^3$	$1.0759 \times 10^2$	$2.5199 \times 10^2$	$2.9302 \times 10^{-4}$	1	$7.7818 \times 10^2$	$3.6772 \times 10^{-1}$	$3.9302 \times 10^{-4}$	$1.0412 \times 10^1$
Foot-pound force (ft-lb)	1.3558	$1.3826 \times 10^{-1}$	$3.2382 \times 10^{-1}$	$3.7655 \times 10^{-7}$	$1.2861 \times 10^{-3}$	1	$4.7255 \times 10^{-4}$	$5.0505 \times 10^{-7}$	$1.3367 \times 10^2$
Cubic foot-atmo- sphere (ft <sup>3</sup> -atm)	$2.8692 \times 10^3$	$2.9259 \times 10^2$	$6.8629 \times 10^2$	$7.9687 \times 10^{-4}$	2.7195	$2.1162 \times 10^3$	1	$1.0688 \times 10^{-3}$	$2.8316 \times 10^1$
Horsepower-hour (hp-hr)	$2.6845 \times 10^6$	$2.7376 \times 10^6$	$6.4116 \times 10^6$	$7.4657 \times 10^{-1}$	$2.5445 \times 10^3$	$1.9800 \times 10^6$	$9.3663 \times 10^2$	1	$2.6480 \times 10^4$
Litre-atmosphere (l-atm)	$1.0133 \times 10^2$	$1.0333 \times 10^1$	$2.4220 \times 10^1$	$2.8142 \times 10^{-6}$	$9.6043 \times 10^{-2}$	$7.4813 \times 10^1$	$3.6316 \times 10^{-2}$	$3.7753 \times 10^{-6}$	1

Other units not used as frequently as above units:

Unit	Symbol	Conversion factor
Kilocalorie	kcal or kg-cal	1 kcal = 1000.00 cal
Centigrade heat unit	c.h.u.	1 Btu = 1.80 c.h.u.
Therm	therm	1 therm = $10^6$ Btu
Thermo	thermo	1 thermo = $10^6$ gm-cal = $10^3$ kg-cal
erg	erg	1 joule = $10^7$ ergs
Pounds centigrade unit	p.c.u.	1 p.c.u. = 1.8 Btu
Foot pounds		1 foot poundal = 32.174 foot pound
Watt hour	watt-hr	1 kwhr = 1000 watt-hr
Cubic decimetre-atmosphere	dm <sup>3</sup> -atm	1 dm <sup>3</sup> -atm = 1 liter-atm
Watt-seconds		1 joule = 1 watt-second
Electron volts		1 joule = $6 \times 10^6$ electron volts

<sup>a</sup>Joule is the SI base unit of energy.

<sup>b</sup>Calorie (international steam table) = 4.1868 joules  
 Calorie (mean) = 4.19002 joules  
 Calorie (thermochemical) = 4.1840 joules  
 Calorie (15° C) = 4.18580 joules  
 Calorie (20° C) = 4.18690 joules

## POWER

	British Thermal Unit per Hour (Btu/hr)	Foot-Pound per Second (ft-lb/s)	Horsepower (hp)	Kilowatt (kw)	Calorie per Second (cal/s)	Watt (w) <sup>a</sup> or Joules per Second (J/s)
British Thermal Unit per hour (Btu/hr)	1	$2.1616 \times 10^{-1}$	$3.9287 \times 10^{-4}$	$2.9308 \times 10^{-4}$	$7.0000 \times 10^{-2}$	$2.9308 \times 10^{-1}$
Foot-pound per second (ft-lb/s)	4.6262	1	$1.1818 \times 10^{-3}$	$1.3558 \times 10^{-3}$	$3.2382 \times 10^{-1}$	1.3558
Horsepower (hp)	$2.5454 \times 10^3$	$5.5000 \times 10^2$	1	$7.4600 \times 10^{-1}$	$1.7810 \times 10^2$	$7.4609 \times 10^2$
Kilowatt (kw)	$3.4120 \times 10^3$	$7.3757 \times 10^2$	1.3405	1	$2.3880 \times 10^2$	$1.0000 \times 10^3$
Calorie per second (cal/s)	$1.4286 \times 10^1$	3.0881	$5.6148 \times 10^{-3}$	$4.1876 \times 10^{-3}$	1	4.1868
Watt (w) <sup>a</sup> or joules per second (J/s)	3.4120	$7.3757 \times 10^{-1}$	$1.3405 \times 10^{-3}$	$1.0000 \times 10^{-3}$	$2.3880 \times 10^{-1}$	1

Other power units not used frequently:

Lumens	(1 lumen = 0.001496 watt)
Candlepower	(1 candle power = 12.556 lumens)
Ft-lb/min	(1 ft-lb/sec = 60 ft-lb/min = 3600 ft-lb/hr)
Horsepower (boiler)	(1 hp = $7.709 \times 10^2$ hp (boiler))
kcal per second	(1 kcal/s = 1000 cal/s)
ergs per second	(1 J/s = $1.0 \times 10^7$ ergs/s)
Horsepower (metric)	(1 hp (metric) = 0.9863 hp (U.S.))
Tons of refrigeration	(1 ton of refrigeration = 12,000 Btu/hr)

<sup>a</sup>Watt or joules/second is the SI unit for power.

## ENERGY CONVERSION CHART<sup>a</sup>

Thermal Energy (Btu) <sup>b</sup>	Oil (Barrels) <sup>c</sup>	Natural Gas (1000 cubic feet)	Coal (Tons)	Nuclear (Grams U-235)	Water (Millions of gallons falling 100 feet)	Electricity (Kilowatt-hours) <sup>d</sup>
1.0	0.00000017	0.00000095	0.000000038	0.000000013	0.00000093	0.00010
5,800,000	1.0	5.5	0.22	0.077	5.4	560
1,100,000	0.18	1.0	0.040	0.014	0.98	100
26,000,000	4.5	25	1.0	0.35	24	2500
75,000,000	13.0	72	2.9	1.0	70	7300
1,100,000	0.19	1.0	0.041	0.014	1.0	100
10,000	0.0018	0.0099	0.00040	0.00014	0.0096	1.0

<sup>a</sup>Values rounded to 2 significant figures.

Example: Given that a 1000 MW(e) power plant operates for 1 day, how much oil is consumed?  $(1000 \text{ MW}) \times (1000 \text{ KW per MW}) \times (24 \text{ hours per day}) \times (0.0018 \text{ barrels per KWe hr}) = 43,000 \text{ barrels of oil}$ . How much U-235 is consumed?  $(1000 \text{ MW}) \times (1000 \text{ KW per MW}) \times (24 \text{ hours per day}) \times 0.00014 \text{ g U-235 per KWe hr} = 3,300 \text{ g } (\sim 7 \text{ lb}) \text{ of U-235}$ .

<sup>b</sup>Btu = British Thermal Units. The amount of heat required to heat 1 pound of water 1° F.

<sup>c</sup>1 barrel of oil = 42 gallons.

A conversion efficiency from heat to electricity of 0.33 is assumed.

Source: *Nuclear Power and the Environment*, American Nuclear Society, April 1976.

**APPROXIMATE CONVERSION FACTORS  
FOR CRUDE OIL<sup>a</sup>**

FROM \ INTO	Metric Tons	Long Tons	Short Tons	Barrels	Kiloliters (Cubic Meters)	1,000 Gallons (Imp.)	1,000 Gallons (US)
	MULTIPLY BY						
Metric Tons .....	1	0.984	1.102	7.33	.116	0.256	0.308
Long Tons .....	1.016	1	1.120	7.45	1.18	0.251	0.313
Short Tons .....	0.907	0.893	1	6.65	1.05	0.233	0.279
Barrels .....	0.136	0.134	0.150	1	0.195	0.035	0.042
Kiloliters (cubic meters) .....	0.863	0.849	0.951	6.29	1	0.220	0.264
1,000 Gallons (Imperial) .....	3.91	3.83	4.29	28.6	4.55	1	1.201
1,000 Gallons (U.S.) .....	3.25	3.19	3.58	23.8	3.79	0.833	1

<sup>a</sup>Based on world average gravity (excluding natural gas liquids).

**BRITISH THERMAL UNIT HEAT VALUES<sup>a</sup>**

		Crude Petroleum (42 Gal. Barrel)	Anthracite Coal (Short Ton)	Bituminous Coal (Short Ton)	Natural Gas—Dry (1000 Cu. Ft.)	Distillate Fuel Oil (42 Gal. Barrel)	Residual Fuel Oil (42 Gal. Barrel)	Liquefied Pet. Gas (42 Gal. Barrel)
Crude Petroleum	42 Gal. Bbl. equals	—	0.228	0.221	5.604	0.996	0.923	1.446
Anthracite Coal	Short Ton equals	4.379	—	0.969	24.541	4.361	4.040	6.333
Bituminous Coal and Lignite	Short Ton equals	4.517	1.031	—	25.314	4.498	4.167	6.532
Natural Gas — Dry	1000 Cu. Ft. equals	0.178	0.041	0.040	—	0.176	0.165	0.253
Distillate Fuel Oil	42 Gal. Bbl. equals	1.004	0.229	0.222	5.628	—	0.927	1.452
Residual Fuel Oil	42 Gal. Bbl. equals	1.084	0.248	0.240	6.074	1.079	—	1.567
Liquefied Petroleum Gas	42 Gal. Bbl. equals	0.692	0.158	0.153	3.875	0.689	0.638	—
Btu Heat Values As Used		5,800	25,400	26,200	1,035	5,825	6,287	4,011

<sup>a</sup>Other Refined Products Btu Values (1000s): Gasoline 5,243; Kerosine 5,670; Lubricants 6,064.8; Wax 5,537.3; Asphalt 6,636; Miscellaneous 5,796; Natural Gasoline 4,620 Per 42 Gallon Barrel.

Source: Annual Statistical Review, Petroleum Industry Statistics, 1964-1973, API, Sept. 1974.

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**CHAPTER I**  
**U.S. ENERGY SITUATION**

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## INTRODUCTION

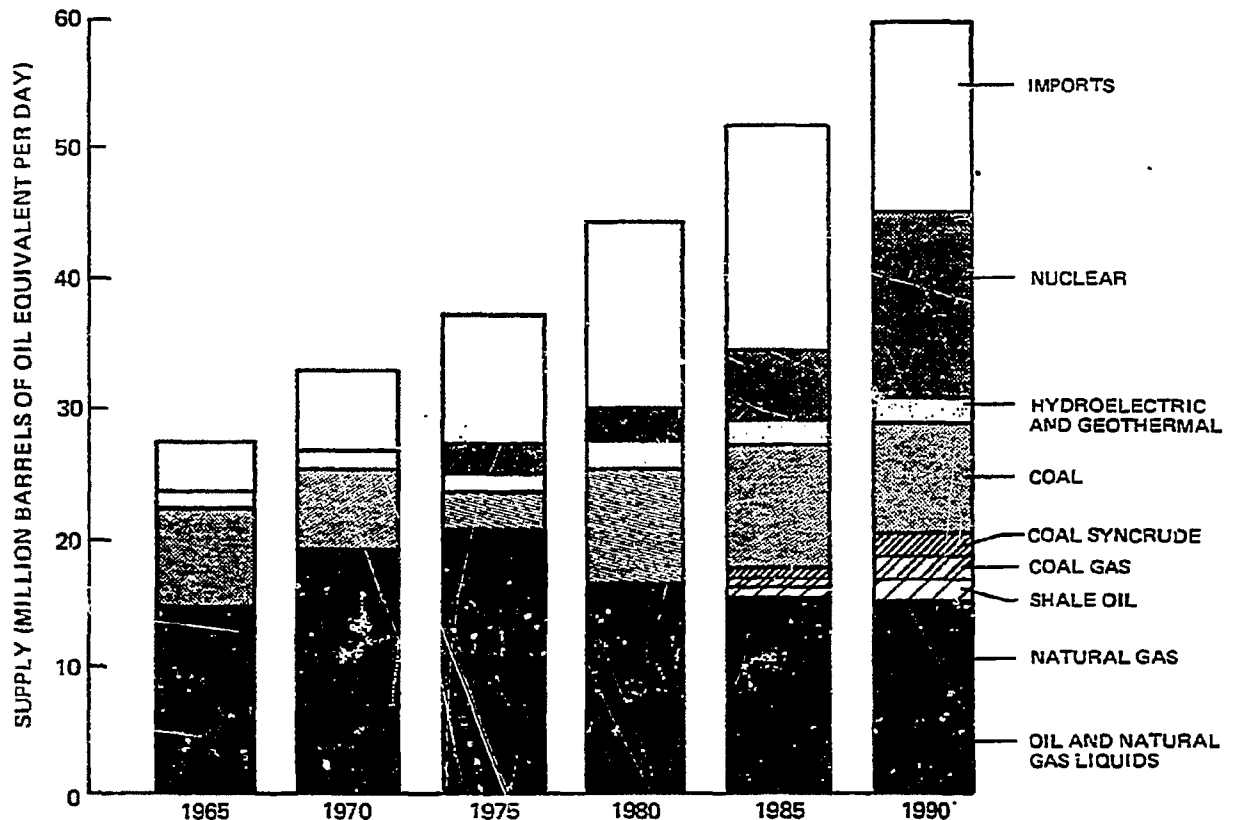
Most of the energy demand in the United States is supplied by petroleum and natural gas. The domestic supply of both of these fuels is dwindling, however, and may be exhausted early in the twenty-first century.

Limited choices confront the United States. The nation will continue to rely on foreign oil in the near-term (Figure I-1). Energy independence in the mid-term could be achieved, but at a cost the nation may not be willing to pay. Long-term alternatives show great promise, but they may be too late to prevent large increases in foreign imports of liquid petroleum products.

Left to the pressures of free market economics, new alternative energy sources could ultimately be developed by private industry as traditional sources diminish and become more expensive. As long as the opportunity exists to import cheaper energy sources, which, in turn, under-

cuts the price of new domestic energy sources, private industry will be reluctant to develop new sources. As a result, the nation will increasingly rely on foreign sources until those sources diminish and the profit of new domestic sources is assured.

Government policymakers recognize the problem and are trying to ensure the nation's commitment to the early development of energy alternatives. There are many alternatives that can be pursued, and each is accompanied by technical, economic, environmental, and social problems. The issues are complex and, without an integrated national plan, it is difficult to set priorities. Additionally, a national consensus, in some cases, may be needed to overcome the traditional economic barriers that confront the development of alternative fuels.



Source: American Petroleum Institute

Figure I-1. U.S. ENERGY SOURCES

## ENERGY DEMAND

The United States consumes approximately 73 quadrillion ( $73 \times 10^{15}$ ) Btu's or 73 quads of energy a year. Total U.S. energy consumption in 1975 is shown in Table I-1, and 1975 energy consumption by major sectors is shown in Table I-2. Figure I-2 shows the complicated energy patterns through which primary energy sources are introduced and used by the economy. (Total energy demand in the United States peaked in 1973 and has decreased since; it is expected to rise, however, with the resurgence of the national economy.)

More than 90 percent of the demand is supplied by three fossil fuels: petroleum, natural gas, and coal. Of

these, coal is the largest fossil energy resource. The United States, however, relies on its least plentiful resources—oil and gas; 76 percent of consumption is from these sources that make up only 7 percent of the nation's proved reserves. Only 18 percent of U.S. energy consumption is supplied by coal, which constitutes 90 percent of proved reserves (Figure I-3). The imbalance is caused by the valuable properties of oil and natural gas that enable these products to be produced, transported, stored, and used in ways that are cheaper, easier, safer, and cleaner than coal.

Table I-1

### U.S. ENERGY CONSUMPTION, 1975<sup>a</sup>

Source	Demand Percent	Trillion Btu	Units
Oil and liquefied natural gas	46.4	32,719	5.64 billion barrels
Gas	28.3	19,948	18.1 trillion SCF
Coal	18.2	12,828	493.4 million tons
Hydro power	4.5	3,229	322.9 billion kwhr
Nuclear	2.6	1,833	183.3 billion kwhr
Total	100.0	70,557	-3.0% from 1974

<sup>a</sup>Preliminary.

Source: U.S. Bureau of Mines, 7 February 1977.

Table I-2

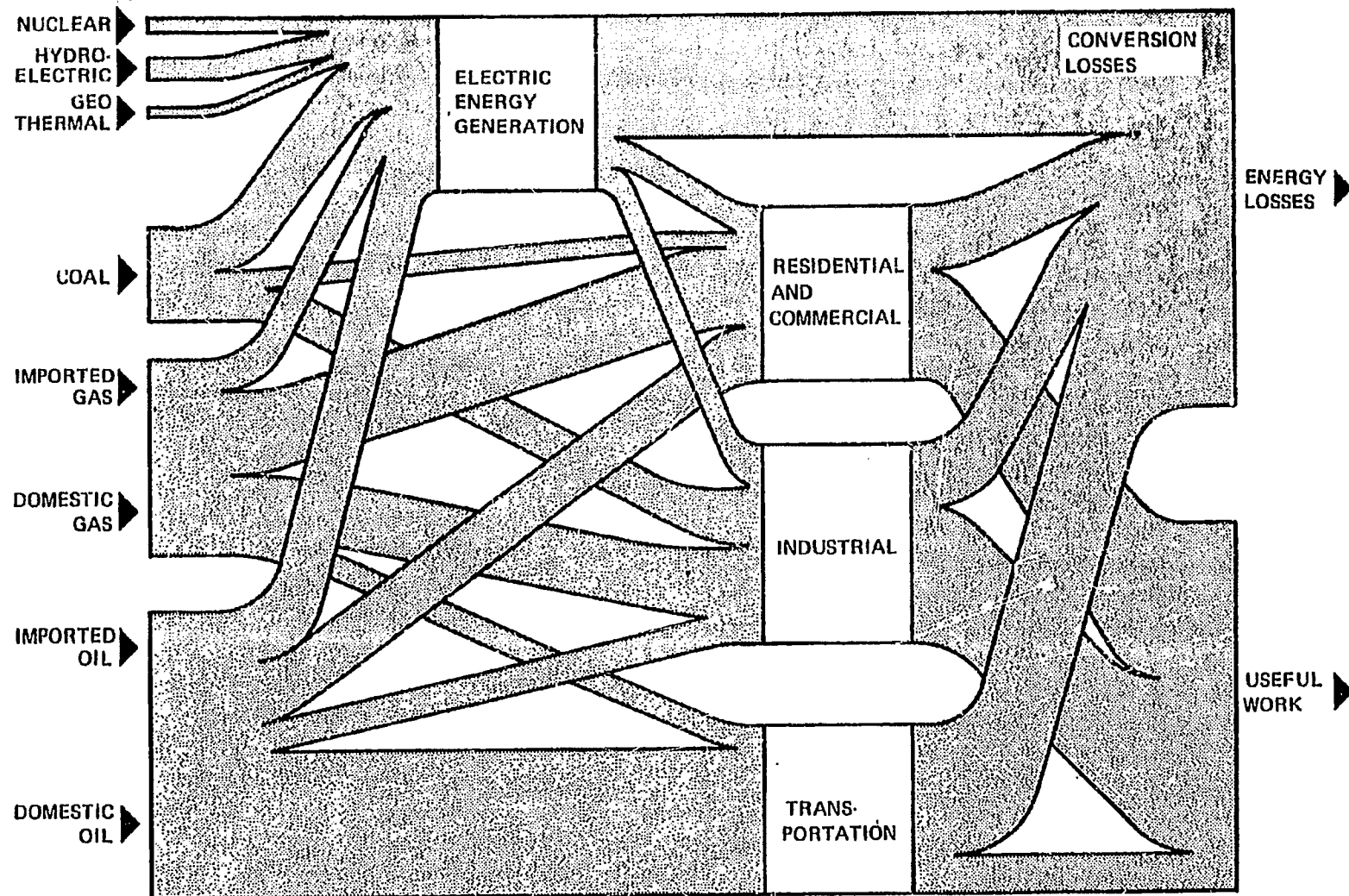
### 1975 U.S. ENERGY CONSUMPTION BY MAJOR SECTORS<sup>a</sup> (Trillion Btu)

	Coal	Petroleum and Liquefied Natural Gas <sup>b</sup>	Natural Gas	Hydro Power	Nuclear	Total	Percent
Household and commercial	246	5,752	7,589	—	—	13,587	19.3
Industrial	3,821	5,517	8,551	35	—	17,924	25.4
Transportation	1	17,933	595	—	—	18,529	26.2
Electricity generation by utilities	8,760	3,239	3,213	3,194	1,833	20,239	28.7
Miscellaneous and losses	—	278	—	—	—	278	0.4
Total	12,828	32,719	19,948	3,229	1,833	70,557	100.0

<sup>a</sup>Estimated.

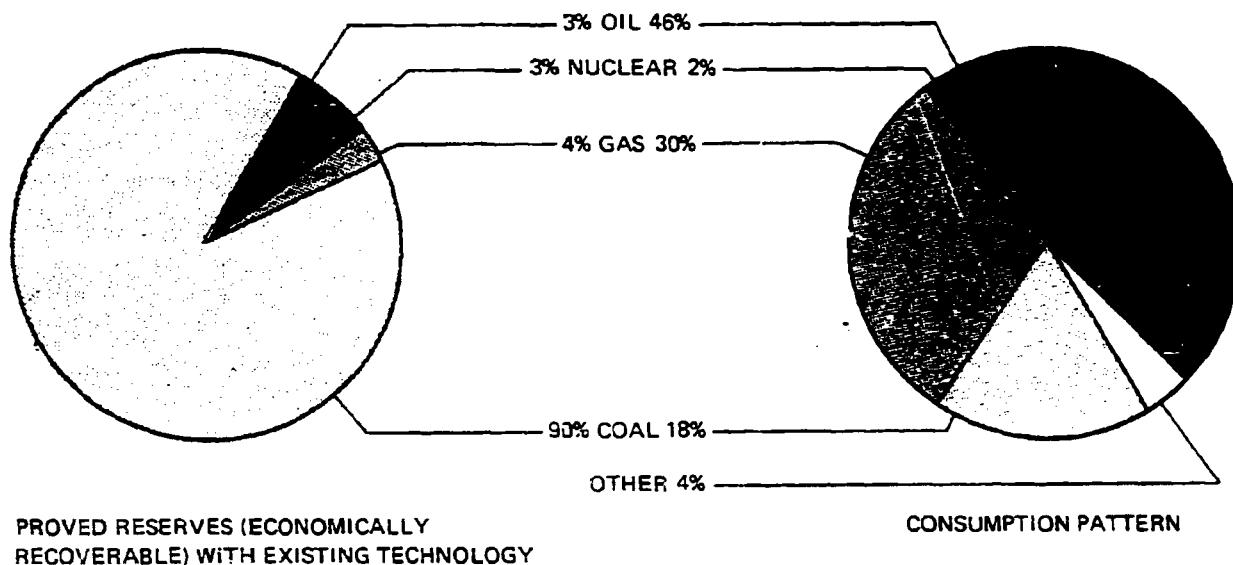
<sup>b</sup>Includes natural gas liquids, liquefied refinery gas, and still gas.

Source: Division of Interfuels Studies, Office of Assistant Director—Fuels, Bureau of Mines, U.S. Department of the Interior.



Source: *The National Energy Dilemma*, Joint Committee on Atomic Energy, 1973.

Figure 1-2. ENERGY CONVERSION PATTERNS, 1980



Source: *National Energy Outlook*, Federal Energy Administration, 1976.

Figure I-3. U.S. ENERGY SUPPLY AND DEMAND, BY FUEL TYPE

## ENERGY SUPPLY

### Oil

Figure I-4 shows estimates of U.S. oil resources and reserves. Four categories of reserves denote the degree of certainty in the estimate. Measured reserves are "proved," that is, they exist and can be recovered economically. Indicated and inferred reserves possibly exist based on examination of geological formations. Undiscovered economic reserves are postulated oil-bearing formations based on historical extrapolations.

The best estimate (90 percent confident) is that there are between 50 billion and 127 billion barrels of undiscovered economic oil reserves. Measured, indicated, and inferred reserves total 62 billion barrels oil oil. Depending on the actual amount ultimately found, undiscovered economic reserves (hypothetical) constitute between 40 and 60 percent of the nation's ultimately recoverable resource estimate. These estimates are based on current technological and economic conditions. As conditions change, the portion of the resource base that is discovered reserves will also change. (Historically, estimates of ultimately

recoverable oil reserves increased as more promising geological areas were explored. Recently, this trend has been reversed. Estimates of undiscovered, recoverable oil and gas in the United States have been declining since 1965 as areas once thought to be promising have proved disappointing.)

Much of the readily recoverable onshore oil in the conterminous United States has already been tapped. If the resource estimates are correct, the United States has already consumed more than 32 percent of its original oil. New production will come from increasingly costly, but more effective, secondary and tertiary recovery methods, new areas on the outer continental shelf, and Alaska.

As the domestic supply of oil decreases, the United States will become increasingly dependent on imported oil. Today imports account for 41 percent of U.S. consumption. Nearly 84 percent of the crude oil imported in the first half of 1976 was supplied by the Organization of Petroleum Exporting Countries (OPEC). U.S. dependence on imported oil from the Arab nations (OAPEC) has increased from 31 percent in 1973 to 43 percent of

	IDENTIFIED RESERVES			ESTIMATED UNDISCOVERED RESERVES
	DEMONSTRATED		INFERRED	
	MEASURED	INDICATED		
ECONOMIC	34.25C	4.686	23.1	50-127
SUB-ECONOMIC	120-140			44-111

← INCREASING DEGREE OF GEOLOGICAL ASSURANCE

↑ INCREASING DEGREE OF ECONOMIC FEASIBILITY

TOTAL U.S. CUMULATIVE PRODUCTION:  
106 BILLION BARRELS (12/31/74)

NOTE: RESERVES SHOWN IN BILLIONS OF BARRELS

Source: *Oil and Gas Resources, Reserves, and Productive Capacities*,  
Federal Energy Administration, June 1975.

Figure I-4. U.S. CRUDE OIL RESERVES

total U.S. crude oil imports. By 2000, oil imports could constitute 83 percent of domestic oil needs.

### Gas

Most of the nation's natural gas is found in and along the Gulf of Mexico. According to the U.S. Geological Survey (USGS), the United States has 439 trillion cubic feet (TCF) of known recoverable natural gas. USGS estimates that an additional 338 TCF to 722 TCF of gas may be recoverable. Thus, the United States has ultimately recoverable gas resources of 777 TCF to 1,161 TCF (133.5 to 199.5 billion barrels of oil equivalent).

Production of natural gas is started when proved and measured reserves are sufficient to support production costs. Generally, investors require that gas fields support production for at least 12 to 15 years before development becomes worthwhile. In the United States, only 237 TCF have actually been measured.

Table I-3 shows the supply and demand for natural gas the United States for 1971 through 1975.

### Coal

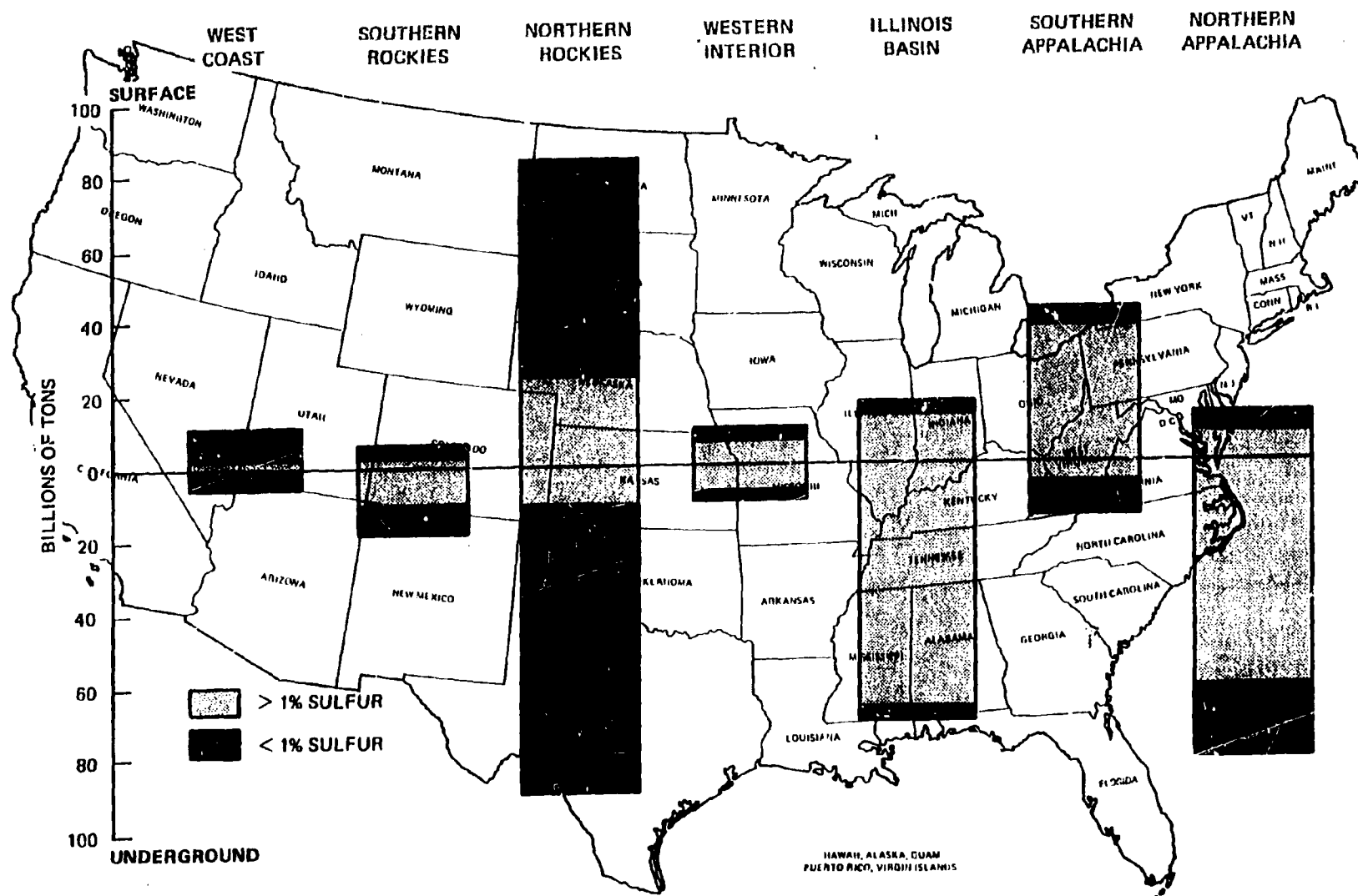
Coal is the nation's most abundant fossil energy resource. The United States has enough low-sulfur coal to

support production growth for the next few centuries. These environmentally acceptable coal deposits are located predominantly in the Northern Rockies (Figure I-5) where, presently, there is virtually no major coal development. The most lucrative of these western deposits requires surface mining. Local and state governments are thus reluctant to permit the environmental and social disruptions that would accompany major development of these coal lands.

The percentage of demand supplied by coal has increased slightly over the last few years and should increase further from now to the end of the century, particularly as methods for converting coal to synthetic fuels are improved and new methods are discovered. (Synthetic fuels derived from coal and oil shale should begin to provide a limited alternative energy source by 1985.)

### Other

Nuclear energy has supplied an increasing amount of the nation's demand for energy, rising from 1.1 percent in 1973 to 2.2 percent in 1975. Nuclear power will increase its share of the energy supply from now to the end of the century, with more exotic forms of energy contributing in a minor way.



Source: Bureau of Mines, Department of the Interior.

Figure I-5. DEMONSTRATED COAL RESERVES



Table I-3

## SUPPLY AND DEMAND FOR NATURAL GAS IN THE UNITED STATES

	1971	1972	1973	1974	1975
Supply (TCF)					
Marketed production <sup>a</sup>	22.49	22.53	22.65	21.60	20.11
Withdrawn from storage	1.51	1.76	1.53	1.70	1.76
Imports	0.93	1.02	1.03	0.96	0.95
Total	24.93	25.31	25.21	24.26	22.82
Disposition (TCF)					
Consumption	22.68	23.01	22.97	22.11	20.41
Exports	0.08	0.08	0.08	0.08	0.07
Stored	1.84	1.89	1.97	1.78	2.10
Lost in transmission, etc.	0.39	0.33	0.20	0.29	0.24
Total	24.93	25.31	25.21	24.26	22.82
Value at wellhead					
Total (thousands of dollars)	\$4,085,482	\$4,180,462	\$4,894,072	\$6,573,402	\$8,945,662
Average (cents per thousand cubic feet)	\$0.182	\$0.186	\$0.216	\$0.304	\$0.445

<sup>a</sup>Marketed production of natural gas represents gross withdrawals less gas used for repressuring and quantities vented and flared.

Note: Domestic production as used in the Bureau publication *Minerals and Materials/Monthly Survey* represents marketed production less the shrinkage (extraction loss) resulting from the extraction of natural gas liquids.

Source: U.S. Bureau of Mines, 4 October 1975.

## ENERGY OUTLOOK

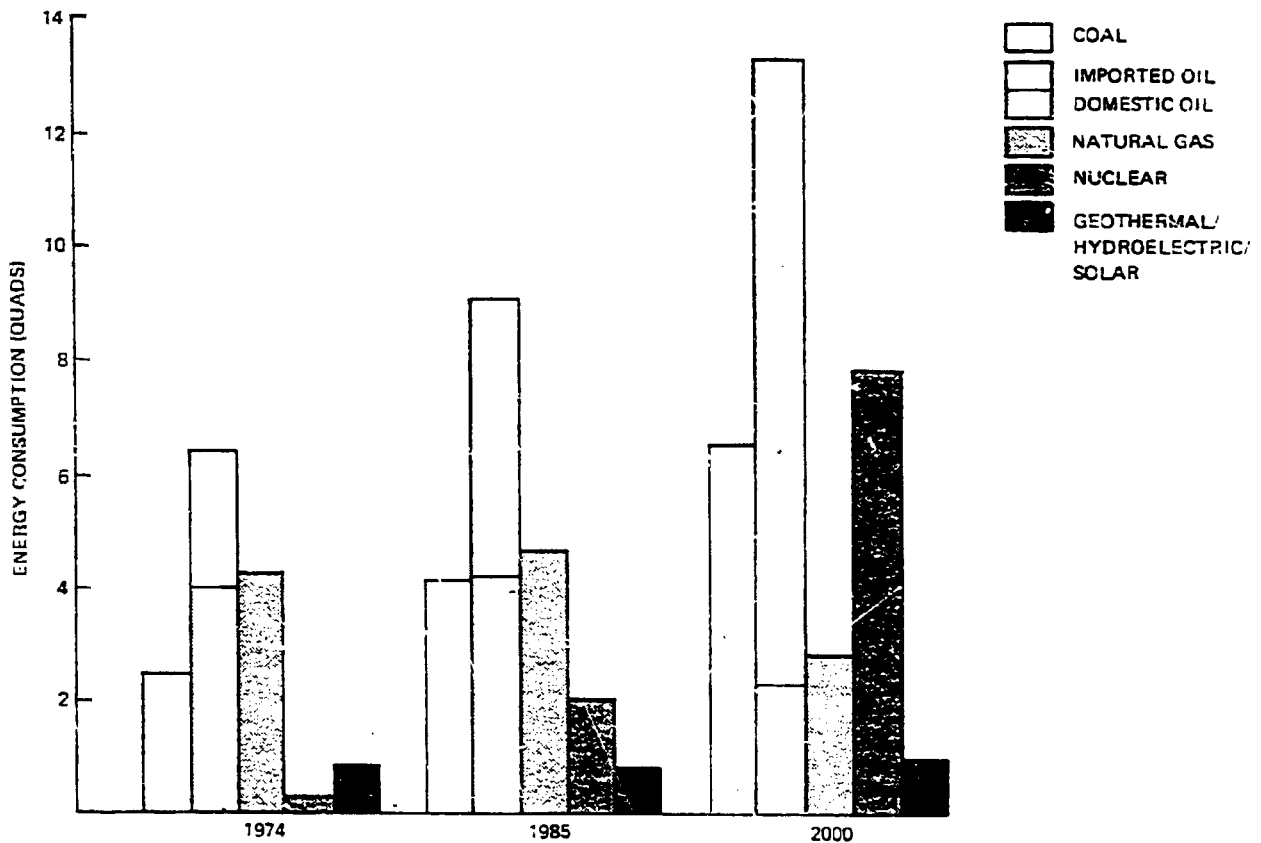
Most of the energy supplied between now and 1980 will come from oil wells, gas fields, and coal mines that are currently producing. (Long lead times are needed for constructing new facilities.) In the meantime, energy consumption will continue to increase (Figure I-6). As a result, the supply of both oil and gas may be exhausted early in the twenty-first century.

Relatively little can be done to change near- (1980) and mid-term (1980 to 1985) energy supply and demand patterns. Industrial and utility power plants have useful lives of up to 20 years. This means that alternative boiler systems will be phased in only after that time. However, there are two possible alternatives to business-as-usual energy consumption that can reduce the demand for oil and gas.

One alternative is to emphasize conservation, which includes an investment in energy-saving technology such as improved gasoline engines and better building insula-

tion. Studies completed by FEA indicate that, by adopting national policies promoting energy conservation, the United States can reduce its need for oil by nearly 8 million barrels per day by 1985 (Table I-4). Measures to reduce demand include:

- Converting the automobile propulsion from its present 30:70 ratio of small to large cars to at least an average of 50:50 by 1985. This will require the production of 75 million lightweight automobiles in the next 10 years.
- Expanding mass transportation facilities in large cities.
- Ensuring that the 20 million housing units required have substantially improved insulation.
- Making industrial processes 10 percent less energy-intensive, on the average.
- Using more efficient energy space heating such as heat pumps.



Source: *Creating Energy Choices for the Future*, Energy Research and Development Administration, 1976.

Figure I-6. PROJECTED U.S. ENERGY CONSUMPTION  
(NO NEW INITIATIVES)

The second alternative is to reduce dependence on oil and gas by the greater use of coal and nuclear fuel for generating electricity. Because of the long lead times required for developing new mines and constructing new power plants, the near-term reduction in oil demand would be minimal; however, a substantial mid-term reduction could be realized, as long as barriers to the direct use of coal and nuclear fuel for electricity are removed.

In the long term, a number of alternative energy sources are promising. The United States and the rest of the world are far from exhausting all the practical, available energy sources. The sources that could constitute the nation's long-term energy supplies are coal, crops, nuclear fission, nuclear fusion, geothermal, hydroelectric, ocean heat, oil shale and tar sands, solar, tides, waste heat, waste materials, water (fusion and hydrogen), and wind-power.

Although the supply of some sources is unlimited, very little can be tapped from the new, more exotic sources in this century. The development cycle of light water nu-

clear reactors is an example. It required 33 years to evolve light water reactor technology and to introduce it commercially. Although other technologies may not need a long development period, all of them will require extensive laboratory, pilot, and demonstration scale tests before they are introduced commercially.

Today, only liquid metal fast breeder reactors (LMFBR) and synthetic fuels from coal and oil shale are ready for demonstration-scale tests. It will be at least 5 to 10 years before the exact value of these two technologies is determined. The value of other less developed technologies will not be recognized for at least a decade. However, this assumes that the United States will be committed to the all out development of these technologies.

There are numerous significant barriers obstructing the development of new energy technology. An uncertain energy policy probably contributes more to the delay than the technical, economic, and social considerations. Table I-5 lists the major barriers for each of the emerging energy technologies.

Table I-4

## ESTIMATED 1985 U.S. ENERGY DEMAND REDUCTION

Category	Million bbl/day
By Conservation	
Industrial conservation measures	1.5
Transportation	
Lower speeds, car pooling	1.0
Airplane load factors	0.3
Space heating efficiency	1.0
By Use of Energy-saving Equipment	
Smaller, more efficient cars	2.0
Other transportation savings	1.1
Better building insulation standards	1.1
Residential and commercial equipment	0.4
Industrial process efficiency	1.0
Total conservation potential	9.4
Less 15 percent for partial overlap	8.0

Source: *U.S. Energy Prospects*, National Academy of Engineering, May 1974.

Table I-5

## BARRIERS TO DEVELOPING ALTERNATIVE ENERGY SOURCES

Technology	Issues and Areas of Uncertainty
Enhanced oil and gas recovery	Federal oil and gas pricing policies
Synthetic liquids and gases and direct utilization of coal	Federal energy policy Disposal of spent material Water consumption Strip mining and reclamation Sulfur oxide standards World oil prices Capital requirements
Geothermal	Lack of comprehensive resource information Lack of proven domestic technology Legal and regulatory complexities
Light water reactors	Limited uranium reserves
Liquid metal fast breeder reactors	Economic uncertainty Safety Radioactive waste management Insufficient engineering base (breeders) Fuel cycle performance (breeders)
Solar heating and cooling	Economic uncertainty Limited geographic applicability Need for convention backup Legal complexities
Solar: electric Solar thermal electric Solar photovoltaic Wind energy Ocean thermal energy conversion	Economic uncertainty Legal complexities Lack of proven technology
Fusion	Very early in the development cycle

Source: *Creating Energy Choices for the Future*, Energy Research and Development Administration, 1976.

**CHAPTER II**  
**ENERGY R&D LEGISLATION**  
**93RD AND 94TH CONGRESSES**

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## INTRODUCTION

Since the Arab oil embargo of 1973, the United States has been seeking to formulate a national energy policy. In 1974, the 93rd Congress enacted legislation which provided for the consolidation of federal energy research, development, and demonstration into the Energy Research and Development Administration (ERDA) and later set guidelines for ERDA to follow in establishing a federal energy research program. The 93rd Congress also encouraged the development of solar and geothermal energy

technology by creating financial incentives for such development.

The 94th Congress continued to move toward a national energy policy by enacting several bills dealing with individual energy issues. While these energy issues certainly warranted consideration, the body of bills enacted by both Congresses still falls short of providing a comprehensive energy policy.

## ENERGY LEGISLATION – 93RD CONGRESS

### SOLAR HEATING AND COOLING DEMONSTRATION ACT OF 1974 (P.L. 93-409)

The Solar Heating and Cooling Demonstration Act that provides for demonstration of solar heating and combined solar heating and cooling was approved by the President on September 3, 1974.

Responsibility for the implementation of this program

has been initially assigned to NASA and NSF; however the Energy Reorganization Act, transferred the program to ERDA. The DOD and HUD are directed by P.L. 93-407 to participate in the demonstration program by installing solar equipment in facilities as directed by ERDA.

### GEOTHERMAL ENERGY RESEARCH, DEVELOPMENT, AND DEMONSTRATION ACT OF 1974 (P.L. 93-410)

The Geothermal Energy R&D and Demonstration Act was approved by the President, September 3, 1974. The act creates a broad program for inventory and assessment of the geothermal base, R&D and demonstration activity, including a provision for a loan guaranty program to encourage commercial development. The act authorizes,

subject to actual appropriation, \$50 million annually for FY 1976 through FY 1980 for geothermal research. ERDA will assume responsibility for the geothermal project from the mandated interagency "Geothermal Energy Coordination and Management Project."

### ENERGY REORGANIZATION ACT OF 1974 (P.L. 93-438)

The Energy Reorganization Act approved by the President on October 11, 1974, abolishes the AEC and calls for the creation of an Energy Research and Development Administration (ERDA), a Nuclear Regulatory Commission (NRC), and an Energy Resources Council.

The act merges AEC's nonregulatory functions, officers, and components with DOI's functions, officers, and components of the Office of Coal Research, those of the Bureau of Mines associated with fossil fuel R&D, and other Interior components associated with underground electric power transmission; the functions of NSF in solar heating and cooling, and geothermal power; and the functions, officers, and components in EPA's nonregulatory related R&D to form ERDA. Initially, ERDA will include

Divisions of Military Application and Naval Reactors, but a joint recommendation, from the Administrator and the Secretary of Defense, on transfer of these division's functions to the Department of Defense (DOD), or another agency, is required within a year. Additionally, the ERDA administrator, with the aid of six assistant administrators for fossil energy, nuclear energy, environment and safety, conservation, national security, and solar, geothermal and advanced energy systems, will exercise central responsibility for government energy R&D. He is also authorized to utilize the technical and management capabilities of other agencies with their consent, provided it does not detract from the basic mission responsibilities of the other agencies.

ERDA will have approximately 6,000 civil service and 86,000 contractor personnel, in what reportedly is the largest single group of the nation's technical and technical management talent. ERDA will also inherit the R&D programs of predecessor agencies and will manage the Congressionally mandated interagency projects in geothermal and solar energy.

The act also creates the Nuclear Regulatory Commission, which includes AEC's licensing and related regulatory functions, the chairman, members of the commission, the general counsel, and other officers and components of the AEC. The functions of the Atomic

Safety and Licensing Board Panel, the Atomic Safety and Licensing Appeal Board, and such personnel as the director of OMB determines necessary for the exercise of NRC's responsibilities are also transferred.

The Energy Resources Council, in the Executive Order of the President, is charged with coordinating energy policy and advising the president and Congress on government energy management. The Council will include the Secretaries of the Departments of Interior and State, the Administrators of ERDA and FEA, the Director of OMB, and any other presidentially designated officials.

### **SOLAR ENERGY RESEARCH, DEVELOPMENT, AND DEMONSTRATION ACT OF 1974 (P.L. 93-472)**

The Solar Energy R&D and Demonstration Act, which contains provisions similar to the Geothermal Energy R&D and Demonstration Act, was approved by the President, October 26, 1974. The act provides for the pursuit of a vigorous program of research to use solar energy on a

commercial scale. The act includes a provision for the creation of a "Solar Energy Coordination and Management Project," which will have overall responsibility for the management and coordination of a solar energy R&D and demonstration program.

### **FEDERAL NONNUCLEAR ENERGY RESEARCH AND DEVELOPMENT ACT OF 1974 (P.L. 93-577)**

The Federal Nonnuclear Energy Research and Development Act, which provides Congressional guidance to ERDA, was approved by the President on December 31, 1974. The act gives ERDA policy guidance for conducting nonnuclear R&D much the same as the Atomic Energy Act does for nuclear energy. This legislation was initiated to promote basic and applied R&D and to demonstrate practical applications of all potentially beneficial energy sources. The Administrator of ERDA is charged with implementing special nonnuclear technology laws, including the Solar Heating and Cooling Demonstration Act of 1974; the Geothermal Energy Research, Development, and Demonstration Act of 1974; and the Solar Energy Research, Development, and Demonstration Act of 1974.

Although the act does not provide any appropriations, it does require that the ERDA administrator initiate and maintain R&D efforts through fund transfers, grants, or contracts, and that he use the facilities of federal agencies and nongovernmental organizations as appropriate.

Federal involvement in any R&D effort depends on the urgency of public need for R&D and demonstration results that would not be provided by other than direct federal financial assistance, and the extent to which non-federal interests could assume responsibility for nonnuclear R&D and demonstration projects.

The various forms of federal assistance and participation the administration might consider include joint federal-industry experimental demonstration or commercial corporations; contractual agreements with nonfederal participants; contracts for the construction and operation of federally owned facilities; federal purchases or guaranteed prices of the products of the demonstration plants or activities; federal loans to nonfederal entities; and incentives, including financial awards. Significantly, the legislators have emphasized when the joint federal-industry corporations and the guaranteed prices should be used to assist the development of particular energy technologies. Moreover, the establishment of a corporation or a price support program must be authorized by specific legislation enacted by Congress.

If the estimated federal investment for construction costs of any proposed demonstration project exceeds \$50 million, Congress must legislate the amount; Congress must also review each federal contribution that exceeds \$25 million.

This act and the Energy Reorganization Act of 1974 require the ERDA administrator to submit a comprehensive plan for energy R&D and demonstration on or before June 30, 1975, and to revise the plan annually. The plan should outline a program for solving immediate and short-

term (to the early 1980s), middle-term (early 1980s to 2000), and the long-term (beyond 2000) energy supply systems and environmental problems. The administrator must also submit a comprehensive nonnuclear energy R&D and demonstration program plan to implement the nonnuclear R&D and demonstration aspects of the comprehensive plan. The activities in specific nonnuclear energy technologies must be assigned and justified according to the short-term, middle-term, and long-term time schedule. Within six months of the enactment of this act, the administrator must also submit regulations establishing procedures for submission of demonstration proposals and specifying the types and form of the information to be contained in the proposals.

The act emphasizes certain nonnuclear energy R&D and demonstration activities, including advancing energy conservation technologies; accelerating commercial demonstrations of technologies for producing low-sulfur fuels; improving the methods for the generation, storage, and transmission of electrical energy; accelerating the commercial demonstration of geothermal energy technologies; demonstrating the production of syncrude from oil shale by "all promising technologies," including in-situ technologies; demonstrating improved methods for the extraction of petroleum resources; demonstrating the economics and commercial feasibility of solar energy technologies; increasing the production of synthetic fuels including hydrogen and methanol; and determining the economics and commercial possibilities of in-situ coal gasification.

The act also calls for accelerating the commercial demonstration of technologies to produce substitutes for natural gas, including coal gasification. The administrator must consider proposals from potential participants based upon federal assistance, which would be in the form of a joint federal-industry corporation, but these proposals must be accompanied by a report justifying use of federal assistance. Also, this section calls for accelerating the commercial demonstration of technologies for producing syncrude and liquid petroleum products from coal, pro-

vided that the potential participants consider federal assistance through guaranteed prices or purchase of the products and submit a report on the advantages of using this form of federal assistance.

A provision on patent policy, licensing, and waivers is included in this act, with the prior approval of the Senate, conference committee, and the executive branch. The act's patent section adopts the basic structure of the patent policy of the National Aeronautics and Space Act, with some modifications derived from the Atomic Energy Act. Within 12 months of enactment, the administrator, the Attorney General, the Secretary of Commerce, and other presidentially-designated officials must submit to the president and Congress a report outlining the applicability of existing patent policies that affect the programs under the act.

In the last section of this act, the Council on Environmental Quality (CEQ) has been authorized and directed to analyze the effect of nonnuclear energy technologies on the environment. Each year, \$500,000 must be made available by fund transfer to the CEQ. Assessments of the availability of adequate water resources shall be performed as a precondition for federal assistance in demonstration plant projects and in commercial application of energy technologies. The Water Resources Council, at the request of the administrator, must undertake water source requirements and water supply availability assessments, the results of which must then be published in the *Federal Register*. One million dollars annually must be made available by fund transfer to the Water Resources Council. Finally, the National Bureau of Standards is required to evaluate all promising energy-related inventions and is authorized to promulgate regulations to fulfill this requirement.

The President may require the allocation of materials and equipment that are scarce, critical, and essential to carry out the purposes of this act. The President must submit any such action to Congress for review.

## ENERGY LEGISLATION — 94TH CONGRESS

### TAX REDUCTION ACT OF 1975 (P.L. 94-12)

The Tax Reduction Act of 1975, signed into law March 29, 1975, provides for a \$22.8 billion tax cut package that includes the repeal of the 22 percent depletion allowance for oil and gas produced on or after January 1, 1975 (with certain exceptions) and limitations on the use of foreign tax credits by oil and gas companies.

The 22 percent depletion allowance will continue for small independent oil and gas producers whose companies have no retail outlets or whose refinery capacity is less than 50,000 barrels a day. Initially, small producers retain

the depletion allowance for the first 2,000 barrels per day or 12 million cubic feet of natural gas; however, this amount is reduced 200 barrels per day from 1976 through 1980. In 1980 the exemption is lowered to 1,000 barrels per day or six million cubic feet of gas. The depletion rate is reduced to 20 percent in 1981, to 18 percent in 1982, to 16 percent in 1983, and to 15 percent in 1984. To prevent taxpayer use of the exemption to avoid all taxes, the deduction resulting from the small producer exemption cannot exceed 65 percent of



the taxpayer's net income from all sources (computed without regard to depletion allowed under the small producer exemption, net operating loss carrybacks, or capital loss carrybacks).

Other exemptions include a 22 percent depletion allowance for natural gas sold under fixed rate contracts in effect February 1975, which does not permit price adjustment after that date to reflect repeal of depletion, and for gas produced and sold by a producer before July

1, 1976, which is subject to Federal Power Commission regulation and which does not permit price adjustment after February 1, 1975, to reflect the depletion allowance repeal. The depletion allowance also remains in effect for oil and gas production (limited to 1,000 barrels per day or six million cubic feet per day) for secondary and tertiary recovery until 1984 and for any geothermal deposit determined to be a gas well.

### ENERGY POLICY AND CONSERVATION ACT OF 1975 (P.L. 94-163)

The Energy Policy and Conservation Act (EPCA) provides for increasing domestic energy supplies and availability, restraining energy demands, and preparing for energy emergencies. In order to achieve the first of these goals, the act requires that certain oil and natural gas burning installations convert to coal. The act also encourages the development of underground coal mines and the production of oil and gas at the maximum efficient rate.

To restrain energy demands, the act moves to improve energy efficiency by requiring automobiles to meet certain fuel economy standards and by implementing energy labeling for consumer products. A program of State Energy Conservation Plans, including both mandatory and voluntary measures, is also established by EPCA to help reduce energy demands.

To prepare for possible energy emergencies, the law provides for the establishment of contingency conservation and rationing programs. A four-part Strategic Petroleum Reserve System to supply petroleum in the event of a national emergency is also provided for in the law. Under EPCA, a Early Storage Reserve (ESR) would con-

tain at least 150 million barrels of petroleum by 1978 as the precursor to the Strategic Petroleum Reserve (SPR). The act also provides that by 1982, the Strategic Petroleum Reserve would reach its full capacity of approximately 500 million barrels. Regional Petroleum Reserve (RPR) storage is part of the SPR.

Petroleum storage in the proposed Industrial Petroleum Reserve (IPR) has been projected by FEA at approximately 185 million barrels. Creation of an IPR is to be at the discretion of FEA based on studies of industry's needs.

The law also contains amendments to the Emergency Petroleum Allocation Act which establish a new oil price policy. The new policy in EPCA establishes a pricing formula for domestically-produced crude oil based on an initial crude oil price rollback and gradual increases in the prices received by domestic producers over a 40-month period. The President is given broad flexibility to set prices for various categories of oil production including the authority to recommend to Congress that various products be decontrolled.

### NAVAL PETROLEUM RESERVES PRODUCTION ACT OF 1976 (P.L. 94-258)

The Naval Petroleum Reserves Production Act represents a dramatic change in national policy toward the Naval Petroleum Reserves (NPR). The act provides that the responsibility for Naval Petroleum Reserves No. 4 be transferred from the Navy to the Department of Interior on June 1, 1977, and that the Navy produce oil from

NPR Nos. 1, 2, and 3 at a "maximum efficient rate."

Procedural guidelines for the transfer of NPR No. 4 are included in Title I of the act along with the requirements that various studies be made. Title II addresses how the Navy should proceed in the production and eventual sales of petroleum from NPR Nos. 1, 2, and 3.

### COASTAL ZONE MANAGEMENT ACT AMENDMENTS OF 1976 (P.L. 94-370)

The Coastal Zone Management Act amendments compensate state and local governments for the social, economic, and environmental impacts of coastal energy activity. The law requires that outer continental shelf exploration, development, and production plans be consistent with approved state program plans. Each state is required to develop a coastal zone management program

in order to be eligible for loans, loan guarantees, and planning grants also provided for in the law.

The National Oceanic and Atmospheric Administration is responsible for implementing the Coastal Zone Management Act amendments. The level of appropriations for new programs under this act will be determined by the 95th Congress.

### FEDERAL COAL LEASING AMENDMENTS OF 1975 (P.L. 94-377)

The Federal Coal Leasing Amendments provide additional revenue to states for the planning, construction, and maintenance of public facilities and for public services by increasing the state's share of federal revenue from coal production to 50 percent. This is an increase of 12.5 percent.

The law also requires that competitive bidding be

implemented and provides that leaseholders that fail to produce coal within 10 years from the lease date not be allowed to bid on additional leases. The law provides for 20-year leases and requires continuous production. The legislation states that preference right leases are to be replaced by a system of two-year exploration licenses without preference rights.

### ENERGY CONSERVATION AND PRODUCTION ACT (P.L. 94-385)

One provision of the Energy Conservation and Production Act extends the Federal Energy Administration until December 31, 1977. The law also directs FEA to develop improved electric rate design proposals and authorizes FEA to fund load management improvement demonstration projects. FEA is also given responsibilities for a program to weatherproof low income housing to be implemented through grants to states.

Stripper wells producing less than 10 barrels of oil per day are exempted by this act from the price controls estab-

lished under the Emergency Petroleum Allocation Act.

The Department of Housing and Urban Development is directed by this act to develop energy conservation performance standards for new residential and commercial buildings within three years. Failure by states to adopt these standards could result in the withdrawal of all federally insured mortgage funds if Congress determines such measures are necessary.

Appropriations for the programs called for by this law are to be considered during the 95th Congress.

### THE ELECTRIC VEHICLE RESEARCH, DEVELOPMENT, AND DEMONSTRATION ACT OF 1976 (P.L. 94-413)

The Electric Vehicle Research, Development, and Demonstration Act authorizes ERDA to establish a program to promote electric vehicle technologies and to demonstrate the commercial feasibility of electric and

hybrid vehicles. As part of the demonstration program the Department of Defense, the Postal Service, GSA, and other federal agencies are to incorporate electric vehicles into their fleets.

### THE ALASKA NATURAL GAS TRANSPORTATION ACT OF 1976 (P.L. 94-586)

The Alaska Natural Gas Transportation Act establishes the procedure by which an Alaskan natural gas transportation route is to be selected. Based on the findings of the Federal Power Commission, the President is to recommend a route to Congress by September 1977, at which

time Congress has 60 days to approve it by joint resolution. The law also provides that normal procedural restrictions in issuing construction permits can be waived in order to speed construction.

# ENERGY LEGISLATION ENACTED BY THE 93RD CONGRESS

Bill Number	Short Title or Subject	Senate		House of Representatives		Approval Dates—Public Law Number
		Committee	Floor Action	Committee	Floor Action	
H.R. 5451	Oil Pollution Control Act Amendments	Commerce (Oceans and Atmosphere)	Passed Sep. 24, 1973	Merchant Marine and Fisheries	Passed May 8, 1973	Oct. 4, 1973 P.L. 93-119
S. 1081 (H.R. 9120)	Trans-Alaska Pipeline	Interior and Insular Affairs	Passed Jul. 17, 1973	Interior and Insular Affairs (Public Lands)	Passed Aug. 2, 1973	Nov. 16, 1973 P.L. 93-153
S. 1570 (H.R. 9681) (S. 1694, 1723 included as amendments)	Emergency Petroleum Allocation	Interior and Insular Affairs	Passed Jun. 5, 1973	Interstate and Foreign Commerce	Passed Oct. 17, 1973	Nov. 27, 1973 P.L. 93-159
H.R. 11324 (S. 2702)	Emergency Daylight Savings Time	Commerce	Passed H.R. 11324, as amended, Dec. 4, 1973	Interstate and Foreign Commerce	Passed Nov. 27, 1973	Dec. 15, 1973 P.L. 93-182
H.R. 11372	National 55 mph Highway Speed	Public Works	Passed as amended, Dec. 14, 1973; agreed on same House amendments and receded on one of its own Dec. 27, 1973	Public Works (Energy)	Passed Dec. 3, 1973; concurred in some Senate amendments and disagreed as to others, Dec. 21, 1973	Jan. 2, 1974 P.L. 93-239
S. 1070 (H.R. 5975)	Implementation of Convention Relating to Intervention on the High Seas in Cases of Oil Pollution Casualties	Commerce (Oceans and Atmosphere)	Passed Nov. 5, 1973	Merchant Marine and Fisheries (Coast Guard and Navigation)	Passed in lieu, Jan. 22, 1974	Feb. 5, 1974 P.L. 93-249
H.R. 11793	Federal Energy Administration Act	Government Operations	S. 2776 passed Dec. 19, 1973. H.R. 11793 passed as amended containing text of S. 2776 Mar. 13, 1974	Government Operations (Legislation and Military Operations)	Passed Mar. 7, 1974	May 7, 1974 P.L. 93-275
H.R. 14368	Energy Supply and Environmental Coordination Act		Passed amended May 14, 1974	Interstate and Foreign Commerce	Passed May 14, 1974 Jun. 6, 1974	Jun. 22, 1974 P.L. 93-319
H.R. 14434	Energy Research and Development Appropriations for Principal Government Agencies	Appropriations	Passed Jun. 12, 1974	Appropriations	Passed Apr. 30, 1974	Jun. 30, 1974 P.L. 93-332
H.R. 14920 (S. 2465) (Supersedes H.R. 14172) (in lieu of H.R. 11762, 11212)	Geothermal Energy Research, Development, and Demonstration Act of 1974		Passed amended Jun. 11, 1974	Science and Astronautics	Passed Jul. 10, 1974	Sep. 3, 1974 P.L. 93-332

**ENERGY LEGISLATION ENACTED BY  
THE 93RD CONGRESS (Cont'd)**

Bill Number	Short Title or Subject	Senate		House of Representatives		Approval Dates—Public Law Number
		Committee	Floor Action	Committee	Floor Action	
H.R. 11854 (S. 2658) (H.R. 10952 digested by H.R. 11864) (H.R. 11179 Cf H.R. 11864)	Solar Heating and Cooling Demonstration Act	Aeronautical and Space Sciences	Passed amended May 21, 1974	Science and Astronautics	Passed Feb. 13, 1974	Sep. 3, 1974 P.L. 93-409
H.R. 11510 (S. 2744)	Energy Reorganization Act of 1974	Government Operations	Passed amended Aug. 15, 1974	Government Operations	Passed Dec. 19, 1973	Oct. 11, 1974 P.L. 93-438
S. 3234 (H.R. 16371)	Solar Energy Research and Development, Program Federal Authorize	Interior and Insular Affairs	Passed Sep. 17, 1974		Passed amended Sep. 19, 1974	Oct. 26, 1974 P.L. 93-473
S. 11251	Tariff, Methanol, Certain Uses Elimination of Duty	Finance	Passed amended Aug. 13, 1974	Ways and Means	Passed May 7, 1974	Oct. 26, 1974 P.L. 93-482
H.R. 16757 (S. 3717)	Emergency Petroleum Allocation Act of 1973, extended to Aug. 13, 1973	Interior and Insular Affairs	Passed Aug. 12, 1974	Interstate and Foreign Commerce	Passed Nov. 19, 1974	Dec. 5, 1974 P.L. 93-511
S. 1283 (H.R. 13565) (Superseded H.R. 6602, 11724, 11857) (H.R. 9295)	Federal Nonnuclear Energy Research and Development Act of 1974	Interior and Insular Affairs	Passed Dec. 7, 1973	Interior and Insular Affairs	Passed amended Sep. 11, 1974	Dec. 31, 1974 P.L. 93-577
S. 10701 (H.R. 10701 in lieu of H.R. 5898, 11951) (H.R. 10701 superseded S. 1751 and H.R. 7501)	Deepwater Ports for Huge Oil Tankers	Referred jointly to Public Works, Commerce, and Interior and Insular Affairs	Passed amended Oct. 9, 1974	Public Works	Passed Jun. 6, 1974	Jan. 3, 1975 P.L. 93-627
H.R. 10710	Trade Reform Act	Finance	Passed amended Dec. 13, 1974	Ways and Means	Passed Dec. 11, 1973	Jan. 3, 1975 P.L. 93-618

**ENERGY LEGISLATION ENACTED BY  
THE 94TH CONGRESS**

Bill Number	Short Title or Subject	Senate		House of Representatives		Public Law and Date Enacted
		Committee	Floor Action	Committee	Floor Action	
S.J. Res. 48	A bill to extend the National Commission on Supplies and Shortages to Dec. 31, 1975	Banking, Housing and Urban Affairs	Passed Mar. 6, 1975	Banking, Currency and Housing	Passed Mar. 10, 1975	Mar. 21, 1975 P.L. 94-9
H.R. 2166 (H. Res. 259 and H. Res. 358)	Tax Reduction Act, 1975 (Repeals oil depletion allowance)	Finance Reported Mar. 17, 1975	Passed amended Mar. 22, 1975	Ways and Means Reported Feb. 25, 1975	Passed Feb. 27, 1975	Mar. 29, 1975 P.L. 94-12
S.J. Res. 94	A bill to extend the Defense Production Act of 1950 and to extend the funding of the National Commission on Productivity and Work Quality for 90 days	Banking, Housing and Urban Affairs	Passed Jun. 10, 1975	Banking, Currency and Housing	Passed Jun. 17, 1975	Jun. 28, 1975 P.L. 94-42
H.J. Res. 560	A bill to extend the National Commission on Supplies and Shortages to Oct. 7, 1976	Banking, Housing and Urban Affairs	Passed Jul. 22, 1975	Banking, Currency and Housing	Passed Jul. 21, 1976	Aug. 5, 1975 P.L. 94-72
H.R. 3130	A bill to establish guidelines for environmental impact statements, preparation of, procedures, clarify	Interior and Insular Affairs	Passed amended May 22, 1975	Merchant Marine and Fisheries	Passed Apr. 21, 1975	Aug. 9, 1975 P.L. 94-83
H.R. 9524	Emergency Petroleum Allocation Act of 1973	Interior and Insular Affairs	Passed Sep. 26, 1975	Interior and Insular Affairs	Passed Sep. 26, 1975	Sep. 29, 1975 P.L. 94-99
H.J. Res. 672	Extending the Defense Production Act and the funding of the National Commission on Productivity and Work Quality	Banking, Housing and Urban Affairs	Passed Sep. 30, 1975	Banking, Currency and Housing	Passed Sep. 29, 1975	Oct. 1, 1975 P.L. 94-100
H.R. 5952	To amend the Water Resource Planning Act to revise membership to the Water Resources Council	Interior and Insular Affairs	Passed Oct. 7, 1975	Interior and Insular Affairs	Passed Oct. 6, 1975	Oct. 16, 1975 P.L. 94-112
S. 2667	Extended Emergency Petroleum Allocation Act of 1973 until Dec. 15, 1975	Interstate and Foreign Commerce	Passed Nov. 14, 1975	Interstate and Foreign Commerce	Passed Nov. 14, 1975	Nov. 14, 1975 P.L. 94-133
S. 1537 H.R. 10031	Extend Defense Production Act through Sep. 30, 1977	Banking, Housing and Urban Affairs	Passed Sep. 15, 1975	Banking, Currency and Housing	Passed Nov. 14, 1975	Dec. 16, 1975 P.L. 94-152
S. 622	Energy Policy and Conservation Act	Interior and Insular Affairs	Passed Apr. 10, 1975	Interstate and Foreign Commerce	Passed Sep. 23, 1975	Dec. 22, 1975 P.L. 94-163
H.R. 3474 S. 598	ERDA Appropriations FY 1976	Interior and Insular Affairs	Passed Jul. 31, 1975	Science and Technology; Joint Committee on Atomic Energy	Passed Jan. 20, 1976	Dec. 31, 1975 P.L. 94-187
H.R. 9861	Department of Defense Appropriations for FY 1976	Armed Services	Passed Nov. 18, 1975	Armed Services	Passed Oct. 2, 1975	Feb. 9, 1976 P.L. 94-212
H.R. 49	Naval Petroleum Reserves Production Act of 1976	Interior	Passed Mar. 24, 1976	Interior	Passed Mar. 31, 1976	Apr. 5, 1976 P.L. 94-258

**ENERGY LEGISLATION ENACTED BY  
THE 94TH CONGRESS (Cont'd)**

Bill Number	Short Title or Subject	Senate		House of Representatives		Public Law and Date Enacted
		Committee	Floor Action	Committee	Floor Action	
H.R. 200	A bill to extend the jurisdiction of the U.S. over certain ocean areas	Interstate and Foreign Commerce	Passed Jan. 28, 1976	Merchant Marine and Fisheries	Passed Oct. 9, 1975	Apr. 13, 1976 P.L. 94-265
H.R. 3981	Coastal Zone Management Act Amendments of 1976	Commerce	Passed Jul. 16, 1976	Merchant Marine and Fisheries	Passed Mar. 11, 1976	Jul. 26, 1976 P.L. 94-370
S. 391	Federal Coal Leasing Act Amendments of 1976	Interior and Insular Affairs	Passed Jul. 31, 1975	Interior	Passed Jan. 21, 1976	Vetoed Jul. 3, 1976 Veto overridden Aug. 4, 1976 P.L. 94-377
H.R. 12169	Energy Conservation and Production Act of 1976	Government Operations	Passed Aug. 5, 1976	Interstate and Foreign Commerce	Passed Aug. 10, 1976	Aug. 14, 1976 P.L. 94-385
H.R. 8800	The Electric Vehicle Research, Development, and Demonstration Act of 1976	Interstate and Foreign Commerce	Passed Jun. 14, 1976	Science and Technology	Passed Sep. 5, 1976	Vetoed Sep. 13, 1976 Veto overridden Sep. 17, 1976 P.L. 94-413
S. 3521	The Alaska Natural Gas Transportation Act of 1976	Interstate and Foreign Commerce, Interior and Insular Affairs	Passed Jul. 1, 1976	Interstate and Foreign Commerce, Interior and Insular Affairs	Passed Sep. 30, 1976	Oct. 22, 1976 P.L. 94-586

**ENERGY LEGISLATION IN 94th CONGRESS--LEGISLATION VETOED**

Bill Number	Short Title or Subject	SENATE		HOUSE OF REPRESENTATIVES		Conference Action	Veto Date
		Committee	Floor Action	Committee	Floor Action		
H.R. 1767 (H. Res. 142) (H.R. 2138, 2139, 2140, 2203, 2316, 2478, 2550)	Oil Imports Presidential Authority to impose fees, suspend 90 days	Finance Reported Feb. 17, 1975	Passed Feb. 19, 1975	Ways and Means Reported Jan. 30, 1975	Passed Feb. 5, 1975		Vetoed Mar. 4, 1975
H.R. 25 (H. Res. 304) (S. 7) (H.R. 25 in lieu of H.R. 2062, 3119, 3463, 3472, S. 652)	Surface Mining Control and Reclamation Act, 1975	Interior and Insular Affairs	Passed amended Mar. 20, 1975	Interior and Insular Affairs Reported Mar. 6, 1975	Passed Mar. 18, 1975	Report filed in House and Senate May 2, 1975. Senate agreed to report May 5, 1975, and House agreed May 7, 1975	Vetoed May 20, 1975. House sustained veto Jun. 10, 1975
H.R. 4035 (S. 621)	Petroleum Product, Presidential decisions removing existing controls, congressional review	Interior and Insular Affairs	Passed Jun. 11, 1975	Interstate and Foreign Commerce Reported Mar. 14, 1975	Passed Jun. 5, 1975		Vetoed Jul. 21, 1975
S. 1849 (S. 623)	Emergency Petroleum Allocation Act Extension	Interior and Insular Affairs	Passed Jul. 15, 1975	Interior and Insular Affairs	Passed Jul. 31, 1975		Vetoed Sep. 9, 1975

**CHAPTER III**

**FEDERAL GOVERNMENT  
ENERGY RESEARCH AND  
DEVELOPMENT**

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## INTRODUCTION

The oil embargo of 1973, a critical balance of payments deficit, and the increasing cost of crude oil have been significant factors in the development and formulation of presidential policy directives and congressional legislation intended to curb U.S. dependence on foreign petroleum products; to develop U.S. energy resources; and to research, develop, and test alternative energy sources.

Efforts to coordinate federal energy R&D policy were initiated through the December 1973 report to the President by Chairman Ray of the Atomic Energy Commission (AEC) and joint government-industry energy R&D panels. In the report, a five-year, \$10 billion program of energy R&D was recommended in order to develop potential domestic energy resources as fast as possible. Based on the recommendations in the AEC report, Congress legislated and the President approved a number of bills that created a single federal energy R&D administration. The two most significant pieces of legislation are the Energy Reorganization Act of 1974 (P.L. 93-428), approved 11 October 1974, and the Federal Nonnuclear Energy Research and Development Act of 1974 (P.L. 93-577), approved 31 December 1974. These acts, and other relating to major energy programs, are discussed in Chapter II.

Throughout the federal government, departments and agencies are involved in energy research, development and

demonstration to varying degrees. There are agencies and departments, however, that serve as the principal sources of energy-related research for the nation. The programs, funding and organization of the agencies and departments which have this responsibility are covered in this order:

- Energy Research and Development Administration
- Federal Energy Administration
- Department of Commerce
- Department of Defense
- Housing and Urban Development
- Department of Interior
- Department of State
- Department of Transportation
- National Aeronautics and Space Administration
- National Science Foundation
- Environmental Protection Agency

Various other federal agencies are responsible for recommending comprehensive national energy policies and priorities. Among these agencies are:

- Council on Environmental Quality
- Energy Resources Council
- Federal Power Commission
- Office of Technology Assessment
- Nuclear Regulatory Commission
- Tennessee Valley Authority

## ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

ERDA officially began its tasks on 19 January 1975, under Executive Order 11834. ERDA has been organized around major energy sources. The organizational components include those related to fossil energy development; energy conservation; solar and geothermal energy; the development of nuclear energy; and environmental and safety research. Also included are organizational components responsible for defense-related activities, national security, and essential staff functions. ERDA's organization is shown in Figure III-1.

Soon after its establishment, ERDA, in compliance with its legislative mandate, began to determine the requirements necessary for the development of a national plan for energy R&D. Using the policy goals established by Project Independence as guidelines, ERDA responded with a set of national technology goals:

- Expand the domestic supply of economically recoverable energy-producing raw materials.
- Increase the use of essentially inexhaustible domestic energy resources.
- Efficiently transform fuel resources into more desirable forms.

- Increase the efficiency and reliability of the processes used in energy conversion and delivery systems.
- Transform consumption patterns to improve energy use.
- Increase end-use efficiency.
- Protect and enhance the general health, safety, welfare, and environment affected by energy.
- Perform basic and supporting research and technical services related to energy.

These goals were incorporated into ERDA's first report to Congress known as *ERDA 48* and have been more recently refined in *ERDA 76-1*. The recommendations and projected impact included in the report are shown in Table III-1; proposed funding appears in Table III-2.

Progress in some areas of ERDA's technology goals has not been as rapid as anticipated. Budget requests have been geared to compensate for these delays as well as new developments in both technology and policy. Areas of emphasis include:

- *Conservation* - A greatly expanded program to improve technology and encourage conservation of energy in buildings, industry, and transportation, thus

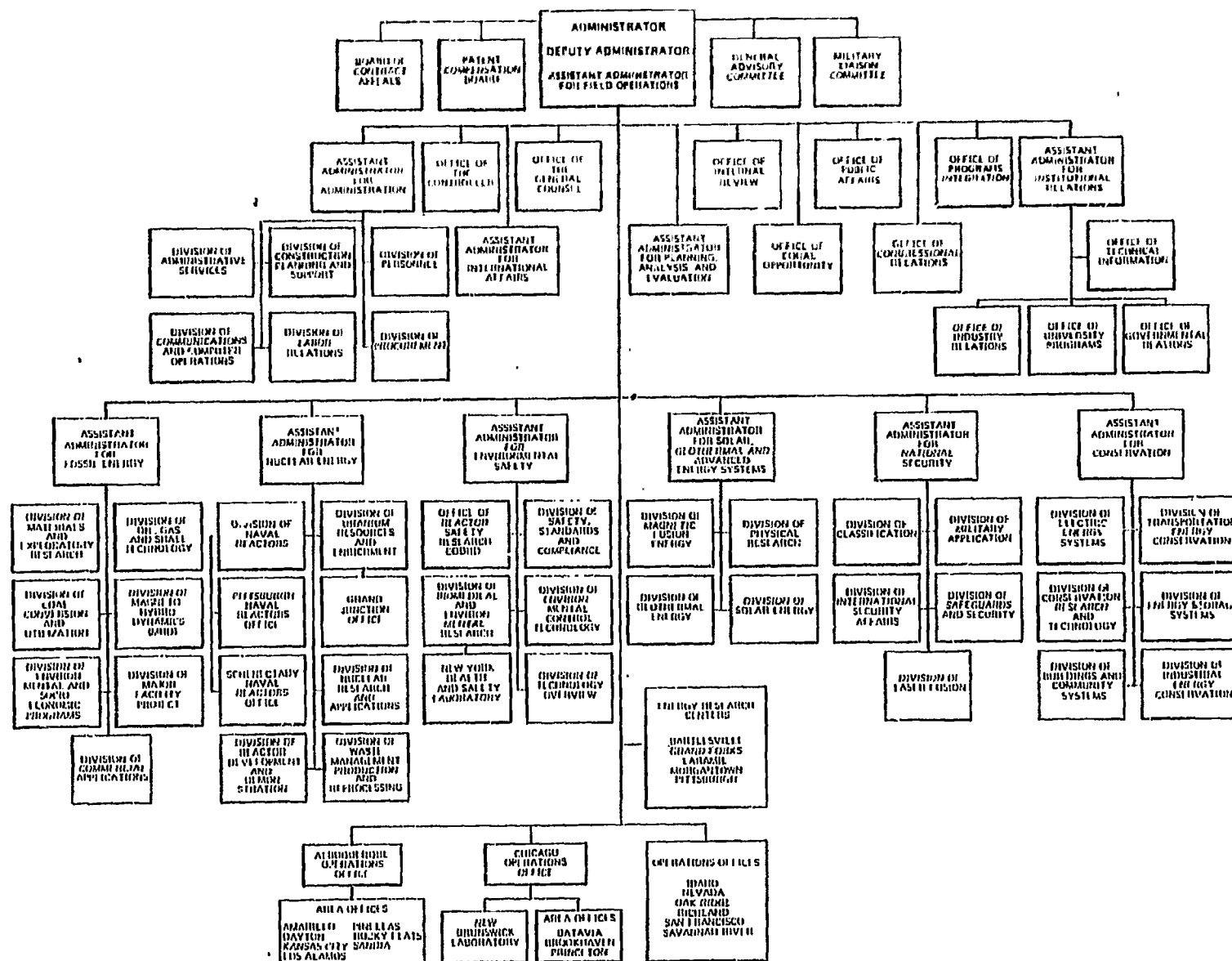


Figure III-1. ORGANIZATION OF ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION (ERDA)

Table III-1

## STATUS OF MAJOR ENERGY TECHNOLOGY GOALS

Technology	Term of Impact <sup>a</sup>	Direct Substitution for Oil and Gas <sup>b</sup>	RD&D Status <sup>c</sup>	Impact in Year 2000 in Quads <sup>d</sup>
<b>GOAL I: Expand the Domestic Supply of Economically Recoverable Energy Producing Raw Materials</b>				
Oil and gas—enhanced recovery	Mid	Yes	Pilot	13.6
Oil shale	Near	Yes	Study/Pilot	7.3
Geothermal	Mid	No	Lab/Pilot	3.1-5.6
<b>GOAL II: Increase the Use of Essentially Inexhaustible Domestic Energy Resources</b>				
Solar electric	Long	No	Lab	2.1-4.2
Breeder reactors	Long	No	Pilot/Demo	3.1
Fusion	Long	No	Lab	—
<b>GOAL III: Efficiently Transform Fuel Resources Into More Desirable Forms</b>				
Coal—direct utilization utility/industry	Near	Yes	Pilot/Demo	24.5
Waste materials to energy	Near	Yes	Comm	4.9
Gaseous and liquids fuels from coal	Mid	Yes	Pilot/Demo	14.0
Fuels from biomass	Long	Yes	Lab	1.4
<b>GOAL IV: Increase the Efficiency and Reliability of the Processes Used in the Energy Conversion and Delivery Systems</b>				
Nuclear converter reactors	Near	No	Demo/Comm	28.0
Electric conversion efficiency	Mid	No	Lab	2.6
Energy storage	Mid	No	Lab	—
Electric power transmission and distribution	Long	No	Lab	1.4
<b>GOAL V: Transform Consumption Patterns to Improve Energy Utilization</b>				
Solar heat and cooling	Mid	Yes	Pilot/Demo	5.9
Waste heat utilization	Mid	Yes	Study/Demo	4.9
Electric transport	Long	Yes	Study/Lab	1.3
Hydrogen in energy systems	Long	Yes	Study	—
<b>GOAL VI: Increase End-Use Efficiency</b>				
Transportation efficiency	Near	Yes	Study/Lab	9.0
Industrial energy efficiency	Near	Yes	Study/Comm	8.0
Conservation in buildings and consumer products	Near	Yes	Study/Comm	7.1

<sup>a</sup>Near—now through 1985; Mid—1985 through 2000; Long—Post-2000.

<sup>b</sup>Assumes no change in end-use device.

<sup>c</sup>Progression of RD&D status: Study stage; Lab—Laboratory scale; Pilot—Pilot plant scale; Demo—Demonstration plant scale; Comm—Commercial scale.

<sup>d</sup>Quad = one quadrillion Btu's or  $10^{15}$  Btu's.

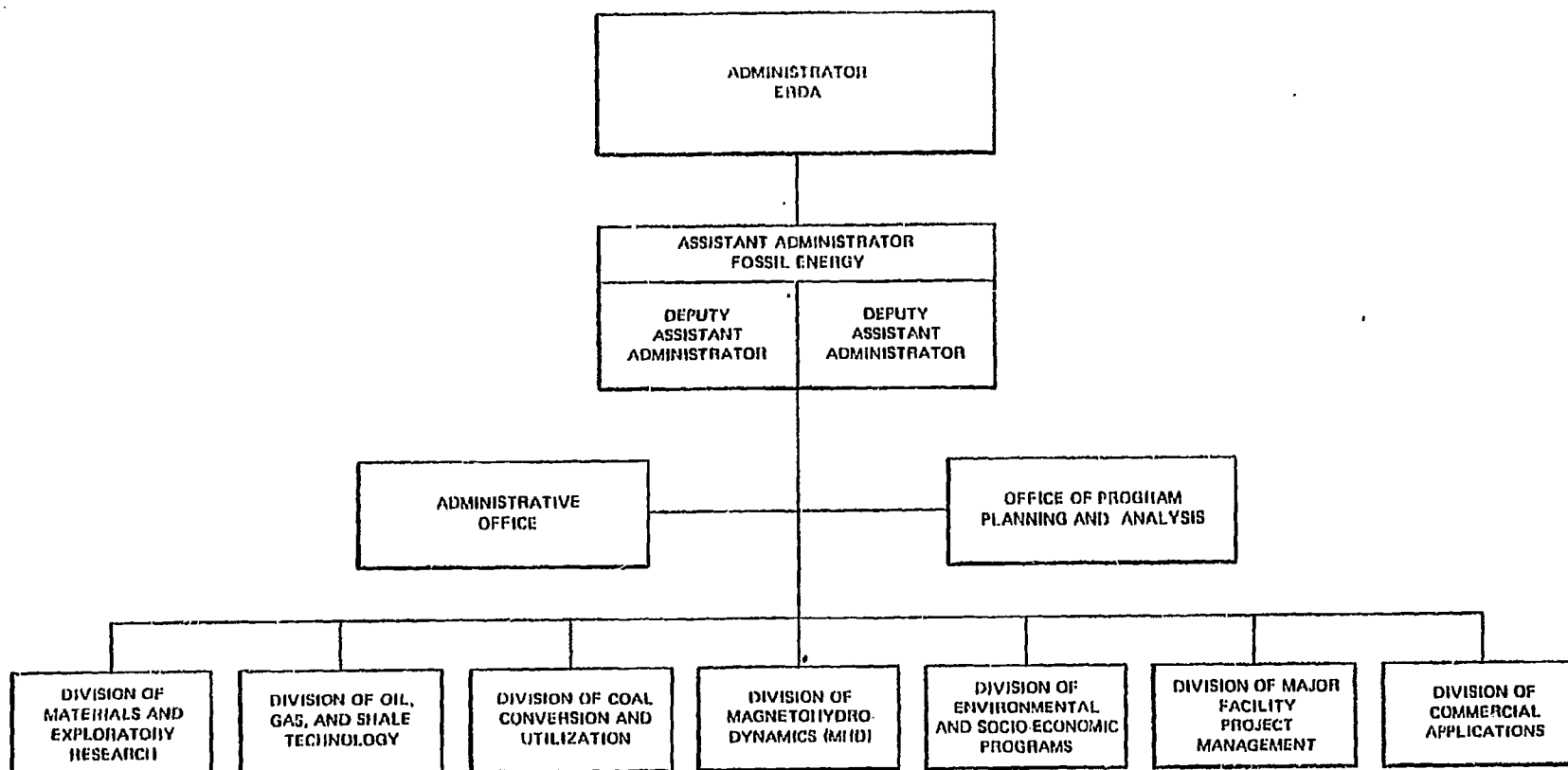
Source: ERDA 76-1.

directly reducing imports of foreign oil and gas.

- **Solar Energy** — To provide a total of 226 units to demonstrate solar heating and cooling in residential and commercial buildings, to accelerate development of solar electric technologies, and to establish the Solar Energy Research Institute.
- **Geothermal Energy** — To increase technology development, resource assessment and support of industry

demonstration plants through loan guarantees to develop our geothermal energy resources.

- **Fusion Power** — To exploit recent breakthroughs and continue research to determine the scientific feasibility of obtaining virtually unlimited fusion power for the long term; to continue construction of the Tokamak Test Reactor at Princeton, New Jersey; and to expand the laser fusion core research program and



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Figure III-2. ORGANIZATION OF ERDA - FOSSIL ENERGY

utilize more fully unique university and industrial capabilities.

- *Fission Reactors* – For continued support of the development of the liquid metal fast breeder reactor along with the necessary safety and environmental research to establish and demonstrate its commercial feasibility. Also, to continue efforts toward increasing utilization and efficiency of existing light water reactors to reduce electric energy costs and conserve fossil fuels.

## Fossil Energy Development

The objectives of fossil energy RD&D are to develop technical options to increase the availability of fossil energy sources and to ensure the development of national fossil energy resources on a technically sound, economically feasible, and environmentally acceptable basis. These objectives are being accomplished through programs in coal, petroleum and natural gas; in situ technology; extraction technology; and resource appraisal. ERDA's fossil energy organization is depicted in Figure III-2.

Near-term activities emphasize increased production and more efficient use of fossil fuel. The long-range activities emphasize the transfer of new, government-developed technologies to the commercial sector. Most programs currently have laboratory systems, pilot plants or large scale demonstration projects in various stages of completion. (Refer to Table III-3.)

### Coal Program

ERDA's coal research is a multidirectional part of its fossil energy development program. The research falls into four sectors: direct combustion of coal, efficient coal combustion, conversion of coal to oil and gas, and demonstration plants for scaling up to commercial needs.

The direct combustion program emphasizes the development of fluidized-bed combustors, capable of burning all types and grades of coal. The advanced power systems program is directed toward improvement of gas turbines used in electric power generation to enable them to operate reliably at higher temperatures with greater efficiency.

The magnetohydrodynamic (MHD) power system program emphasizes development of electrical utility power generation systems, using powdered coal as the primary fuel. When combined with steam generating steam systems, MHD offers greater potential for significant improvements in overall power system thermal efficiencies than any other advanced power cycle.

The objective of the coal conversion program is to develop and demonstrate more efficient and economic

second and third generation technologies for liquefaction and gasification. This will provide fuels compatible with the existing network of fuel transportation systems, storage systems, and marketing organizations. The refined fuels must meet requirements for the generation of electric power, home and industrial heating, transportation fuels, and raw materials for production of chemicals.

The demonstration plant program will bridge conversion technology from the pilot plant to commercial development. The program, in partnership with industry, seeks to demonstrate, at near commercial scale, second generation technology by providing part of the capital requirements for plant construction as well as funds for technical support.

### Petroleum and Natural Gas Program

The enhanced oil and gas recovery program has been identified as an area of high priority with near-term impact. Methods under development offer a way of recovering more oil and gas from fields in the United States that are already known, and often nearing depletion by conventional methods, thus enlarging our domestic energy supply. The program has expanded rapidly from its inception in 1974 with a cost-sharing contract program between ERDA and the U.S. oil industry.

Goals of the nation's enhanced oil and gas recovery program are to add 2 billion barrels of oil and 10 trillion cubic feet of natural gas to proved domestic reserves and to increase daily production by 500 thousand barrels of oil and 3 billion cubic feet of natural gas by 1980. Ultimate recovery expected through enhanced oil and gas recovery equals an estimated 60-plus billion barrels of oil and 300-plus trillion cubic feet of natural gas.

### In-Situ Technology Development

The two programmatic divisions of in-situ technology development are in-situ coal gasification and oil shale recovery. The basic strategy of both programs is to develop improved techniques to facilitate the commercialization of each process.

The objectives of coal gasification are to develop and demonstrate a commercial technology for converting coal in place into low- and medium-Btu gas. This includes plans to transfer this technology into the commercial industrial sector through cooperative programs. This method reduces the environmental consequences of coal mining and allows unminable coal to be used for energy.

The oil shale in-situ program will serve as a technological base for development of a commercial shale-oil and gas industry.

Table III-2

**ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION  
BUDGET REQUESTS<sup>a</sup> FOR FY 1977 AND FY 1978<sup>b</sup>  
(Millions of Dollars)**

	Estimated Request FY 1977		Estimated Request FY 1978 <sup>b</sup>	
	Budget Authority	Budget Outlay	Budget Authority	Budget Outlay
<b>Energy Research Development and Demonstration Programs</b>				
Conservation	161	125	318	244
Fossil energy	483	445	640	519
Solar heating and cooling	86	61	90	86
Solar electric and other	204	122	245	164
Geothermal	55	49	88	68
Fusion power development	416	322	433	392
Liquid metal fast breeder reactor	686	595	656	651
Nuclear fuel cycle and safeguards	406	336	611	486
Other fission	146	122	148	137
Special foreign currency fund	0	2	2	3
Subtotal	2,643	2,179	3,201	2,750
<b>Supporting Research</b>				
Environmental and biomedical research	181	175	215	200
Basic energy sciences	156	137	175	162
Subtotal	337	312	390	362
<b>Financial Incentive Activities</b>				
Geothermal resources development fund	30	4	30	7
Synthetic fuels project	0	0	300	3
Subtotal	30	4	330	10
<b>Total energy research, development and demonstration programs</b>	<u>3,010</u>	<u>2,495</u>	<u>3,921</u>	<u>3,122</u>

<sup>a</sup>Includes capital equipment.<sup>b</sup>Carter administration figures.**Solar Energy Development**

The primary goal of the solar energy program is to develop and demonstrate as early as practical those solar energy applications that are commercially attractive and environmentally acceptable. The four major program units that have been established to meet this overall goal are solar thermal applications, photovoltaic applications, wind energy conversion, and ocean thermal conversion.

**Solar Thermal Applications**

The program consists of three major elements: (1) demonstration program for both commercial and residential applications, initially utilizing available systems; (2) a development program to support the demonstration program on a near-term basis utilizing available sub-systems and components, and (3) a research and development program to advance solar heating and cooling technology

Table III-3

**ERDA'S FOSSIL ENERGY DEVELOPMENT  
BUDGET REQUEST FOR FY 1977 AND FY 1978<sup>a</sup>**  
(Millions of Dollars)

	Estimated Request FY 1977		Estimated Request FY 1978 <sup>a</sup>	
	Budget Authority	Budget Outlay	Budget Authority	Budget Outlay
<b>Coal</b>				
Liquefaction	73.0	85.0	107.4	110.0
Gasification				
High Btu	44.1	58.8	51.5	43.0
Low Btu	33.1	39.9	74.4	47.5
Advanced power systems	22.5	12.8	25.7	24.0
Direct combustion	51.9	56.8	53.4	57.0
Advanced research and supporting technology	37.1	36.6	40.3	42.2
Demonstration plants	100.3	68.1	113.9	54.2
Magnetohydrodynamics	40.0	29.0	50.5	37.3
Other plant and capital equipment	7.0	1.3	9.6	5.3
<b>Total Coal</b>	<b>409.0</b>	<b>388.3</b>	<b>526.7</b>	<b>425.0</b>
<b>Petroleum and Natural Gas</b>				
Enhanced oil recovery	23.9	21.8	46.4	40.3
Enhanced gas recovery	14.9	11.3	22.3	19.7
Drilling, exploration and offshore technology	2.4	1.6	1.6	2.0
Processing and utilization	1.8	1.8	1.4	1.4
Other capital equipment	0.2	0.1	0	0
<b>Total Petroleum and Natural Gas</b>	<b>43.2</b>	<b>36.6</b>	<b>71.7</b>	<b>63.4</b>
<b>Oil Shale and In Situ Technology</b>				
Oil shale	22.7	13.7	28.9	22.1
In situ coal gasification	8.2	6.7	12.6	13.0
Other capital equipment	0.1	0.1	0	0
<b>Total Oil Shale and In Situ Technology</b>	<b>31.0</b>	<b>20.5</b>	<b>41.5</b>	<b>35.1</b>
<b>TOTAL FOSSIL ENERGY</b>	<b>483.2</b>	<b>445.4</b>	<b>639.9</b>	<b>519.0</b>

<sup>a</sup>Carter administration figures.

essential to timely progress of the demonstrations and potential large-scale applications. In addition, this program includes development of policy measures to accelerate utilization and a plan for collection and dissemination of information. In addition to heating and cooling, solar heat can be converted to electricity. These projects have been planned:

- Completion of the conceptual design of 10 MW solar electric pilot plant in FY 1977 and completion of detailed design and fabrication of the pilot plant to ensure initial operation in FY 1980.
- Completion of initial operation and evaluation of the total energy test bed in FY 1977.
- Completion of the 5 MW solar thermal test facility in



FY 1978. This will permit testing and evaluation of the major subsystem concepts under development for the central receiver approach to solar thermal conversion to electricity.

### Solar Photovoltaic Conversion

- Selection of baseline systems and applications by the end of FY 1977 that will provide a solid framework for advancing the widespread use of solar photovoltaic conversion systems.
- Initiation of major series of experiments on multi kilowatt photovoltaic energy conversion systems in FY 1978 to provide valuable operational experience and stimulate development of the industrial base.
- Achievement of a price goal of less than \$2,000 per peak kilowatt for concentrating photovoltaic systems by FY 1979.

### Wind Energy Conversion

- Completion in FY 1977 of design, fabrication, and installation of two multihundred kilowatt wind energy systems to be installed at two climatically different sites in cooperation with utilities to obtain early operational information.
- Completion in FY 1977 of design, fabrication, and installation of a one-megawatt-scale wind energy system, also to be installed in cooperation with utilities at user sites. These systems will be designed for high wind velocity sites.
- Initiation of field testing in FY 1977 of several advanced wind energy conversion concepts.
- Initiation of field testing in FY 1977 of a number of wind energy conversion systems suitable for small-scale use.

### Ocean Thermal Conversion

- Completion in FY 1977 of studies considering planning alternatives and cost-benefit-risk tradeoffs.
- Completion of the development of criteria for and site selection of a test facility in FY 1977. Results obtained from the test program will provide a basis for the design of the 25 megawatt pilot plant.
- Development of critical components and subsystems in parallel with the testing program, so that candidates for large-scale testing in the test facility can be narrowed to the most promising.

### Solar Technology Support and Utilization

This program includes the establishment under P.L. 93-473 ("The Solar Energy Research, Development and Demonstration Act of 1974") of the Solar Energy Research Institute. This institute, which was initially organized in FY 1976 and becomes operationally available in FY 1977, will conduct technical and analytical work supporting the National Solar Energy Program.

### Biomass Conversion

This program is directed toward the investigation of the economic and technical feasibility of converting agricultural and forestry residues and plant biomass into useful clean fuels.

### Geothermal Energy Development

The ERDA geothermal program is comprised of three elements: a research, development and demonstration program under "Geothermal Energy Development," and a loan guarantee program under "Geothermal Resources Development Fund." These programs are responsive to Title I and Title II, respectively, of the Geothermal Energy Research, Development and Demonstration Act of 1974.

ERDA, as the lead agency in geothermal energy development, has formed the Geothermal Advisory Council to provide policy and overall coordination and management guidance for the federal program. Representatives from the Federal Energy Administration, the Department of Interior, the National Science Foundation, the National Aeronautics and Space Administration, the Environmental Protection Agency and the Department of Treasury serve on the council.

Within the overall federal program, each agency has developed or is developing programs to carry out its role. The federal program has seven objectives:

- *Engineering Research and Development:* To provide for basic and fundamental engineering research in all geothermal related technologies.
- *Hydrothermal Technology:* To provide hardware development required for demonstrations.
- *Advanced Technology Applications:* To establish the technological feasibility of exploiting geopressured fluids, hot dry rock, normal gradient, and nonassociated radiogenic heat resources.
- *Demonstration Projects:* To provide for full-scale commercial demonstration of geothermal resources in generation of electric power.

- *Environmental Control and Institutional Studies:* To develop policy recommendations for alleviating institutional, technological, and environmental uncertainties which impede geothermal development.
- *Resource Exploration and Assessment:* To improve the technology for geothermal reservoir assessment and exploration methods, and to conduct national and regional resource assessments and the leasing of geothermal resources on federal lands.
- *Resources Development Fund:* To enhance the private sector's ability to obtain capital for the development of geothermal energy systems.

### Conservation Research and Development

Energy conservation research and development is a new program, established within ERDA, to develop and demonstrate technology for improving efficiency of energy production and utilization and reduction of energy waste.

Primary subprograms cover energy utilization in residential and commercial buildings, industrial processes, and transportation, and the development of electrical energy systems, conversion, and storage techniques:

- Building conservation is directed at accelerating and complementing programs in the private sector related to the development of energy-saving technologies for more efficient energy use in buildings, community systems, and consumer products. The activity includes development of retrofit equipment to existing structures as well as new equipment for new structures, products, and communities.
- Industry conservation is directed toward complementing industry activities to develop economically competitive technologies to reduce industrial and agricultural energy consumption. This will be executed by evaluation of the processes and the equipment and technologies used, and by evaluation of selected energy extensive industrial processes to determine targets of opportunity for energy conservation.
- Transportation energy conservation considers automobiles, trucks, buses, urban transit, aircraft, ships, pipelines, and rail systems, and focuses on a variety of means to reduce energy consumption.
- Electrical energy systems covers systems management and structuring, electric power transmission, and electric energy systems demonstration.
- Energy storage systems is directed at the reduction of fuel consumption by residential and commercial buildings, industry, utilities, and transportation. Storage research includes batteries, hydrogen storage, superconducting electromagnetic storage, flywheels, underground compressed air, underground pumped hydro storage, and thermal storage for heating, air

conditioning, and industrial processing and utility use.

- Energy conversion is concerned with research and development to improve efficiency of existing and new advanced energy-conversion systems. These include waste heat utilization, low-grade heat with bottoming cycles and high-grade heat with topping cycles. Improvement of component efficiencies such as heat exchangers, compressors, pumps, motors and generators are also involved, along with materials development and fuel cell R&D. Rankine, Brayton and Sterling cycles, and extra high-temperature conversion machines (72,800° F) are also of primary interest.
- Waste systems and utilization is dedicated to recovery of fuels, recyclable materials, and energy from urban, agricultural, forestry, and industrial waste.
- Interprogram applications is concerned with identification and resolution of social, economic and legal market penetration energy problems. Other related activities are coordination of interagency conservation programs; comprehensive systems analyses studies; and coordinating transfer of conservation technology to the public and private sectors.

### Fusion Power Research and Development

#### Magnetic Fusion

The primary goal of this program is the development of a new energy source based on nuclear fusion. Based on a recent assessment of scientific progress, ERDA is prepared to undertake the deuterium-tritium (DT)-fueled experiment which will produce several megawatts from thermonuclear energy. This experiment will involve construction of a major experimental facility, a Tokamak Fusion Test Reactor (TFTR), whose principal objectives are to demonstrate fusion energy production from the burning of DT in a Tokamak prior to the first experimental power reactor (EPR); build a Tokamak capable of repeated operation on DT fuel; and demonstrate engineering features of large systems in advance of construction of EPR. Authorization to initiate architect-engineering services and procurement of long-lead materials required for TFTR is being requested in the plant and capital equipment budget. Concurrently, a number of large confinement experiments will study plasma and reactor-related questions in nonburning hydrogen experiments.

Engineering research and development will be aimed at developing the technical base required for near-term experiments and for the design, construction, and operation of practical power plants. In addition, experimental and theoretical studies of fusion plasma phenomena will be pursued. The studies will aid the development of the body

of knowledge required to predict thermonuclear plasma behavior in confinement systems and fusion power reactors.

### Laser Fusion

The laser fusion program is directed toward the determination of the scientific feasibility of laser- and electron-beam-initiated thermonuclear burn using principles of inertial confinement and applications of this technology to such areas as nuclear weapons effects simulation, nuclear weapons physics modeling, military power systems, and commercial power production.

Program strategy involves the maintenance of a research, development, and application core research program within the ERDA laboratories. At the same time, full utilization will be made of unique university and industrial capabilities in support of the core program. Broadly based efforts in universities and industry will complement and extend the national laser fusion program base.

### Fuel Cycle Research and Development

The fuel cycle research and development effort consists of four major activities: uranium resource assessment, uranium enrichment technology, nuclear fuel cycle, and waste management. The overall fuel cycle program has as its major objectives:

- Completing the first national assessment of domestic uranium resources by 1981 to identify for industry likely areas for expansion of the supply of uranium fuels.
- Assisting in the development and demonstration of technology, and development of adequate safeguards for reprocessing spent reactor fuel and recycle of recovered uranium and plutonium.
- Developing and demonstrating the required technology and appropriate sites for the safe processing, storage, and management of radioactive wastes.

Objectives have also been established for four other major program activities.

### Uranium Resource Assessment

Successful development of nuclear power depends heavily on the availability of natural uranium. Over the next decade, a considerable expansion in production capacity will be needed to meet feed requirements for ERDA enrichment plants and for continued growth in nuclear power. The main objective is expansion of the domestic supply of uranium. Over the long term the

program will define and characterize the available U.S. nuclear fuel resource base for use in government and industry planning. Expanded production capacity and resources will be needed to achieve long-range goals for nuclear power. Research and development will develop improved uranium exploration, assessment, and production technology.

### Uranium Enrichment Technology

The uranium enrichment program includes the operation of the gaseous diffusion plants at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio, for the enrichment of uranium as U-235 for fuel in nuclear power reactors. Uranium concentrates from private sources and ERDA stocks are processed into feed materials and enriched in U-235. In addition, significant efforts are under way to increase the efficiency and further expand the capacity of the existing diffusion plants.

The main objectives of this program include:

- Developing advanced technology for the Cascade Improvement (CIF) and Cascade Upgrading (CUP) Programs to increase the current gaseous diffusion production capacity by a total of 10.8 million separative work units per year.
- Developing advanced gas centrifuge technology to make it economically competitive with gaseous diffusion.
- Assisting the nuclear industry to develop a competitive private enriching industry by making ERDA enrichment technology available to industry.
- Investigating and developing laser isotope separation techniques, which would have the potential significantly reducing the cost of obtaining enriched materials for variety of uses.

### Nuclear Fuel Cycle

This program is to assist industry in the timely installation of fuel reprocessing plants to ensure recycle of nuclear fuels. The program will emphasize those reprocessing and recycle areas in which sufficiently significant technical uncertainty exists to require ERDA involvement. The primary objective of the program is to develop and assure the availability of cost-effective safeguard systems for application to ERDA facilities handling significant amounts of special nuclear material and for transfer to private industry as needed in the fuel cycle facilities of various types of nuclear power reactors. An additional objective is to assist in guarding against any diversion of nuclear material from peaceful uses.

## Waste Management

The waste management program will provide the technology to close the end of the nuclear fuel cycle. This program includes identification of the waste products requiring isolation, the development of processes to prepare the waste products for terminal storage, and the development of terminal storage facilities required for isolation of the waste. This R&D is required to support the light water reactors (LWR) and breeder programs, and for commercial waste now being generated. The principal goal is to assure the availability of terminal storage facilities when fuel reprocessing wastes are transferred to federal custody about 10 years from now.

## Fission Power Reactor Development

Fission power effort consists of five major programs: liquid-metal fast-breeder reactor, water-cooled breeder reactor, gas-cooled reactor, light-water reactor technology, and supporting activities. Emphasis is being placed on the liquid metal fast breeder reactor.

The major objectives of the reactor efforts include:

- Developing the broad technological, engineering, and industrial base necessary for establishing the breeder as a safe, reliable, and economical nuclear energy source.
- Demonstrating, on a commercial basis, the design, licensing, construction, and operation of the Clinch River Breeder Reactor as part of a utility system.
- Confirming the capability of breeding in a light-water reactor using a thorium-U-238 cycle, and providing technology to assist industry in the evaluation and application of the concept.
- Evaluating a gas-cooled reactor as an alternate fast breeder with the potential of an increased breeding rate higher than that of the liquid metal fast breeder.
- Developing technology to assist private industry in the design, construction, and operation of high-efficiency, high-temperature gas-cooled thermal reactors for electric power and process heat.
- Assisting private industry through a cooperative program aimed at increasing the productivity of existing light water reactors and developing technology to reduce the time and cost of building new light water reactors.
- Conducting studies and other activities in support of current and potential reactor development efforts.

## Environmental and Safety Research

### Biomedical and Environmental Research Program

This program's principal objective is to provide data on the health and environmental effects of pollutants released to the environment by on-line and developing energy technologies. These data must be developed so that sound biomedical and environmental information is obtained to ensure that future energy needs can be met with acceptable impact on man and his environment.

Research and development is conducted to define and quantify the impact of energy technologies on human health, studies in molecular and cellular biology to complement research in other areas, to address the character, distribution, transport and fate of energy-related pollutants in land, freshwater, marine, and atmospheric environments.

### Operational Safety Program

This program provides for operation of the aerial radiological monitoring system (ARMS); federal support for the remedial action program for uranium mill tailings in Grand Junction, Colorado; and the performance of safety studies and the development of operational guidelines.

### Environmental Control Technology

The objective of this program is to assess all ongoing and planned energy technology development activities to ensure that proper emphasis is given to environmental control research, development, and demonstration on a timely basis. Evaluation of advanced management and disposal techniques for radioactive wastes, transportation R&D, and the management and disposal of excess radioactive contaminated facilities are also carried out in this program.

### High Energy Physics

High energy physics is the study of the fundamental structure of matter and the basic forces of nature through which all physical processes occur. The necessity of probing these phenomena at small distances and very high energies requires the design, development, and operation of large particle accelerators. Four major accelerator facilities are

utilized in the high energy physics program. These include the zero gradient proton synchrotron at Argonne National Laboratory, an alternating gradient proton synchrotron at Brookhaven National Laboratory, the 200-400 GeV proton synchrotron at Fermi National Accelerator Laboratory, and the electron linear accelerator together with the electron colliding beam device at the Stanford Linear Accelerator Center.

The positron-electron project (PEP) will provide reaction energies for studies of the fundamental nature of matter and energy, using the annihilation process in which the intermediate pure energy state is inaccessible through the other types of machines. The objective is to have the first beam stored in the positron-electron joint project by FY 1981.

### Basic Energy Sciences

The objective of the basic energy sciences program is to develop an understanding of physical phenomena basic to the energy technologies of all ERDA programs. Research in this program is conducted in: nuclear sciences; material sciences; and molecular, mathematical, and geosciences. The work is focused on scientific areas judged to have the greatest potential impact on energy applications, although in such research it is not always possible to prejudge how or where the results will be applied. The program is designed to develop experimental and theoretical insights, concepts, improved instrumentation, and other innovations for continued progress in energy research, development, and demonstration. The program includes experimental determination of data, preparation of specialized materials and laboratory demonstration of new processes and concepts. This program is placing greater emphasis on nonnuclear research.

### Nuclear Materials Security and Safeguards

The objectives of the safeguards supporting effort are to protect the public from harm resulting from the use of nuclear materials and facilities and to develop, demonstrate, assess, and assure the availability of effective safeguards systems for application to commercial fuel cycles.

The program is implemented through threat definition, safeguards evaluation, and facilities, transportation, and fuel cycle safeguard implementation. ERDA and NRC fulfill the federal government's safeguards responsibilities to the public, except DOD which protects all nuclear materials in its possession.

### Naval Reactor Development Program

The naval reactor development program provides for the design and development of improved naval nuclear propulsion plants and reactor cores in a wide range of power ratings to meet military requirements. The pressurized water nuclear propulsion plants and cores under development are suitable for installation in naval vessels ranging from small submarines to large combatant surface ships. Development continues on improved reactor concepts, components, and materials for application to submarines and surface warships, with particular emphasis on obtaining higher power long-life cores necessary for increased ship speed and size; simplifying operating and maintenance requirements; and increasing reliability and maintainability of reactor plant components. During FY 1977 development of an advanced reactor core with longer life for application to nuclear powered guided-missile frigates will continue, as will development of advanced reactors for submarines and an increased propulsion plant for Trident submarines. In addition, conceptual design studies of nuclear propulsion plants for potential application in ballistic missile submarines will be done.

### Space Nuclear Systems Program

The emphasis within the space electric power development program is two-fold: to develop and provide nuclear power generators for scheduled flight launches and to pursue the required technology advancements for future missions. The technology efforts for normal program evaluation will require higher funding in FY 1977 than in previous years and will be directed at future DOD missile and the continuing NASA planetary exploration program in the early 1980's.

The terrestrial power development program involves: the development of technology in support of specific terrestrial user requirements for isotope generator systems; application of space technology to terrestrial energy related applications; and analysis and technology evaluation that could lead to the beneficial utilization of the large quantities of radioisotope wastes generated in the commercial electric power program.

### Nuclear Explosives Application

Nuclear explosive applications is a new program that provides for the re-establishment and maintenance of technology support in the area of peaceful nuclear

explosives (PNE). Principal emphasis in FY 1977 will be on the initiation of laboratory studies relating to radioactive waste disposal cavities, development of a better understanding of the effects of multiple nuclear explosions in a closely paced array, development of a limited capability to respond to foreign requests for PNE assistance in feasibility studies, and participation in international meetings and studies.

The objectives of the program are to investigate certain potential applications, and to provide a minimum level of technological support for use by the United States in peaceful nuclear explosive verification discussions. A further objective is to provide a limited means for the U.S. Government to respond positively to requests for foreign assistance under Article V of the Non-Proliferation Treaty.

## National Security

### Weapons Program

The weapons program estimates provide for design, development, and underground testing of new weapons types; for maintenance and development of test detection methods related to international treaties; for production of nuclear weapons; and for maintenance of stockpile weapons in a state of constant readiness. These activities are conducted at government-owned, contractor-operated facilities. The budget seeks to balance research, development, and testing necessary for near- and long-term nuclear technology for maintenance and modernization of the

nuclear arsenal. The requested budget will arrest the downward trend of laboratory R&D and advanced development effort, restoring the level to that of 1975 (about 7900 man years). In production and surveillance, the budget allows for the delivery to stockpile of new weapons approved by the President and for preproduction costs for new weapons systems.

### Weapons Material Production

The weapons material production program produces all special nuclear materials needed for weapons manufacture and other military purposes as expressed by the Materials Planning Estimate, which reflects requirements that have been coordinated with DOD.

### Program Support

Broad-based activities embracing all of the energy and supporting technology programs include information services, general systems studies, general technology transfers, and manpower development. Program direction activities cover the salaries, travel, and other costs associated with program direction and the administration of ERDA.

Supporting activities programs include community operations, security investigations, information services, general system studies, general technology transfer, manpower development, the EEO-assigned facilities, and the cost of work for other programs.

## FEDERAL ENERGY ADMINISTRATION

The Federal Energy Administration (FEA) was established on 7 May 1974 to direct and conduct programs related to production, conservation, use, control, distribution, rationing and allocation of all forms of energy. *Project Independence* was formulated to incorporate energy conservation and development into the context of the nation's social, environmental, and economic condition.

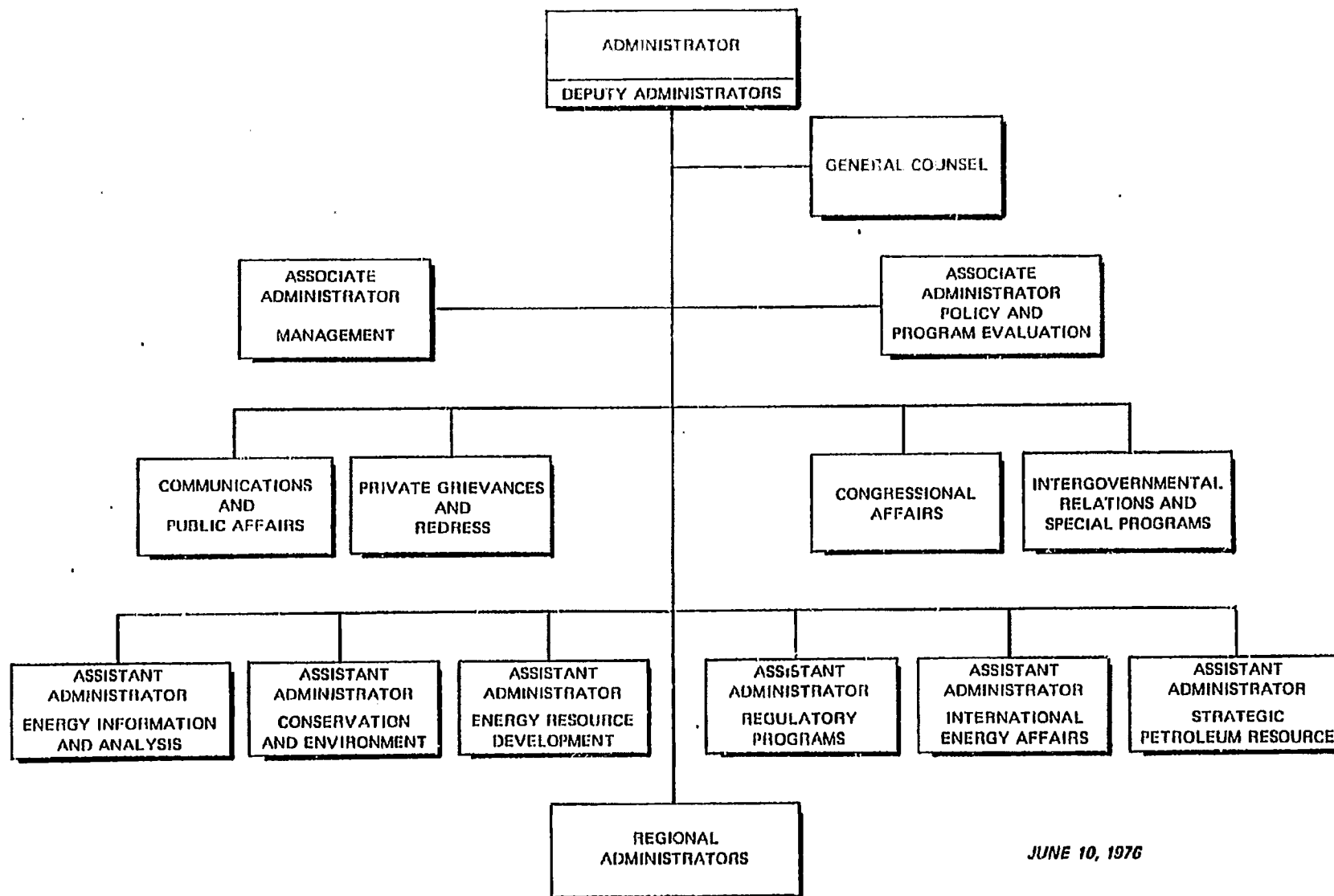
The Energy Policy and Conservation Act (EPCA), signed 22 December 1975, now determines most of the activities and future direction for FEA. The EPCA establishes national policies on oil price and allocation controls, conservation measures, supply initiatives, and emergency authorities such as contingency planning for protection against another embargo. Specific provisions of the act include:

- Standby authorities enabling the President to implement rationing and mandatory conservation plans to meet domestic and international energy needs during a future supply interruption.
- Creation of a Strategic Petroleum Reserve to offset

the impact of a supply cut-off.

- Provision for loan guarantees to develop underground coal mines.
- Ceiling prices on domestic oil, while providing for incentives to stimulate certain types of oil production.
- Conservation of energy through voluntary and mandatory programs applicable to industry, the states, and the federal government.
- Energy efficiency standards for automobiles, and energy efficiency targets for appliances and other consumer products.
- Expansion of the EPCA coal conversion program to reduce demand for natural gas and petroleum products.

Implementation of this program will require a coordinated effort by FEA's seven major divisions (see Figure III-3). A brief description of the FY 78 program for each of these seven areas is given here.



JUNE 10, 1976

Figure III-3. ORGANIZATION OF FEDERAL ENERGY ADMINISTRATION (FEA)

## Executive Direction and Administration

Executive Direction and Administration encompasses the responsibilities of the FEA Administrator as well as those supporting services necessary for the execution of the Administrator's responsibilities: providing advice to the President and Congress relating to the establishment of a National Energy Policy; working with the Secretary of State on the development of an integrated domestic and foreign energy policy; and implementing the programs resulting from these domestic and foreign policies.

The supporting services include legal, financial, personnel, management and procurement. Public affairs, congressional affairs, and state energy coordination are also the responsibility of this division.

## Energy Policy and Analysis

The Office of Policy and Analysis has as its chief objective the formulation of a national plan to meet the country's needs. Included in the process for developing this plan are the review, coordination, and evaluation of energy policy and legislation. Statistical and analytical studies are made to provide quantitative analysis of various policy alternatives and assess their economic and social impact. Because of the data processing systems used by this office, it also serves as the national energy data clearinghouse for FEA, state and federal government agencies, for Congress, and the general public.

## Energy Regulatory Programs

The regulatory programs monitor compliance with existing regulations and those mandated by the Emergency Petroleum Allocation Act through the use of audit and enforcement powers. The information accumulated allows continuous review, development, and update of the national energy contingency plans.

## Energy Conservation and Environment

The Office of Energy Conservation and Environment has set three goals for its program in FY 1978.

- Reduce the energy demand growth rate in the United States.
- Develop and oversee implementation of voluntary

and mandatory energy conservation programs that promote the efficient use of energy.

- Ensure that environmental concerns are balanced with national energy goals.

## Energy Resource Development

Energy Resource Development (ERD) is responsible for developing and implementing programs and projects to increase production and utilization of energy from existing domestic sources and to aid development of other domestic energy sources.

The development of oil, natural gas, coal, oil shale, nuclear, solar, and geothermal energy is encouraged by ERD through plans, programs and projects centered around increasing domestic production. ERD is responsible for developing energy sources and facilities and for preparation of programs to mitigate the adverse effects of new energy sources and to remove impediments to the expansion of energy supplies. The impact of present and prospective energy alternatives and technologies also must be analyzed by ERD.

## Strategic Petroleum Reserves Offices

The Energy Policy and Conservation Act (P.L. 94-163) established the Strategic Petroleum Reserves Office in FEA to establish, manage, and maintain national strategic petroleum reserves. These responsibilities include establishment of a 150-million barrel early storage reserve by the end of 1978, with additional reserve planning to bring the total to 325 million barrels by 1980, and to 500 million by the end of 1982.

## International Energy Affairs

The Office of International Energy Affairs (IEA) reviews and coordinates all FEA international activities. National Security Council matters, international agreements, multinational energy negotiations, transportation of energy from abroad, and liaison with defense and nuclear energy agencies. This involves the development of policy options for oil sharing, mandatory conservation, emergency supply, and support for multinational energy programs, and development and evaluation of United States export-import foreign policy.



## DEPARTMENT OF COMMERCE

The Department of Commerce (DOC) established an Office of Energy Programs in late 1973 to implement an energy conservation program. The objectives of this program are to achieve savings within the business community and to promote the goal of Project Independence to develop a national "energy conservation ethic."

Four approaches have been adopted by the Office of Energy Programs to attain these objectives. The first is to encourage business firms to conserve energy in the operation of their own buildings and manufacturing processes. Second, the business community is encouraged to manufacture and market more energy-efficient products. Third, businesses are asked to help spread the word on energy conservation through their employees, customers, and local communities. Finally, the department is participating directly in energy conservation through an internal program aimed at reducing consumption.

While the Office of Energy Programs plays an important role in DOC program planning, the National Bureau of Standards (NBS) represents a more technical approach to energy conservation. Within NBS, the Office of Energy Conservation oversees and coordinates energy conservation in buildings, appliances, utilities and industry.

The development of computer techniques for estimating energy requirements, establishment of performance criteria for evaluating systems provided for by the Solar Heating and Cooling Demonstration Act; and studies relating to magnetohydrodynamics (MHD) and liquefied natural gas (LNG) are all important programs now being pursued by this office.

The Office of Energy Programs also provides analytical input to the Office of Energy and Strategic Resource Policy established in June 1976. The function of this office is to develop and coordinate the formulation of energy, commodity, strategic resource, and ocean policies for the Department of Commerce. This office provides assistance

to the Secretary and to the Energy Resources Council. By working closely with the Department of Commerce and other departments, the office monitors energy-related commodities for short-supply export controls as well as international developments affecting U.S. imports.

Other divisions within the department also have energy program responsibilities. An example, the Maritime Administration, which, through its association with industry representatives, encourages the reduction of petroleum consumption through the elimination of waste, conservation of energy, and utilization of energy-efficient procedures.

The U.S. Merchant Marine Academy, as part of its conservation efforts, has undertaken a project to develop an improved combustion technique to increase marine boiler efficiency by at least 6 percent.

Another department program involves the Office of Science and Technology, Office of Telecommunications, and FEA which are developing a telecommunication plan to substitute for travel. A demonstration of this plan is being carried out using a decentralized federal agency as a test.

The planning of deep water ports, coastal zone refineries, and nuclear power plants are all subject to the management of the National Oceanic and Atmospheric Administration (NOAA). NOAA is responsible for key aspects of coastal zone management and planning for outer continental shelf (OCS) oil and gas development, including environmental assessment and onshore impacts. NOAA's Assistant Administrator for Coastal Zone Management is responsible for directing the financial assistance program established by the recently enacted Coastal Zone Management Act Amendments (P.L. 94-370). Under this program state and local governments are to be compensated for adverse environmental, social, and economic impacts of the development of energy resources on the outer continental shelf.

## DEPARTMENT OF DEFENSE

Recognizing that fulfillment of its responsibility for national security depends heavily upon the use of petroleum-based fuels, the Department of Defense has instituted a program for energy R&D. DOD, the largest single government user of energy in the United States, addresses problems such as energy conservation, synthetic fuels characterization, systems design, and engine efficiency in its R&D programs. Energy has also become an important consideration in the development and acquisition of any new major weapon system. Since the oil embargo of 1973 and the resulting higher prices, DOD has made additional efforts to identify energy alternatives to supplement or

replace petroleum energy sources used by DOD. DOD energy organization appears in Figure III-4.

In September of 1973 a Defense Energy Task Group (DETG) was established to conduct an in-depth analysis of the energy situation within DOD and to provide recommendations for improving the management of DOD energy resources. DETG completed its preliminary analysis in November 1973, and submitted a report listing many critical issues and recommending policy guidelines. These guidelines were updated in the 22 July 1974 DETG Phase II report that stated these DOD energy R&D goals:

- Establish a DOD energy R&D program that will

**Figure III-4. ORGANIZATION OF DEPARTMENT OF DEFENSE ENERGY ACTIVITIES**

Table III-4.

## DOD ENERGY-MOTIVATED R&amp;D PARTICIPATION GUIDELINES

Operations	Research	Exploratory Development	Advanced Engineering Development
<b>I. Aircraft Operations - Air Force Lead</b>			
A. Improved propulsion aircraft turbines with reduced specific fuel consumption	Lead*	Lead	Lead
B. Improved aerodynamic drag reduction	Lead	Lead	Lead
C. Multifuel capability	Lead	Lead	Lead
D. Alternate fuel for aircraft operations			
1. syncrudes	Promote*	Promote	Promote
2. hydrogen and methane	Monitor*	Monitor	Monitor
E. Improved aircraft operational procedures	Lead	Lead	Lead
<b>II. Ship Operations - Navy Lead</b>			
A. More efficient ship propulsion			
1. Improved efficiency conventional power plants: diesel and steam	Lead	Lead	Lead
2. Advanced gas turbines	Lead	Lead	Lead
3. Advanced topping cycle such as supercritical carbon dioxide Brayton cycle	Monitor	Monitor	Monitor
4. Turbine driven superconducting generator motor propulsion driven systems	Lead	Lead	Lead
5. Nuclear ship propulsion (less reactors)	Lead	Lead	Lead
B. Multifuel capability			
C. Burn less critical fuels			
1. syncrude fuels	Promote*	Promote	Promote
2. other alternate fuels	Monitor	Monitor	Monitor
D. Combined chemical dash power and nuclear cruise power systems	Lead	Lead	Lead
E. Reduction in nonpropulsive energy consumption-improved conversion efficiency			
1. total energy/waste heat recovery systems	Participate*	Participate	Monitor
2. integrated energy/waste/water management system	Participate	Participate	Participate
<b>III. Installations and Buildings - All Military Departments &amp; ARPA</b>			
A. Optimum utilization of technology & equipment			
1. Conduct analyses of DOD buildings and installations to determine the optimum way to invest available DOD energy conservation dollars to maximize Btu's saved per dollar	Monitor	Monitor	Monitor
2. Conduct further performance and economic analyses on primary and supplementary heating and cooling; provide buildings for trial use	Monitor	Monitor	Monitor
3. Total energy systems that recover and use waste heat	Participate	Monitor	Monitor
4. Improve efficiency base and building energy (heating and cooling) distribution systems	Promote	Promote	Promote
5. Optimum location of new buildings and site placement	Promote	Promote	Promote
6. Energy independence for remote bases	Lead	Lead	Lead
B. Advanced technology			
1. Advanced power plants of improved efficiency that are convertible to substitute fuels such as coal and syncrude	Monitor	Monitor	Monitor
2. Advanced methods of energy storage and distribution	Monitor	Monitor	Monitor
3. Alternate energy sources and fuels (e.g., solar, geothermal, nuclear)	Monitor	Monitor	Monitor

Table III-4.

## DOD ENERGY-MOTIVATED R&amp;D PARTICIPATION GUIDELINES (Cont'd)

Operations	Research	Exploratory Development	Advanced Engineering Development
<b>IV. Ground Operations - Army</b>			
<b>A. Vehicles</b>			
1. Stratified charge gasoline engines	Participate	Participate	Participate
2. High-performance, high-speed diesel engines with good efficiency over a wide load range	Participate	Participate	Participate
3. Open-cycle gas turbines with recuperators to increase efficiency	Participate	Participate	Participate
4. Multispeed lockup transmissions with high efficiency and smooth operation	Participate	Participate	Participate
<b>B. Mobile electrical power systems</b>			
1. Stirling engine - generators	Lead	Lead	Participate
2. Small fuel cells	Lead	Lead	Participate
3. Efficient turbo-alternators	Lead	Participate	Participate
<b>C. Multifuel capability</b>	Lead	Lead	Lead
<b>D. Advanced fuels and power systems</b>			
1. Refined syncrude fuels	Promote	Promote	Promote
2. Hydrogen	Monitor	Monitor	Monitor
3. Closed Brayton regenerative gas turbines	Participate	Participate	Participate
4. Fuel additives (e.g., methanol)	Participate	Participate	Participate
5. Nuclear energy systems such as nuclear powered total energy depots and radioisotope power generators	Participate	Participate	Participate

Source: Defense Energy Task Group Phase I Report, November 1973.

contribute the most to national defense.

- Establish through R&D new and better options for maintaining a dependable supply of energy for overseas DOD operations.
- Establish DOD energy R&D programs, such as synthetic fuels utilization, which would minimize U.S. dependence on oil imports.
- Establish energy conservation R&D programs that would reduce DOD fuel operating costs.
- Identify DOD energy R&D programs that have application in the civilian sector.

Within the energy R&D guidelines and supplementary guidance provided to the military services, a set of DOD energy-motivated R&D participation guidelines were recommended by the Defense Energy Task Group as shown in Table III-4. Application of these guidelines further implies a clear understanding of the definition of terms used in the matrix.<sup>1</sup> These definitions are:

**Lead.** DOD is the major source of R&D funding.

**Participate.** DOD provides a share of the necessary funding in conjunction with other federal agencies or private industry.

**Monitor.** DOD does not fund hardware development directly but observes progress closely, makes DOD's needs known, and provides resources, analyses, and

indirect support (e.g., building insulation test facilities) for specific military adaptations.

**Promote.** DOD does not fund hardware development directly but may provide appropriate incentives (e.g., guarantee a market for syncrude subject to the availability of funds), resources, and analyses for specific military uses.

On 14 December 1976, the Defense Energy Office completed a draft of the Defense Energy Initiatives Plan (DEIP) for consideration by the Defense Energy Policy Council. The guidelines proposed in the plan provide a framework for the development of more detailed energy program plans. While incorporating many of the recommendations of the DETG Phase II report, the DEIP stresses the need for more specific policy guidance relating to:

- DOD participation in national energy policy development.
- DOD active support on national security grounds of major national energy initiatives.
- Strategic petroleum reserves.
- Petroleum energy logistics.
- Energy research, development, and demonstration.

<sup>1</sup> Defense Energy Task Group, *Management of Defense Energy Resources Phase II Report*, 22 July 1974.

## DEPARTMENT OF HOUSING AND URBAN DEVELOPMENT

The Department of Housing and Urban Development (HUD) is involved in implementing energy-related programs established by both the Housing and Community Development Act of 1974 and the Solar Heating and Cooling Demonstration Act of 1974.

HUD responsibilities under the Housing and Community Development Act call for the development of energy conservation standards for model building codes, primarily insulation materials and procedures standards.

The nation's first large-scale test of solar energy in housing is being sponsored by HUD under the Solar Heating and Cooling Demonstration Act. This is a joint ERDA/HUD/DOD program to investigate the practical widespread application of solar energy for home heating and cooling.

Five cycles of demonstration grants are provided by this national solar energy program. By January 1976 the funds for the first cycle of grants already approached the 6 million dollars HUD had made available for the program. The first cycle of HUD solar demonstration projects, emphasizing solar space heating and cooling and domestic hot water, consisted of 136 dwelling units in 27 states and Puerto Rico. The grants for the second cycle of projects are now being awarded and three more cycles of grants are planned for the next three years. To implement the residential demonstration portion of this program, HUD is establishing residential demonstration projects, developing solar systems standards, identifying constraints, developing markets, and disseminating information.

## DEPARTMENT OF INTERIOR

Since its establishment in 1849, the Department of Interior (DOI) has been involved in managing federal lands and resources directly relating to energy. DOI responsibilities include the administration of mineral leasing programs on federal lands and the outer continental shelf; promotion of mine health, safety, and efficiency programs; management of hydroelectric power systems; collection of mineral data and analysis; continuation of energy, metallurgical, and mining research and development; execution of an emergency preparedness and natural disaster energy and minerals program; and other energy-related functions. As evidenced by this listing, DOI has retained an important role in the nation's energy program even after the establishment of ERDA and the Federal Energy Administration.

The activities of those divisions of DOI that have responsibilities related to energy are described here and appear in the organization chart in Figure III-5.

### Assistant Secretary for Energy and Minerals

Most of the department's energy activities are carried out by the Geological Survey, Bureau of Mines, Mining Safety and Enforcement Administration, the four regional power administrations, and the Office of Minerals Policy Development, which function under the Assistant Secretary for Energy and Minerals.

### Office of Minerals Policy Development

This office was established on 17 April 1974 to provide

a mechanism for overseeing the development of policy programs and legislative initiatives. It is also responsible for minerals conservation programs, analyses of policy options, coordination of policy analysis and mineral data analysis within the department. The office serves as staff to the Assistant Secretary for Energy and Minerals in forecasting, evaluating, and appraising mineral plans and programs.

### U.S. Geological Survey

The U.S. Geological Survey (USGS) has as its basic function the classifying of all public lands and "the examination of the geological structure, mineral resources and products of the national domain." These responsibilities were established in the 1879 legislation creating USGS. Other USGS duties include conducting geological surveys (including geophysical and geochemical studies to develop data and knowledge for use in evaluating the nation's mineral resources); regulating operations of private industry on mining; and letting oil and gas leases on public lands. The USGS has responsibility for administration of the National Petroleum Reserve in Alaska. To fund this additional work, USGS has requested \$353.6 million for FY 1978, an increase of \$38.2 million over FY 1977.

Among its other energy-related duties, the USGS is responsible for establishing maximum production rates for oil wells on the outer continental shelf (OCS), maintaining production accounts, and preparing and publishing maps and reports of mineral resources on federal land. It maintains a Computerized Resources Information Bank (CRIB), designed to include both domestic and international entries on minerals and mineral resources.

AUGUST 1970

**Figure III-5. ORGANIZATION OF DEPARTMENT OF INTERIOR**

## Bureau of Land Management

The Bureau of Land Management (BLM) was established in 1946 to assume the responsibility for the conservation, management, and development of 473 million acres of national resource lands. Its primary area of energy concern is administration of mining and mineral leasing on 369 million acres of mineral estate, and approximately 1.1 billion acres of the outer continental shelf (OCS).

The BLM budget is designed to ensure optimum use, development, and protection of the federal lands and their resources. BLM has requested \$6.1 million for FY 1978 to accelerate the regional coal environmental impact statement, assess reclamation potential of specific lands, and implement scheduling of the coal activity recommendation system. Funding has also been requested to support programs in OCS environmental baseline and monitoring studies and in surface management and protection for the National Petroleum Reserve in Alaska.

## Bureau of Mines

The Bureau of Mines (BOM) was established by the Organic Act of 16 May 1910, as amended. It is the major federal agency for handling issues and problems associated with mineral extraction and processing. In this connection it collects data and keeps statistics for all minerals and fuels and does research on coal mining technology. Funds requested for this work in FY 1978 total \$208.8 million. Programs emphasized in FY 1978 include metallurgy research, mining research, and demonstration of mined land reclamation technology.

## Mining Enforcement and Safety Administration

The Mining Enforcement and Safety Administration conducts programs to control health hazards and reduce injuries in mineral extraction operations; formulates standards for health and safety; and carries out inspections, investigations, and other enforcement measures. It also administers the Federal Metal and Nonmetallic Mine Safety Act and portions of the Federal Coal Mine Health and Safety Act of 1969.

## Bureau of Reclamation

The Bureau of Reclamation has the responsibility of implementing the Reclamation Act of 1902, which authorizes the Secretary of Interior to locate, construct, operate, and maintain work for the storage, diversion, and development of waters for the reclamation of arid and semiarid lands in the western United States. This program has

significant impact on the development of energy resources in those areas because it gives the bureau power to investigate and develop plans for the regulation, conservation, and use of water and related resources.

## Office of Water Research and Technology

The objective of the Office of Water Research and Technology (OWRT) program is to develop knowledge to solve water resource problems and to continue development of desalination processes. OWRT research includes finding solutions to energy-related problems involving water, such as:

- Assess the impact of coal mining and oil shale development on local and regional water resources.
- Develop strip spoil reclamation for reuse and water quality protection.
- Develop a methodology to minimize any adverse water-related consequences resulting from fossil fuel development in the western United States and Appalachia.
- Conduct analytical modeling of water supply allocation.
- Develop acid mine drainage control.
- Study conservation of cooling and process water needs.
- Develop ways to reuse and recycle water.
- Study water conservation.

## Fish and Wildlife Service

As part of the Fish and Wildlife Service's responsibility to protect living natural resources, it contributes to the management of the land and water environments sustaining these creatures. These efforts include: biological monitoring (surveillance of pesticides, heavy metals, and thermal pollutions); ecological studies; environmental impact assessment (river basin studies, including hydroelectric dams, nuclear power sites, and environmental impact statement review); and area planning and preservation (involving river basins, wilderness areas, and special studies such as oil shale and geothermal energy).

## Regional Power Administration

There are four major power regions in the United States in which electric power and energy from federal hydroelectric projects is marketed and distributed. The projects are operated by either Army Corps of Engineers or Bureau of Land Reclamation.

The Bonneville Power Administration for the Pacific Northwest markets power produced by the Federal

Columbia River Power Systems. The Alaska Power Administration conducts surveys to determine the most appropriate means of developing and utilizing Alaska's water,

power, and related resources. The Southeastern Power Administration and Southwestern Power Administration provide marketing services to their regions.

## DEPARTMENT OF STATE

The global scope of the energy issue has made the Department of State an important party in development of international energy policy and negotiations relating to oil and other energy sources. The Office of Fuels and Energy provides staffing for these activities. This office works very closely with the Departments of Treasury and Commerce, OMB, and FEA in dealing with problems as they arise. ERDA's involvement with various international projects in energy research and development is also assisted by the Office of Fuels and Energy.

Another major involvement by the Office of Fuels and Energy is its responsibility for U.S. participation in the International Energy Agency (IEA). Since its organization

in November 1974, IEA has been working to establish oil-sharing agreements to meet present needs and to encourage cooperation among the members to aid conservation efforts to reduce dependence on imported energy.

The Office of Nuclear Energy and Energy Technology Affairs at the Department of State provides assistance for long-term energy development cooperation among nations, primarily nuclear energy safeguards and security. This office also provides input for U.S. participation in IEA activities. The office works closely with the International Affairs Office of ERDA and other federal agencies to monitor international energy R&D activities.

## DEPARTMENT OF TRANSPORTATION

### United States Coast Guard

The Coast Guard's Office of Research and Development is charged with the administration of a program responsive to the needs of the Coast Guard for new or improved systems, equipment, methods, and procedures.

The basic strategy for the Coast Guard's energy R&D program has two objectives:

- Conservation through the application of alternate strategies and alternate engineering.

- Substitution of presently used conventional energy sources by a more practical application of a conventional source and by nonconventional such as solar, wind, and wave energy.

Current R&D includes conservation projects for the cutter fleet, a solar heating and cooling demonstration program for shore facilities, and a program to develop solar-, wind-, and wave-operated power packages for aids to navigation.

## NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Energy research and technology efforts in the National Aeronautics and Space Administration (NASA) have been primarily to identify space program technology that can be applied to solving energy problems. Another important aspect of NASA's energy program has been its cooperative effort with other agencies to speed the development of photovoltaics, solar heating and cooling, and electric power generation by wind power.

For FY 1977, NASA has not requested direct funding for energy research and development; instead it will make its "capabilities and expertise available to ERDA and other

agencies, as requested, to proceed with energy technology activities on a reimbursable basis".

NASA receives reimbursable funds from ERDA for a joint ERDA-NASA technical, economic, and environmental study to determine the feasibility of a satellite solar electric power generating system. Other reimbursable agreements with ERDA being implemented call for NASA's support of residential and commercial solar heating and cooling, wind energy, solar photovoltaics, and geothermal energy programs.



**TABLE III-5**  
**NATIONAL SCIENCE FOUNDATION/RESEARCH**  
**APPLIED TO NATIONAL NEEDS BUDGET**  
(Millions of Dollars)

	Actual FY 1975	Estimated FY 1976	Estimated TQ 1976	Estimated FY 1977
Resources	\$38.8	16.1	3.0	10.0
Environment	23.8	27.0	6.4	24.5
Productivity	16.9	24.5	6.3	24.4
Intergovernmental science and R&D incentives	2.8	4.6	1.2	4.6
Exploratory research and technology assessment	1.2	1.4	0.4	1.4
Total	83.6	72.6	17.3	64.9

Source: NSF FY 1977 Budget Submission to Congress.

### NATIONAL SCIENCE FOUNDATION

The National Science Foundation (NSF) was established to serve as the nation's center for both basic research and research directed toward improvements in technology and productivity. The Foundation's program goals for FY 1977 are directed toward the application of science and technology to many of the major problems confronting the nation: unemployment, inflation, energy, transportation, stagnating productivity, and the increasing cost of government.

Studies directly relating to energy are conducted by the Foundation's program of Research Applied to National Needs (RANN). An amount of \$64.9 million is included in the FY 1977 budget for the RANN program to support

research in five major areas: resources, environment, productivity, intergovernmental sciences and R&D incentives, and exploratory research and technology assessment. FY 1977 funding has been reduced by \$8.7 million from FY 1976. This cutback reflects the further phaseout and shift to other government agencies of research in energy resources and energy environmental effects. (See Table III-5)

Research supported under the RANN resources program emphasizes the management of resource systems, renewable resources, and nonrenewable resources. Funding for this program in FY 1977 has been reduced by \$56.1 million in recognition of ERDA's role as the lead agency in such work.

Table III-6  
**ENVIRONMENTAL PROTECTION AGENCY**  
**ENERGY R&D BUDGET**  
(Millions of Dollars)

	Actual 1975		Estimated 1976	Total FY and TQ 1976	Estimated TQ 1976	Estimated FY 1977	
	Appropriation	Outlay	Appropriation	Outlay	Appropriation	Appropriation	Outlay
Energy R&D	88.3	23.2	100.0	120.0	20.8	96.4	120.0

Source: EPA FY 1977 Budget Submission to Congress.

## ENVIRONMENTAL PROTECTION AGENCY

The Environmental Protection Agency (EPA) protects the public health and welfare from the adverse environmental effects of programs designed to meet the nation's energy needs. Because of the potentially acute health and ecological effects both traditional and new technologies for fuel processing, conversion, and utilization, the EPA has programs underway to develop the health and technical data bases to assess these problems. Research and development toward this end are mandated by the Clean Air Act, the Federal Water Pollution Control Act, and the Resources Recovery Act. (See Table III-6.)

EPA's approach to its aspect of the nation's energy R&D program is organized into four areas (see Figure III-6):

- *Conversion, Utilization, and Technology Assessment*  
Identification, characterization, assessment and development of control technology for pollutants created by utility and industrial combustion sources.
- *Energy Extraction and Processing Technology*  
Rapid increase in extracting and processing domestic energy resources in an environmentally compatible manner.

- *Energy Health and Ecological Effects*

Identification and regulatory control of all adverse environmental effects resulting from energy extraction, conversion, and use.

- *Technical Support*

Based on expertise developed from R&D programs, provide technical support to EPA regional and program offices. Support includes cooperative regionally oriented R&D projects, baseline condition monitoring to develop data for regulatory functions, and expert witness testimony are utilized.

Problems of immediate concern to EPA are:

- Conversion of oil- and gas-fired boilers to burn high sulfur coal, resulting in the additional emission of particulates, sulfur compounds, and other combustion residues.
- Increased demand for coal and oil shale will accelerate area mining for these sources in semiarid western areas, requiring extensive restoration of mined lands, and having serious effect on ground and surface water resources.

## OTHERS

### Council on Environmental Quality

The Council on Environmental Quality (CEQ) was established by the National Environmental Quality Act of 1969. It consists of three members, appointed by the President, with the responsibility of formulating and recommending national policies to promote improvement of the quality of the environment.

The CEQ includes an energy program staff, which has been assigned to assess the effect on the environment of various aspects of energy. CEQ has arranged with federal agencies, including NSF, and academic organizations to carry out a number of specific studies, including:

- Environmental impact assessment of oil and gas operations in the Atlantic and Alaska OCS.
- Offshore nuclear power plants and attendant environmental hazards.
- Study of siting and safety of liquid natural gas facilities.
- A general report on the environmental impact of end uses of various types of energy.
- Effects of interfuel competition on environmental concerns.

- Environmental impact of deepwater port development.

### Energy Resources Council

The Energy Resources Council was established by the Energy Organization Act of 1974. It is designed as an interim, interagency coordinating unit having these members:

Secretary of Interior, Chairman  
FEA Administrator  
ERDA Administrator  
Secretary of State  
Director of the Office of  
Manpower and Budget (OMB)  
Assistant to the President for Economic Affairs  
Secretary of the Treasury  
Secretary of Defense  
Attorney General  
Secretary of Commerce  
Secretary of Transportation  
Chairman of Nuclear Regulatory Commission (NRC)

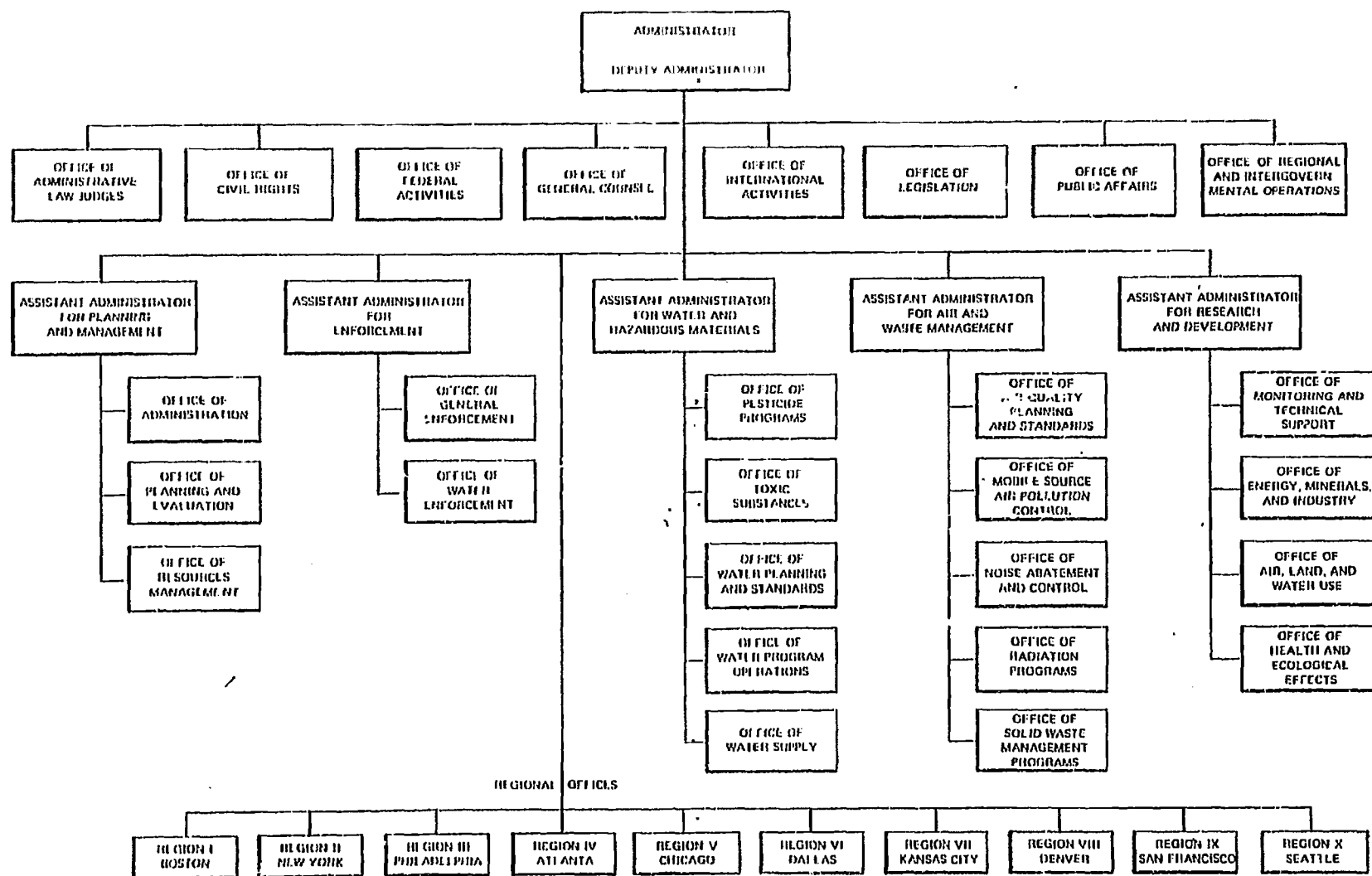


Figure III-6. ORGANIZATION OF ENVIRONMENTAL PROTECTION AGENCY

Administrator of EPA  
Chairman of CEQ  
Director of NSF  
Executive Director of the Domestic Council  
Administrator of General Services  
Administration (GSA)  
Special Assistant to the President for  
Consumer Affairs

The council is to terminate upon establishment of a permanent department responsible for energy and natural resources, or two years after the council becomes effective, whichever occurs first.

### Federal Power Commission

The Federal Power Commission (FPC), created in 1920, monitors and regulates wholesale electric rates, issues natural gas certificates and rates, performs water resource appraisal studies, conducts environmental impact studies, develops electric power and natural gas, regulates natural gas pipelines, and performs studies on electric and natural gas systems to determine resource data and requirements and to encourage coordination and reliability of the systems.

FY 1977 funding will continue for FPC's market and resource analysis of the natural gas industry and an energy utilization program. In the latter program, information on energy conservation programs will be identified and distributed and the interacting effects of the U.S. energy supply system and its capital distribution and marketing requirements will be analyzed.

### Office of Technology Assessment

In the Legislative Branch, the Office of Technology Assessment (OTA) is responsible for providing Congress

with early indications of the probable beneficial and adverse impacts of technology and its applications, including identification and analysis of alternative technologies' methods of implementing specific programs. The OTA also identifies areas in which additional research or data collection is required in order to assess a technology program. The OTA coordinates research efforts with the Congressional Research Service, the General Accounting Office (GAO), and NSF.

### Nuclear Regulatory Commission

The Nuclear Regulatory Commission (NRC) was established, with ERDA, in the Energy Reorganization Act of 1974. NRC has all the regulatory and licensing authority and functions of the former Atomic Energy Commission, which was abolished by this legislation, and is thus the federal agency responsible for the regulation of nuclear power generation.

### Tennessee Valley Authority

The Tennessee Valley Authority (TVA) programs include such energy-related activities as:

- Regional water resources development, including river and flood control projects, water quality management, navigation development, and concurrent environmental planning for recreation, fisheries, and waterfowl resources development.
- General resource development, including R&D programs in forestry, fish and game, watershed protection, and land reclamation after surface mining.
- Programs to supply an area of 80,000 square miles with electricity, including planning, construction, and maintenance of nuclear power plants and a pumped storage hydroelectric project.

**CHAPTER IV**  
**INTERNATIONAL ENERGY**  
**RESEARCH AND DEVELOPMENT**

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## INTRODUCTION

The sudden end of low-cost energy has brought tremendous problems to industrialized countries as well as to developing countries that lack hydrocarbon resources. Before the energy crisis, more intensive energy R&D could have been pursued in industrialized countries, but the ready availability of low-cost energy blunted incentive. Now that the rest of the world, like the United States, has experienced the crisis, greater attention is being paid to energy conservation and the development of alternate resources.

Although there are ongoing projects in energy R&D in many countries, the range and scope of these projects are small compared to those in the United States. Table IV-1

presents the approximate governmental energy R&D budgets of major nations. With few exceptions, all advanced energy R&D elsewhere parallels work in the United States. The most important foreign contributions are the development of specific techniques and devices that are parts of overall systems. However, the events leading to the energy crisis, the realization of the technical challenges posed by these events, and the need to turn to advanced technology for medium- and long-term solutions have resulted in emerging energy R&D programs in many industrialized nations. Additionally, there have been significant moves toward international cooperation in energy R&D to meet the threat of the energy crisis.

Table IV-1

### INTERNATIONAL GOVERNMENTAL ENERGY R&D BUDGETS (Millions of dollars)

Fiscal Year Ending	Nonnuclear <sup>a</sup> (rounded off)	Nuclear (rounded off)	Total Energy R&D	Gross Domestic Product (1975) (billions)	Energy R&D as a Percent of Gross Domestic Product
December 1976: Canada	30	90	120	\$ 152	0.00079
December 1976: France	90	310	398	300 <sup>c</sup>	0.00132
December 1976: Germany (FRG)	60	450	517	423	0.00122
March 1977: Japan	60	330	387	488	0.00079
March 1976: United Kingdom	150	250	398	226	0.00176
June 1976: United States (ERDA)	1,200	800	2,000	1,499	0.00133

<sup>a</sup>Includes fusion.

Source: *International Cooperation in Energy R&D*, Joint Oversight Hearings before the Subcommittee on Energy R&D and the Subcommittees on Domestic and International Scientific Planning and Analysis of the Committee on Science and Technology, June 29 and 30; July 1 and 2, 1976, p. 17.

## INTERNATIONAL COOPERATION IN ENERGY R&D

The United States cooperates internationally in energy R&D both multilaterally under the aegis of international organizations and bilaterally with individual countries to exchange information and personnel, to jointly construct and operate facilities and experiments, and to perform parts of joint R&D programs.

### S. Multilateral International Energy R&D Agreements

Important international organizations have been formed by energy consuming countries for mutual cooperation in energy-related matters. The International Energy Agency

(IEA), International Atomic Energy Agency (IAEA), and the Committee on the Challenge of Modern Society (CCMS) provide vehicles for information exchange and cooperative programs in such fields as energy R&D, emergency energy supply allocations, energy pricing policies, etc. In addition to providing a forum for discussion of common problems, these organizations perform numerous oversight functions for ongoing programs and are in fact, many times the third parties in multinational agreements. In this capacity, they are recognized as equal entities with the other signatories. The United States is a member nation of these international organizations and has entered into multilateral energy R&D agreements in which these organizations are participants.

## International Energy Agency

The International Energy Agency (IEA) grew out of negotiations at the Washington Energy Conference of February 1974. The IEA is a semi-autonomous agency established under the general umbrella of the Organization for Economic Cooperation and Development (OECD). The IEA has two primary objectives: the first, sparked by the Arab oil embargo, is the establishment of an emergency petroleum allocation system within member nations; the second is the establishment of a program of long-term cooperation to reduce dependence on imported oil. This second goal requires development of alternate energy sources, increased domestic production, and energy conservation. The countries participating include: Austria, Belgium, Canada, Denmark, Federal Republic of Germany, Greece, Ireland, Italy, Japan, Luxembourg, the Netherlands, New Zealand, Norway, Spain, Sweden, Switzerland, Turkey, the United Kingdom, and the United States. The Commission of the European Communities (EC) also takes part in IEA activities.

IEA structure is shown in Figure IV-1. The United States has been most involved in the activities of the Committee on Energy Research and Development. Fifteen working parties comprising representatives of those nations interested in participating in a particular project have been established. Under the chairmanship of a designated lead country or organization, each working party seeks to develop a cooperative program of mutually beneficial projects related to various energy technologies. The United States has been designated the IEA lead country for working party efforts in the areas of conservation, nuclear safety, ocean thermal energy conversion, and energy R&D strategy. Various U.S. agencies are participating in all 15 working parties. The U.S. commitment to IEA in 1976 was \$136 million or approximately 25 percent of the total IEA budget of \$552 million. Table IV-2 presents the annual contribution of the member countries to IEA joint projects. Multinational energy R&D agreements under the auspices of IEA are shown Table IV-3.

## International Atomic Energy Agency

The International Atomic Energy Agency (IAEA), an autonomous member of the United Nations family of organizations, is the primary international organization which devotes its attention to the development and application of nuclear power for peaceful purposes. The United States has been strongly supportive of the IAEA and its objectives since its inception in 1957. The current scope of IAEA R&D activities includes work on nuclear safety and standards, nuclear material safeguards, nuclear materials transfer accountability, scientific information exchange, and a technical assistance program for the lesser

developed countries. (Refer to Table IV-4.)

While the IAEA does not emphasize cooperative R&D, several activities have an important effect on the progress of nuclear technology throughout the world. In the important areas of international safeguards against diversion of nuclear material, for example, the IAEA research and development program involves improvement of safeguards techniques and instrumentation. The United States through ERDA, the Nuclear Regulatory Commission (NRC), and the Arms Control Disarmament Agency (ACDA) conducts its own extensive R&D safeguards effort and coordinates closely with the IAEA to ensure that its joint efforts are complementary and not duplicative.

Under the recently proposed U.S. offer of \$5 million for five years to strengthen the IAEA safeguards program, the United States will consult with the IAEA to determine in which particular areas U.S. special R&D efforts should be undertaken to complement IAEA programs.

With strong U.S. encouragement and support, the IAEA initiated in 1970 development of a comprehensive, international system for collection and dissemination of nuclear information. This highly successful International Nuclear Information System (INIS) now covers almost 100 percent of the world's nuclear information and supplants *Nuclear Science Abstracts*, previously published by the United States.

The United States has led in the development of technologies aimed at the protection of the environment and safety of nuclear power plants. Since the establishment of the IAEA, the United States has made available, insofar as possible, the results of this technology to IAEA member states. In this connection, the United States strongly supports the IAEA's program for the early development of internationally recommended codes of practice and safety guides for the safety of nuclear power stations.

The major areas of U.S. involvement with IAEA are:

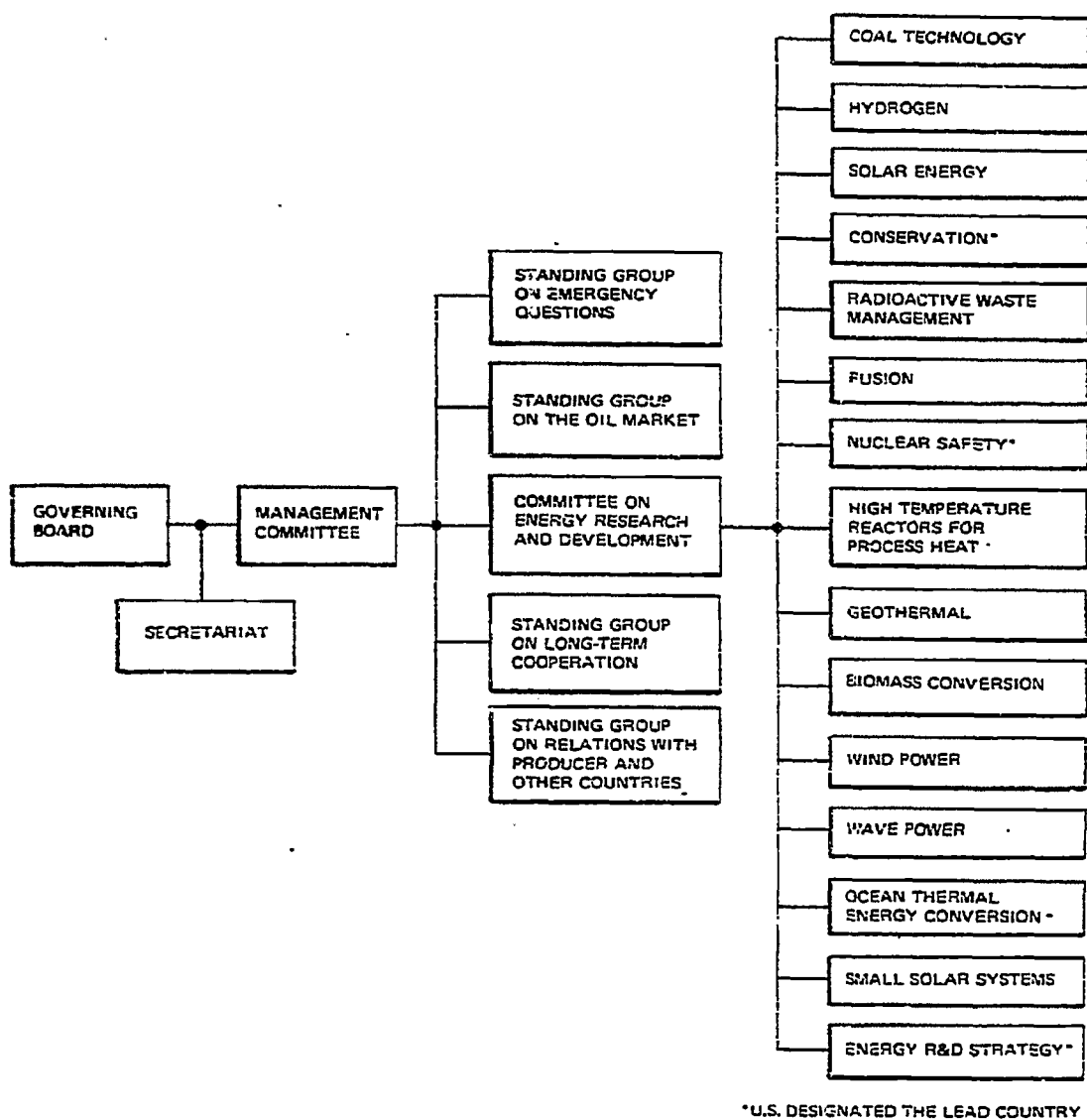
- Safeguards accountability of nuclear material
- Regional fuel cycle center study
- Nuclear safety and standards
- Scientific information exchange
- Technical assistance program.

The U.S. 1976 commitment to IAEA was \$9.5 million or approximately 28 percent of the IAEA regular assessed budget.

## Committee on the Challenges of Modern Society

The Committee on the Challenges of Modern Society (CCMS) was created in November 1969 by the North Atlantic Council of the North Atlantic Treaty Organization (NATO) to deal with energy, environmental, and other problems which significantly impair the quality of life in modern industrialized societies. Although all NATO members are automatically members of CCMS, non-NATO





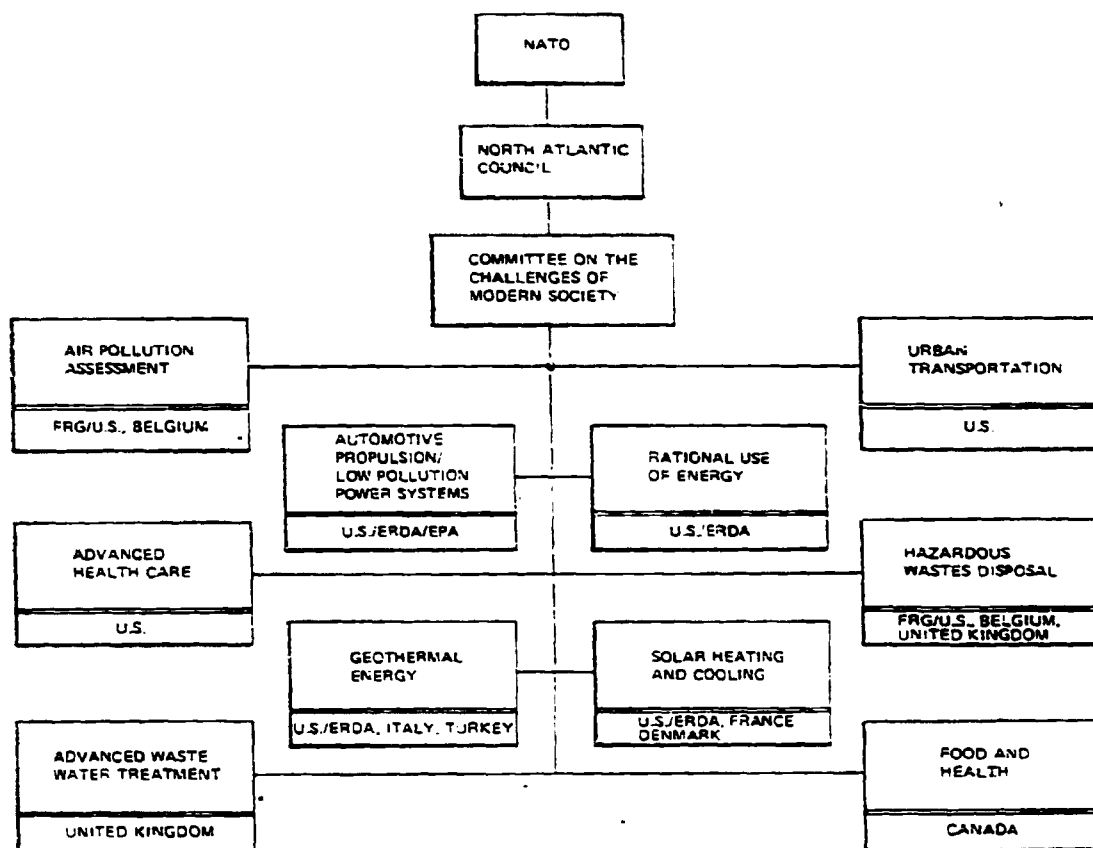
Source: *International Cooperation in Energy R&D*, Joint Oversight Hearings before the Subcommittee on Energy R&D and the Subcommittees on Domestic and International Scientific Planning and Analysis of the Committee on Science and Technology, June 29 and 30; July 1 and 2, 1976, p. 17.

Figure IV-1. INTERNATIONAL ENERGY AGENCY ORGANIZATIONAL STRUCTURE

members may also be included in some of the ongoing R&D projects. The major energy R&D projects are generally managed by a designated country. Under this CCMS pilot country method, a particular NATO member assumes the responsibilities for providing the leadership, administrative support, and conference and program facilities for each project. Other countries participate in an informal way consistent with their individual needs.

The ten areas under investigation by CCMS at the

present time are shown in Figure IV-2. The United States is the pilot country for Solar Energy (with France and Denmark as co-pilots), Geothermal Energy (with Italy and Turkey as co-pilots), the Rational Use of Energy (Energy Conservation), Automotive Propulsion Systems, Advanced Health Care, and Urban Transportation. The U.S. is co-pilot with Belgium and the Federal Republic of Germany for Air Pollution Assessment. Details of activities of four major areas appear in Table IV-5.



COMPLETED PILOT STUDIES: AIR POLLUTION, COASTAL WATER POLLUTION, DISASTER ASSESSMENT, INLAND WATER POLLUTION, ENVIRONMENT AND REGIONAL PLANNING, ROAD SAFETY

Source: *International Cooperation in Energy R&D*, Joint Oversight Hearings before the Subcommittee on Energy RD&D and the Subcommittees on Domestic and International Scientific Planning and Analysis of the Committee on Science and Technology, June 29 and 30; July 1 and 2, 1976, p. 17.

Figure IV-2. SUMMARY OF CURRENT CCMS PILOT STUDIES

#### U.S. Bilateral International Energy R&D Agreements

The active network of bilateral energy R&D agreements between agencies of the United States and individual foreign governments has been brought under the

management of ERDA. ERDA is involved in or has under discussion bilateral energy relationships with some 30 countries; about one-half of these are in nonnuclear areas. The active bilateral agreements are listed in Table IV-7. Technology areas and status of programs appear in Table IV-7.

Table IV-2

**ANNUAL CONTRIBUTION OF MEMBER NATIONS TO  
INTERNATIONAL ENERGY AGENCY JOINT PROJECTS**  
(Thousands of U.S. Dollars)

Agreement Signed	Tonn (years)	United States	Federal Republic of Germany	Japan	United Kingdom	Austria	Belgium	Canada	Denmark	Ireland	Italy	Netherlands	Norway	Spain	Sweden	Switzerland	Turkey
Director safety-data exchange, May 1976	a	(1)	(1)	(1)	(1)	(1)	(2)	(1)			(1)	(1)	(1)	(1)	(1)	(1)	
Loss of flow test, - on 20, 1976	4	(2) <sup>b</sup>	(4) 1,000 <sup>b</sup>														
Loss of flow test, Feb 23, 1976	(4)	(2) <sup>b</sup>		(4) 1,000 <sup>b</sup>													
Loss of flow test, (5)	4	(2) <sup>b</sup>							(5)				(5)		(5)		
Power burst facility, Mar. 8, 1976	4	(2,3) <sup>b</sup>		(3)													
Power burst facility, (8)	4	(2,3) <sup>b</sup>	(3)														
Mining technology clearhouse (7), Nov. 20, 1975	3	70	27		20 <sup>b</sup>	4	0				6			8			6
Coal resources and (8), Reserves data bank, Nov. 20, 1976	3	(11)	203		263 <sup>b</sup>		05				65						64
Coal resource (8) assessment survey, Nov. 20, 1976	3	203	76		71 <sup>b</sup>						13	12		17	11		13
Coal technical (10) data service, Nov. 20, 1976	3	387	124		118 <sup>b</sup>	17	25				20	17		20	10		20
Industrial composition of coal (12) Nov. 20, 1976	8	(13) 1,000	(13) 1,000		(13) 1,000 <sup>b</sup>												
Intense neutron source, Nov. 20, 1976	4	(14)		(16)				(16)							(16)	(16)	
Energy conservation in building complexes, Jan. 20, 1976	6	(10) 30	(14) <sup>b</sup>														
Energy systems analysis, steering group, meeting Feb. 17, 1976	c	160 (10)	(10)	(20)	(20)		(20)	(21)	(20)	(20)		(20)	(20)	(20)	(20)	(20)	

<sup>a</sup>Indefinite<sup>b</sup>Activity site<sup>c</sup>From 1 March-November 1976.

## Notes

(1) Information exchange only.

(2) Supplies Idaho facility

(3) Plus up to 3 scientists in exchange

(4) Plus up to 3 scientists at facility - on now.

(5) Signing with Scandinavian group (includes Finland) expected

(6) Signing expected

(7) Total annual contribution not to exceed \$85,000/yr - \$105,000

(8) Total annual contribution not to exceed £200,000/yr at January

1976 exchange rate and price levels - \$590,000.

(9) Total annual contribution not to exceed £174,000/yr - \$416,000

(10) Total annual contribution not to exceed £324,000/yr - \$760,000

(11) Operating data bank at USGS, otherwise contribution would be \$310,000

(12) Total contribution over 8 yr is estimated at £10,616,000 = \$24,000,000

at May 1976 price levels and exchange rate

(13) Average annual cost over life of agreement.

(14) Supplies Los Alamos Scientific Laboratory (LASL) facilities.

(15) Up to 6 scientists at LASL.

(16) Total contribution = \$240,000 payable at beginning

(17) Capital investment in facilities - 13,000,000 DM plus 1,000,000 DM/yr operating expense

(18) Cost for U.S. staff plus Brookhaven overhead.

(19) Approximately 3 full-time staff and support at Juelich.

(20) 1 staff member on site at Brookhaven or Juelich

(21) No participation yet; expected to send staff member to Brookhaven.

Source: *International Cooperation in Energy R&D*, Joint Oversight Hearings before the Subcommittee on Energy (11241) and the Subcommittees on Domestic and International Scientific Planning and Analysis of the Committee on Science and Technology, June 20 and 30, July 1 and 2, 1976 p. 17.

Table IV-3

## ACTIVITIES OF IEA COMMITTEE ON ENERGY R&amp;D

IEA Working Party	Participants/ Start-End Dates (* Lead Country)	Cooperative Activities/ Technical Scope (ERDA is U.S. lead except where noted.)	Current Status
1. Coal Technology	Austria Belgium West Germany (FRG) Italy Netherlands Spain Sweden Turkey United Kingdom* United States  Start: Nov. 1975 End: Nov. 1976 <sup>2</sup>	<b>Current</b> Mining Technology Clearing House (U.S./BOM) Collection of R&D project descriptions relating to underground and surface coal mining and coal preparation technology.  World Coal Resources and Reserves Data Bank Service (U.S./USGS) Collection of coal resources and reserves data from participating nations.  Coal Technical Information Service Establishment of a central information storage and retrieval system.  Economic Assessment Service for Coal Assessments relating to coal utilization, effluent disposal, coal conversion, cost and availability of coal.  Fluidized Combustion of Coal A cooperative experimental project to be funded equally by U.S., United Kingdom, and FRG and operated in the United Kingdom.  <b>Proposed</b> Coal pyrolysis Fundamental coal research Continuous feeding of coal slurry under pressure (pending legal solutions) Conference on basic coal science Continuous feeding of fine coal into pressurized reactors Microbiological treatment of gasification liquors	Participating nations have provided data and clearing house is established.  Participating nations are providing the basic data and the service is in operation.  The service is in operation.  Related studies underway.  Construction RFP issued in fall of 1976.
2. Hydrogen Production	Belgium Canada FRG Japan	<b>Current</b> No current agreement as yet; however, four coordinating committees have been formed: -Thermochemical production (EC lead)	Several meetings, one workshop, and several reports issued. Exchanges of program information and plans.

<sup>2</sup>Except fluidized combustion of coal agreement will terminate in 1984.

Table IV-3

## ACTIVITIES OF IEA COMMITTEE ON ENERGY R&amp;D (Cont'd)

IEA Working Party	Participants/ Start-End Dates (* Lead Country)	Cooperative Activities/ Technical Scope (ERDA is U.S. lead except where noted.)	Current Status
2. Hydrogen Production (cont'd)	Netherlands Sweden United Kingdom United States Commission of European Communities (EC)*  Start: 1975 End: Indefinite	<ul style="list-style-type: none"> <li>Electrolysis of water (U.S. lead)</li> <li>Thermochemical/nuclear heat interface (FRG lead)</li> <li>Systems analysis and technology assessment (United Kingdom lead).</li> </ul> <p>Proposed</p> <p>Umbrella agreement with provision for cooperative projects incorporated as developed, by annexes:</p> <ul style="list-style-type: none"> <li>Chemical engineering evaluation of thermochemical processes (FRG, U.S., EC, United Kingdom, Belgium, Japan, Netherlands)</li> <li>Coupling of thermochemical process with heat source (FRG, U.S., EC, Japan)</li> </ul>	<p>Draft agreement in preparation. Draft annex proposal being circulated.</p> <p>Draft annex proposal being circulated.</p>
3. Solar Energy	Austria Belgium Denmark FRG Ireland Japan* Netherlands Spain Sweden Switzerland United Kingdom United States  Start: Feb. 1976 End: Indefinite	<p>Proposed</p> <p>Development of solar heating, cooling, and hot water supplying systems</p> <p>Development of components for solar heating, cooling, and hot water supply systems</p> <p>Performance testing of solar collectors</p> <p>Development of an insolation handbook and instrument package</p> <p>Use of existing meteorological information for solar energy application</p>	Draft implementing agreement being circulated among all participants.
4. Conservation	Austria Belgium Canada Denmark FRG Greece Ireland	<p>Proposed</p> <p>Conservation in building complexes (FRG lead)</p> <p>Thermal characteristics of buildings (U.S. lead)</p> <p>Energy cascading (Austria lead)</p> <p>Heat pumps with thermal storage (Austria lead)</p> <p>Heat transfer and heat exchangers (United Kingdom lead)</p>	<p>Agreement signed June 28, 1976.</p> <p>Expert group established; draft agreement text.</p> <p>Expert group established; draft text in preparation.</p> <p>Expert group established; draft text in preparation.</p> <p>Expert group established; agreement text being drafted.</p>

Table IV-3

## ACTIVITIES OF IEA COMMITTEE ON ENERGY R&amp;D (Cont'd)

IEA Working Party	Participants/ Start-End Dates (* Lead Country)	Cooperative Activities/ Technical Scope (ERDA is U.S. lead except where noted.)	Current Status
4. Conservation (cont'd)	Italy Japan Netherlands New Zealand Spain Sweden Switzerland United Kingdom United States* EC  Start: Feb. 1975 End: Indefinite	Combustion (U.S. lead)  Thermal energy storage (FRG lead)	Separate expert group recommended; draft text being prepared under heat transfer group. Expert group established; drafting of text underway.
5. Radioactive Waste Management	Austria Belgium Canada Denmark FRG Ireland Italy Japan Netherlands Spain Sweden Switzerland United Kingdom United States EC OECD-Nuclear Energy Agency (NEA)* (France)  Start: May 1974 End: Indefinite	Current Catalog—R&D programs and plans.  Proposed Promising cooperative areas: —Geological disposal of radioactive waste —Solidification of high level waste —Sea bed disposal of radioactive waste —Control of gaseous and airborne waste Other areas under discussion: —Processing of transuranium contaminated waste —Decontamination and decommissioning	Catalog is complete.

Table IV-3

## ACTIVITIES OF IEA COMMITTEE ON ENERGY R&amp;D (Cont'd)

IEA Working Party	Participants/ Start-End Dates (* Lead Country)	Cooperative Activities/ Technical Scope (ERDA is U.S. lead except where noted.)	Current Status
6. Fusion	Belgium Canada FRG Italy Japan Netherlands Sweden Switzerland United Kingdom United States EC*  Start: Oct. 1976 End: Indefinite	<b>Current</b> Participation in intense neutron source experiment at Los Alamos Scientific Laboratory (LASL).  <b>Proposed</b> Fusion Power Coordinating Committee (FPCC) made up of participating nations, establishing practical mechanisms to exchange information and coordinate the planning of national/international fusion programs and endeavoring to expand arrangements in following areas: —Superconducting magnets (SCM) —Plasma — wall interaction  —Large-scale experiments	Canada, Japan, Sweden, Switzerland, and United States signed agreement May 1976.  Japan, United States, and EC—negotiating. Workshop in FRG with participating nations—October 1976. Progress held up pending decision on potential Soviet participation.
7. Nuclear Safety	Austria Belgium Canada FRG Italy Japan Netherlands Norway Spain Sweden Switzerland United Kingdom United States*  Start: Feb. 1976 End: Indefinite	<b>Current</b> Information exchange agreement (U.S./NRC). Participation in loss of flow test facility (LOFT) operations in Idaho (U.S./NRC). Participation in Power Burst Facility (PBF) operations in Idaho (U.S./NRC).  Participation in U.S. heavy section steel test program (HSST) at ORNL (U.S./NRC). Safety research index (U.S./NRC).  <b>Proposed</b> Fuel cycle safety, i.e., mine tailings, fuel transport, marine disposal, criticality, etc. (U.S./NRC)	All 13 participants signed agreement May 1976. FRG and Japan signed; representatives on site. Scandinavian countries; negotiations complete. FRG negotiations complete; representatives on site; Japan signed; representatives on site; Italy, Austria, Spain, Scandinavian countries negotiating. United Kingdom and FRG negotiating.  Second issue in preparation.  Responses being collected from interested countries.
8. High-Temperature Reactors for Process Heat	FRG* Sweden Switzerland	<b>Current</b> Working group established to —handle problems created by nuclear process heat,	Inaugural meeting held on April 8, 1976.

Table IV-3

## ACTIVITIES OF IEA COMMITTEE ON ENERGY R&amp;D (Cont'd)

IEA Working Party	Participants/ Start-End Dates (* Lead Country)	Cooperative Activities/ Technical Scope (ERDA is U.S. lead except where noted.)	Current Status
8. High-Temperature Reactors for Process Heat (cont'd)	Austria EC Ireland Italy Japan United Kingdom United States NEA/OECD  Start: Apr. 1978 End: Indefinite	--Identify high priority problem areas to be tackled using coordinated resources. --exchange information on program activities.  <b>Proposed</b> Survey of current activities Identify requirements of nuclear process heat Develop capabilities to meet requirements Layout plans for short-, medium-, and long-term goals.	Initiated efforts.
9. Geothermal	Austria Canada FRG Italy* Japan Netherlands Sweden Switzerland Turkey United Kingdom United States  Start: Apr. 1978 End: Indefinite	<b>Proposed</b> Direct contact heat exchangers  Small geothermal power plant  Hot dry rock as geothermal source	A prototype heat exchanger is being proposed for testing at a site in Vienna. Design specifications for components of a 5 Mw(e) plant have been developed for possible future IEA hardware development project. IEA awaiting proposals from interested countries.
10. Biomass Conversion	Belgium Canada FRG Ireland* Japan Sweden Switzerland United Kingdom  Start: Feb. 1978 End: Indefinite	<b>Current</b> Exchange of information on participating countries' activities.  <b>Proposed</b> Tree farm as energy source	Essentially complete.  Site visits planned for Ireland and Sweden.



Table IV-3

## ACTIVITIES OF IEA COMMITTEE ON ENERGY R&amp;D (Cont'd)

IEA Working Party	Participants/ Start-End Dates (* Lead Country)	Cooperative Activities/ Technical Scope (ERDA is U.S. lead except where noted.)	Current Status
11. Wind Power	Belgium Canada Denmark FRG Ireland Italy Japan Netherlands* New Zealand Sweden United Kingdom United States  Start: Mar. 1976 End: Indefinite	<b>Current</b> Information exchange on wind programs between participating countries.  <b>Proposed</b> Prediction of wind flow characteristics from meteorological data. Economic and user requirement studies. Technology--standards agreement and hardware development.	Exchange essentially complete.  Subgroups currently drafting preliminary project proposals
12. Wave Power	Belgium Canada Denmark Ireland Japan Netherlands Sweden United Kingdom* United States  Start: Apr. 1976 End: Indefinite	<b>Current</b> Review of current national programs.  Collection and distribution of wave height and period data.	Completed at working party meeting April 12, 1976. Underway.
13. Ocean Thermal Energy Conversion (OTEC)	Belgium Canada FRG Italy Japan Sweden United Kingdom United States	<b>Current</b> Exchange of information on status of various country programs in OTEC, nature of environmental impacts requiring further study, and suggestions for applications for lesser developed countries.  <b>Proposed</b> Thermal resource assessment: vertical current variations	Working party has met.

Table IV-3

## ACTIVITIES OF IEA COMMITTEE ON ENERGY R&amp;D (Cont'd)

IEA Working Party	Participants/ Start-End Dates (* Lead Country)	Cooperative Activities/ Technical Scope (ERDA is U.S. lead except where noted.)	Current Status
13. Ocean Thermal Energy Conversion (cont'd)	Start: Mar. 1976 End: Indefinite	and temperature differences. Technology development and demonstration: heat exchanger materials, working fluids. Utilization: manufacturing economically desirable products from high-seas location. Mariculture: kelp for biomass conversion, shellfish. Environmental impact assessment.	
14. Small Solar Power Systems	Austria* Belgium FRG Italy Spain Sweden Switzerland United States  Start: Feb. 1976 End: Indefinite	<b>Current</b> 600-Kw solar thermal electric power system identified as cooperative project.  <b>Proposed</b> 600-Kw solar thermal electric power system, flatplate collectors, steam boiler, to be set up in Spain.	System identification completed.  Details of proposed system and of country participation under discussion before draft agreement.
15. Energy Systems Analysis	Belgium Canada Denmark FRG Ireland Japan Netherlands Norway Spain Sweden Switzerland United Kingdom United States* EC  Start: Mar. 1976 End: Indefinite	<b>Current</b> An analytical basis for the assessment of energy technologies in support of the formulation of a strategy for energy R&D programs in the various IEA countries and for the IEA itself is being developed.  <b>Proposed</b> Analysis of interfuel substitution strategies, energy-economic relationships, and environmental issues.	An international working staff of approximately 20 individuals from the participating nations are located on-site at Brookhaven National Laboratory on Long Island and in Juelich, Germany. An initial report is planned.

Source: *International Cooperation in Energy R&D*, Joint Oversight Hearings before the Subcommittee on Domestic and International Scientific Planning and Analysis of the Committee on Science and Technology, June 29 and 30; July 1 and 2, 1976. p. 17.

Table IV-4

## ACTIVITIES OF INTERNATIONAL ATOMIC ENERGY AGENCY

IAEA Activity	Participants/ Start-End Dates (* Lead Country)	Cooperative Activities/ Technical Scope (ERDA is U.S. lead except where noted.)	Current Status
1. Safeguards R&D	U.S./ACDA U.S./ERDA U.S./NRC U.S./State  Start: 1968 End: Indefinite	<b>Current</b> 1976 Department of State funding, managed by ERDA: Training                   \$120,000 Consultants               30,000 Instrumentation          60,000 Safeguards information system modifications     00,000 \$300,000  <b>Proposed</b> U.S. proposes to increase support of IAEA safeguards effort by \$1 million/year for five years. Details being developed, with inputs from IAEA, ERDA, ACDA, and NRC In addition 1976 foreign aid bill contains \$1 million for IAEA safeguards training activities (1976 regular IAEA budget allocates \$8,443,000 for safeguards of which U.S. contributes 28 percent or \$1,804,000.)	Work is underway. U.S. provides a member of IAEA Senior Safeguards Advisory Committee. Advanced nondestructive radioassay instruments being provided for use by IAEA inspectors.  12 IAEA staff at Los Alamos Scientific Laboratory (LASL) training session in 1976.  Train IAEA staff and member state officers in physical protection techniques and materials accountability.
2. Regional Fuel Cycle Center Study (RFCC)	Austria Argentina Belgium Pakistan Finland Switzerland Spain U.S./ERDA U.S./ACDA United Kingdom USSR France FRG Sweden Japan Canada  Start: Fall 1976 End: Spring 1977	<b>Current</b> Develop methodology for assessment of alternate strategies for RFCC's to permit evaluation of advantages/disadvantages. Report methodology to member states with examples. Provide forum for member states to work out strategies for establishment. Study considers economic, technical, legal, and institutional aspects covering spent fuel storage, reprocessing, mixed oxide fuel fabrication, transportation, waste management, and environmental impacts. Total cost of study estimated by IAEA at \$900,000.	Study underway; work being done by consultant group; U.S. providing 10-15 consultants. Preliminary results of study will be reported at IAEA nuclear fuel cycle conference in May 1977.

Table IV-4

## ACTIVITIES OF INTERNATIONAL ATOMIC ENERGY AGENCY (Cont'd)

IAEA Activity	Participants/ Start-End Dates (Lead Country)	Cooperative Activities/ Technical Scope (ERDA is U.S. lead except where noted.)	Current Status
3. Nuclear Safety and Standards	Most IAEA member nations  Start: 1975 End: 1980	Current Broad range of nuclear safety guides (NRC lead U.S. agency).	International codes of practice and safety guides for nuclear plant safety under development in following areas: design, siting, quality assurance, operations, and government organization and regulations.
4. Scientific Information Exchange and Technical Assistance Program	All IAEA member nations  Start: 1959 End: Indefinite	Current Scientific information exchange, International nuclear information system (INIS). —Fusion technology  —World power and research reactors  —Technical symposia and publications  Technical assistance program.	Atomindex has computerized nearly 100 percent of world's nuclear literature. Includes catalog of all fusion installations and devices and key personnel (not yet computerized). An updated listing of essential information on all power and research reactors in the world. Nuclear energy information disseminated annually through numerous technical publications and about 16 international seminars and symposia. Majority of members using this program. Approximately \$9.0 million/year spent on effort with additional provided by U.S. (i.e. \$1.4 million in 1975).

Source: *International Cooperation in Energy R&D*, Joint Oversight Hearings before the Subcommittee on Energy RD&D and the Subcommittees on Domestic and International Scientific Planning and Analysis of the Committee on Science and Technology. June 29 and 30; July 1 and 2, 1976, p. 17.

Table IV-5

## SELECTED CCMS ENERGY ACTIVITIES

CCMS Activity	Participants/ Start-End Dates (* Lead Country)	Cooperative Activities/ Technical Scope (ERDA is U.S. lead except where noted.)	Current Status
1. Solar Heating and Cooling Pilot Study	Australia Canada Greece Jamaica Portugal Turkey United States* Belgium Germany Israel Luxembourg Saudi Arabia United Kingdom Brazil France Italy Netherlands Sweden Denmark  Start: 1973 End: Possibly 1977	<b>Current</b> Development of an international data format to report programs and results in solar heating and cooling in buildings. Zero energy house demonstration project.  <b>Proposed</b> Tropical and Mediterranean studies on the application of solar energy are being considered.	Formats have been developed and are being sent to participating countries.  Denmark, Germany, United Kingdom, and Netherlands are currently testing demonstration houses.
2. Geothermal Energy Pilot Study	United States* Mexico France Iceland Turkey Portugal Greece New Zealand Italy United Kingdom Indonesia Uganda Philippines Kenya	<b>Current</b> Exploitation of underground dry hot rock (DHR).  Small geothermal power stations.  Information exchange.  Nonelectrical use of geothermal resources.	Five visiting scientists have participated in the DHR experiment at Los Alamos Scientific Laboratory; invitation extended. Final specification report was completed and distributed to participants, concluding this portion of pilot study. A memorandum of understanding information exchange was signed between U.S./ERDA, and Italy's CNR and ENEL in May 1976. The U.S., France, and Iceland are working on a publication comparing the results of several computer cost predictions with actual cost experience of nonelectrical systems.

Table IV-5

## SELECTED CCMS ENERGY ACTIVITIES (Cont'd)

CCMS Activity	Participants/ Start-End Dates (* Lead Country)	Cooperative Activities/ Technical Scope (ERDA is U.S. lead except where noted.)	Current Status
2. Geothermal Energy Pilot Study (cont'd)	Nicaragua FRG Canada El Salvador Haiti Guatemala Sweden  Start: 1973 End: Open	Reservoir engineering and brine reinjection.  Proposed A concluding DIER international meeting is tentatively scheduled at Los Alamos Scientific Laboratory in mid-1977. A concluding meeting on nonelectric economics is tentatively planned for the U.S. in the spring of 1977. Plans are being formulated to have reservoir engineering and brine injection transferred to a cooperative project between the U.S. and Mexico.	Pending
3. Rational Use of Energy Pilot Study	Austria Belgium Ireland Denmark Netherlands FRG Portugal New Zealand Italy United States* United Kingdom EC France Canada Norway With Switzerland and Sweden as observers  Start: 1974 End: 1977	Current Establishment of an international climatic reference year. Electric utility load management. International industrial data base.  Modular integrated utility system (MIUS) and total energy systems (TES) (U.S./HUD).  Proposed Discussions underway for creating comparative data bases in food processing, paper pulp, and aluminum.	Completed.  Final report in draft. Cement report is completed. Steel data base is completed. Polyvinyl chloride report is in draft form with recommendations under discussion. Methodology is under discussion. Plans are underway to prepare a current glossary of special terms relating to MIUS and TES; to assemble an international catalogue of projects related to MIUS and TES; to establish a file of project progress evaluation reports on MIUS and TES; to develop a standard methodology for performance measurement and data collection and reporting from testing and demonstration of MIUS and TES related projects.

Table IV-5

## SELECTED CCMS ENERGY ACTIVITIES (Cont'd)

CCMS Activity	Participants/ Start-End Dates (* Lead Country)	Cooperative Activities/ Technical Scope (ERDA is U.S. lead except where noted.)	Current Status
4. Automotive Propulsion Low Pollution Power Systems Pilot Study	France Italy United Kingdom United States* FRG Netherlands Canada With Sweden and Japan as observers  Start: Nov. 1973 End: Open	<b>Current</b> Information exchange of national programs. Standardization of emission-measuring procedures (U.S./EPA).  Coordination of automotive propulsion system pro- grams with research on safety vehicles.  <b>Proposed</b> A study on noise pollution emitted by light and heavy duty vehicles is under consideration.	<b>Complete.</b> Under the leadership of FRG, plans are underway to coordinate standard test and measuring procedures. <b>Inactive.</b>

Table IV-6

**U.S. BILATERAL INTERNATIONAL ENERGY  
R&D AGREEMENTS**

Energy Area	Active	Pending
Nuclear		
Breeder reactors	FRG, United Kingdom, USSR, Japan, Netherlands	France, Italy
Thermal reactors		
Reactor safety	FRG, Spain, Japan	France
Fuel cycle and waste management	Canada, FRG	France, United Kingdom, Japan
Fusion	United Kingdom, USSR	France
Exchange of nuclear documentation	United Kingdom, Canada, France, Japan	
Fundamental properties of matter	USSR	
Nuclear science information and personnel exchange	Romania	
Fossil		
Coal	United Kingdom, Poland	USSR
MHD	USSR, Poland	Japan
Geothermal	Italy, USSR, Iceland	Japan
Solar		
Thermal	USSR	Japan, Spain
Electric	France, USSR	Japan, Spain
Conservation		
Electric systems	USSR	

Source: *International Cooperation in Energy R&D*, Joint Oversight Hearings before the Subcommittee on Energy RD&D and the Subcommittee on Domestic and International Scientific Planning and Analysis of the Committee on Science and Technology. June 29 and 30; July 1 and 2, 1976. p. 59.



Table IV-7

## SUMMARY OF U.S. BILATERAL ENERGY ACTIVITY

Nation	Technology Area/ Start-End Dates	Cooperative Activities/Technical Scope	Current Status
Federal Republic of Germany	Liquid metal fast breeder reactors (LMFBR)  Start: Jun. 1976 End: Jun. 1986	<p><b>Current</b> Exchange of personnel, equipment, materials, seminars, visits, information in these areas:</p> <ul style="list-style-type: none"> <li>- Reactors, neutronics, fuels, fuel recycle,</li> <li>- Reactor and reactor coolant system components,</li> <li>- Coolant technology, nonnuclear test facilities in support of LMFBR programs,</li> <li>- Quality assurance and nondestructive practices,</li> <li>- Reactor safety, design and operation of LMFBRs</li> <li>- Economic and environmental considerations in the development of LMFBRs.</li> </ul> <p><b>Proposed</b> Negotiate details of cooperation in each area and present recommendations to Joint Committee</p>	Preparations underway for negotiating details of cooperation in each area.
	High-temperature reactor research  Start: Mar. 1971 End: Mar. 1976 (Extended)	<p><b>Current</b> Information exchange: documents, conferences, visits, long-term assignments dealing with high-temperature gas reactor fuels, reactor internals, and fuel reprocessing.</p> <p><b>Proposed</b> Activity contemplated by this agreement will be conducted under the proposed U.S./ERDA-FRG gas-cooled reactor agreement under negotiation</p>	Extended by agreement between ERDA and Juelich Nuclear Research Center until signature of proposed agreement on gas-cooled reactors between ERDA and Federal Ministry for Research and Technology of FRG, is negotiated.
	Radioactive waste management  Start: Dec. 1974 End: Dec. 1979	<p><b>Current</b> Information exchange: visits, meetings, and joint projects in these areas:</p> <ul style="list-style-type: none"> <li>- Disposal of radioactive waste in salt deposits,</li> <li>- Retrievable surface storage facilities,</li> <li>- Waste management research and development,</li> <li>- Waste from decommissioning of nuclear installations,</li> <li>- Operating aspects of storage or disposal of low and intermediate level wastes,</li> <li>- Transportation of radioactive waste.</li> </ul> <p><b>Proposed</b> Exchange of personnel between Battelle Pacific Northwest Laboratories at Richland, Washington, and Karlsruhe, Germany</p>	Documents are being exchanged; emphasis on transformation of high level radioactive waste into glass ingots.

[illegible]

**FF-AT**

**FF-AT**

Nation	Technology Area/ Start-End Dates	Cooperative Activities/Technical Scope	Current Status
France (cont'd)	Solar (cont'd)  Nuclear (proposed)	<b>Proposed</b> French hope to test their own solar boiler in ERDA 5-MWT solar thermal test furnace being planned for Sandia Laboratory, Albuquerque, New Mexico. This will require a separate agreement.  <b>Current</b> Exchange of personnel, materials, equipment, meetings, and information and joint projects in fission reactor, nuclear fuel cycle, and fusion energy technology.  <b>Proposed</b> Continue negotiations.	This agreement being negotiated between ERDA and French Atomic Energy Commission. Under the agreement three protocols are also being negotiated (dealing with liquid metal-cooled fast breeder reactors (LMFBR), high-temperature gas reactors, and management of radioactive waste.  Principal unresolved matter is French reluctance to conclude meaningful agreement with ERDA pending establishment of commercial arrangements for sale of their technology to U.S. industry.
United Kingdom	Coal  Start: Jul. 1974 End: Jul. 1977 (signed by U.S./BOM)	<b>Current</b> Exchange of personnel, equipment, research material, and basic information on all aspects of the utilization of coal from resource identification to end-use including: -Identification of reserves, -Extraction technology, -Conversion to other forms, -Transport in various forms, and -The impact of economic, legal, environmental, health, safety, and other requirements on this use of coal.  <b>Proposed</b> Exchange of devices for measuring the sulfur and ash content of coal.	ERDA is in the process of concluding an agreement with UK/National Coal Board (NCB) separate from the UK/NCB-U.S./BOM agreements.

Table IV-7

## SUMMARY OF U.S. BILATERAL ENERGY ACTIVITY (Cont'd)

Nation	Technology Area/ Start-End Dates	Cooperative Activities/Technical Scope	Current Status
United Kingdom (cont'd)	<p>Controlled thermonuclear research</p> <p>Start: Sep. 1958 End: Open ended</p> <p>Fast reactors</p> <p>Start: Feb. 1965 End: Jul. 1976</p>	<p><b>Current</b> Exchange of information relating to controlled thermonuclear fusion. Exchange of personnel, meetings.</p> <p><b>Current</b> Exchange of reports, letters, drawings, specifications, visits, and attachment of personnel dealing with all types of fast reactors for civil, land-based power stations, including construction and operation of prototype reactors, except for detailed reactor design and fuel manufacturing know-how.</p>	<p>Visits and exchange of information have continued on a routine basis.</p> <p>This agreement is expected to be superseded by an agreement between ERDA and the United Kingdom Atomic Energy Authority in the field of liquid metal-cooled fast breeder reactors, currently being negotiated.</p>
Italy	<p>Geothermal (ENEL)</p> <p>Start: Jun. 1976 End: Jun. 1980</p> <p>Geothermal (CNR/ENEL)</p> <p>Start: May 1978 End: May 1981</p>	<p><b>Current</b> Research, development, and demonstration applications of geothermal energy in project areas: - Stimulation of hot dry rock and hydrothermal reservoirs - Reservoir physics and engineering - Environmental control technology - Utilization of hot brine resources - Deep drilling.</p> <p><b>Proposed</b> Exchange of personnel, information, and techniques Joint projects Loan instruments</p> <p><b>Current</b> Every four months exchange information in computer format dealing with the location, size, and characteristics of geothermal wells and fields, bibliographic information, and heat transmission data.</p> <p><b>Proposed</b> Establishment of data base. ERDA to collect data on the Americas, Oceania, Iceland, Asia except for USSR. CNR/ENEL to collect data on Europe except for Iceland, Africa, USSR.</p>	<p>Implementation agreement signed June 7, 1976.</p> <p>Implementation agreement signed June 7, 1976. Implementation agreement signed June 7, 1976. Details being developed under negotiations. Under negotiations.</p> <p>Preparing for implementation of agreement recently signed (previously covered under CCMS).</p>

Table IV-7

## SUMMARY OF U.S. BILATERAL ENERGY ACTIVITY (Cont'd)

Nation	Technology Area/ Start-End Dates	Cooperative Activities/Technical Scope	Current Status
Netherlands	<p>Sodium Component Testing (LMFBR)</p> <p>Start: Oct. 1970 End: Dec. 1979</p>	<p><b>Current</b> Exchange of information and personnel and testing of components in sodium components test facilities at Hengelo, The Netherlands, and Liquid Metal Engineering Center, Santa Susana, California.</p> <p><b>Proposed</b> Cooperation under this agreement is expected to be subsumed under U.S./ERDA-FRG LMFBR agreement signed June 8, 1976</p>	Exchange of information in progress.
Spain	<p>Nuclear Health and Safety</p> <p>Start: 1966 End: 1976 (renewable annually)</p> <p>Solar</p> <p>Start: Awaiting completion of entry into force formalities End: 5 years from entry into force</p>	<p><b>Current</b> Investigation of low levels of plutonium oxide in agricultural area after U.S. military plane crash near Palomares resulted in dispersal (but no explosion) of nuclear weapons.</p> <p><b>Proposed</b> Planning is underway for extensive reexamination of people from Palomares who participated in cleanup operations, as well as analysis of air, soil, and vegetation samples</p> <p><b>Proposed</b> Solar energy center in Spain.</p>	<p>U.S./AEC (now ERDA) provided whole-body counter and other equipment to investigate health and safety aspects. Since 1967 funding to date has totalled \$244,000 (about \$25,000/year).</p> <p>Treaty provides for the expenditure of \$23 million over a five-year period on projects of mutual interest. Although it has high priority interest, solar center must compete with other civil projects being considered.</p>
Canada	<p>Nuclear</p> <p>Start: Feb. 1965 End: Nov. 1976</p>	<p><b>Current</b> Heavy water reactor exchange.</p> <p><b>Proposed</b> Memorandum of understanding on -Radioactive waste management -Heavy water reactor fuel cycle and support facilities -Systems analysis of heavy water reactors</p>	<p>Inactive.</p> <p>Being negotiated.</p>

Table IV-7

## SUMMARY OF U.S. BILATERAL ENERGY ACTIVITY (Cont'd)

Nation	Technology Area/ Start-End Dates	Cooperative Activities/Technical Scope	Current Status
USSR	<p>Peaceful uses of atomic energy Start: June 1973 End: June 1983</p> <p>Fast breeder reactors (FBR)</p>	<p><b>Current</b> Mutually agreed basic and applied problems with the design, development, construction, and operation of nuclear power plants using fast breeder reactors.</p> <p><b>Proposed</b> Expansion of joint projects in FBR and possible exchange of scientists for R&amp;D</p>	<p>Presently conducting two joint seminars per year in FBR. Joint projects involving exchange of FBR materials and exchange of information</p>
	Fusion	<p><b>Current</b> Development of prototype and demonstration scale fusion reactor including theoretical, experimental, and design-construction studies at all stages up to industrial-scale.</p> <p><b>Proposed</b> Continued cooperation in following areas: —Large fusion experiments and technology leading to fusion power plant by 2000 —Tokamaks, advanced concepts, supporting physics, supporting technology, materials studies, system engineering, environment, safety</p>	<p>Emphasis on specialist meetings and joint work; previous emphasis on orientation exchange.</p>
	Fundamental properties of matter	<p><b>Current</b> Joint theoretical and experimental studies, particularly in high, medium, and low energy physics. May also include design, planning, and construction of joint facilities in these areas.</p> <p><b>Proposed</b> Program of cooperation, if fully implemented, will provide access to several new USSR facilities and a better overall picture of the capabilities of Soviet facilities in high-energy physics and in materials science such as studies of surface physics, neutron inelastic scattering, and radiation damage.</p>	<p>Cooperation primarily in high energy physics. Joint experiments at Fermi Laboratory, Batavia, Illinois, on 200 GEV accelerator involving long-term visits at Batavia by Soviet physicists who have brought with them Soviet equipment for use at Fermi Laboratory. The USSR 72 GEV accelerator at Serpukhov has also been involved in this exchange.</p>

Table IV-7

## SUMMARY OF U.S. BILATERAL ENERGY ACTIVITY (Cont'd)

Nation	Technology Area/ Start-End Dates	Cooperative Activities/Technical Scope	Current Status
USSR (cont'd)	Light water reactor (LWR) technology (proposed)	<b>Proposed</b> Information exchanges in following areas: - Reactor safety regulation including in-service inspection and peak load management - Reactor safety research - Reactor materials and in-pile testing - Operation of nuclear power stations and water chemistry - Design and construction of LWR power stations - Fabrication of components for power stations	
	Thermionics (proposed)	<b>Proposed</b> Exchange of delegations of specialists to determine if mutually agreeable basis for exploring possibility of further cooperation in this area exists.	
	Cooperation in field of energy Start: June 1974 End: June 1978 (with automatic five year extensions) Coal technology	<b>Proposed</b> Exploration of possibilities for cooperation in coal technology. Coal preparation, the topic identified for mutually beneficial cooperation, is already being actively pursued under the U.S.-USSR Environmental Protection Agreement.	Negotiations near completion.
	Oil technology	<b>Proposed</b> Exploration of possibilities for cooperation in oil technology.	Final stages of negotiations on topics to be recommended to the Joint Committee near completion. Upon approval of topics by the Joint Committee on Energy, project groups will be established to implement cooperation.
	Gas technology	<b>Current</b> Exploration of possibilities for cooperation in gas technology. <b>Proposed</b> Upon approval of topics by the Joint Committee on Energy, project groups will be established to implement cooperation.	A number of areas for mutually beneficial cooperation have been explored; definitive agreement on topics has not yet been reached.

Table IV-7

## SUMMARY OF U.S. BILATERAL ENERGY ACTIVITY (Cont'd)

Nation	Technology Area/ Start-End Dates	Cooperative Activities/Technical Scope	Current Status
USSR (cont'd)	Heat rejection and water supply systems for thermal power plants	<p><b>Current</b> Design and operation of heat rejection and water supply systems for thermal and nuclear power plants, including intake structures and piping, circulating pumps, condensers, outlet piping and structures, cooling towers, artificial reservoirs, spray ponds, and associated equipment.</p> <p><b>Proposed</b> Exchange of specialists in five areas of heat rejection; exchange of bibliographies and reports; symposium on methods of utilizing waste heat or on evaporative cooling towers.</p>	Moderately active. An ambitious program was identified in 1974, but not yet fully implemented.
	Superconducting transmission technology	<p><b>Current</b> Design and development of commercial superconducting transmission lines.</p> <p><b>Proposed</b> Loan of U.S. cryogenic refrigerator for joint testing of a Soviet cable in Moscow scheduled to begin in 1977. Loan of Soviet 100 meter cable to U.S. for joint testing scheduled for 1979.</p>	Very active, with several visits taking place each year for joint experiments.
	Magnetohydrodynamics (MHD)	<p><b>Current</b> Design, construction, and operation of commercial scale, open cycle MHD plants.</p> <p><b>Proposed</b> Testing of U.S. and USSR electrode materials in each country. Testing of U.S. channel in the Soviet U-26 MHD facility in January 1978. Study of high magnetic field MHD phenomena at the U-26 using a U.S. superconducting magnet in 1977.</p>	Very active, with frequent exchanges of personnel and equipment for joint experiments and testing.
	Solar	<p><b>Current</b> General technology for the utilization of solar energy, including solar heating and cooling, solar thermal power stations, and direct photovoltaic conversion. Workshop on photovoltaics scheduled in the USSR.</p>	Workshops have been held for two of the three areas agreed upon for cooperative activity: heating and cooling, and thermal power stations.



Table IV-7

## SUMMARY OF U.S. BILATERAL ENERGY ACTIVITY (Cont'd)

Nation	Technology Area/ Start-End Dates	Cooperative Activities/Technical Scope	Current Status
USSR (cont'd)	Solar  Geothermal	Proposed Seminars on all three areas scheduled for early 1977 in the USSR.  Current General technology for the utilization of geothermal energy, including drilling methods, reservoir modeling, reservoir production, utilization technology, and environmental protection.	Inactive, due to Soviet refusal to allow U.S. exports access to the only geothermal electric power plant in the USSR located on the Kamchatka Peninsula.
Poland	Coal  Start: Oct. 1974 End: Dec. 1980	Current Mining technology—mechanization of longwall systems, classification of roofs in U.S. mines, degasification of mines, surface protection, removal and recovery of fine-size coal and refuse particles from coal, preparation plant water. Coal liquefaction—catalysts for hydrogenation processes, ash removal from coal liquefaction processes, carbonization of solid residues from coal liquefaction processes, effect of hydrogen donor solvent on coal extraction, noncatalytic coal liquefaction in the presence of hydrogen. U.S./ERDA research contribution is \$5.25 million (P.L. 480 funds). Coal gasification for MHD power generation—to test coal gasification concept utilizing MHD exhaust gases in coal-fueled MHD plants. U.S./ERDA research contribution in this area is \$1.3 million (P.L. 480 funds).	In process of starting.  In process of starting.  In process of starting.
Romania	Basic nuclear science information and personnel exchange  Start: 1968 End: 1979	Current Nuclear science information, nuclear physics, solid state physics, reactor physics, high-energy physics, radioisotope research and applications, instrumentation for nuclear research, radiation protection, prospecting, extraction, and concentration of radioactive ores.	This cooperative effort has not been very active largely because of U.S./ERDA policy that visitors must pay their own expenses; Romania has shortage of hard currency.

Table IV-7

## SUMMARY OF U.S. BILATERAL ENERGY ACTIVITY (Cont'd)

Nation	Technology Area/ Start-End Dates	Cooperative Activities/Technical Scope	Current Status
Romania (cont'd)	Basic nuclear science information and per- sonnel exchange(cont'd)	<b>Proposed</b> The Romanians have proposed that U.S./ERDA upgrade and expand the agreement to include nuclear power re- actor technology and controlled thermonuclear research. U.S./ERDA has not encouraged this expansion because of the unlikelihood of achieving a balanced information exchange. U.S./ERDA has informed the Romanians that we are prepared to consider cooperative activities in the areas of MHD, hydrogen production, and energy storage.	

## INTERNATIONAL ENERGY R&D

In February 1975, the OECD published a report summarizing *Energy R&D-Programs and Perspectives*. Much of the information contained in Annex I to that report

has been tabulated in the following section. The information is arranged alphabetically by energy source, with the countries involved listed alphabetically after each source.

### COAL

#### Production

Australia	R&D on cost reductions in mining. Research on mining thick seams (CRETA measures) at depth. Underground strata control research.
Belgium	Study of improvement of mining techniques and, more particularly, of automation.
Canada	R&D on underground mining technologies, especially on those for the thick deep seams containing a large part of Canada's western coal. R&D on gas outbursts and on roof stability in coal mines. R&D on a hydromechanical system, to extract coal from a 50-foot coal seam having a pitch averaging between 30 and 50 degrees. High-pressure water is used to blast the coal from the seam.
France	General mining problems such as control of seams, pressure, dust, ventilation, gas outburst, fire hazards, telecommunication, logistics. Coal mining technologies and transportation technologies.
Federal Republic of Germany	Research funded for 1975 and 1976 totaled 228 million DM. This research and development aimed at improving coal mining capacity, developing new automation techniques and improving security and working conditions.
Ireland	Development of a high-ash block for mechanical extraction in the Arigna coal fields, to be used for generating electricity nearby.
United Kingdom	R&D on increasing efficiency of deep coal mining, mainly mechanized longwall face mining. Improvements of coal cutting machinery, of strata control techniques,

United Kingdom  
(cont'd)

mechanization of face end operations; improved environmental, communications, and transport systems; prototype machinery testing; better coal preparation; better mine safety, prevention of accidents from gas, fire, and dust.

#### Improved Combustion

Australia	Improved combustion R&D: particulate matter emission, drying of brown coal, spouted bed coal technology, nitrogen oxides in combustion, fluidized bed carbonization, coal pulverizing, industrial boiler adaptation to clean air legislation, flame radiation. Fly-ash and nitrogen oxides formation research to reduce air pollution. Disposal of coal washeries waste, or conversion into energy. Fluidized bed combustion of coal preparation plant refuse. Mine and coal preparation plant effluent control.
Canada	Air pollution control: particulate matter, sulfur dioxide; water pollution control: coal washeries; reduction of pollutants in mines.
Federal Republic of Germany	Development of new hard coal power stations with fluidized bed combustion.
Netherlands	R&D on stack-gas desulfurization.
United Kingdom	R&D to support and improve existing designs for fossil-fueled electricity generation. Fluidized bed combustion R&D: atmospheric pressure combustion, low sulfur oxide emission; pressurized combustion for combined power cycles; dewatering of colliery tailings. R&D to improve efficiency of gas appliances and for industrial purposes.

## COAL

### Coal Gasification

Canada	R&D on underground gasification for low-Btu gas; first field trial in 1976. Progress would also benefit in situ tar sand extraction technologies.	United Kingdom (cont'd)	COED process. Catalytic conversion of Lurgi gas to methane in commercial-scale Lurgi pilot plant. Preparation for development of full-scale slagging gasification technology.
Federal Republic of Germany	Includes projects for pressurized gasification combined with gas and steam turbine (conversion factor from thermal to electric energy up to 45 percent), and the application of nuclear process heat from very high temperature gas reactors to coal gasification. Other projects are fixed-bed gasification under pressure; tube furnace gasification of lignite, using its natural moisture; high-temperature Winkler gasification of lignite; fluidized-dust gasification of lignite, slurried with oil.	USSR	Conducted research on in situ gasification, but its main concern has been improving the productivity of conventional mining methods and the transportation of the product.
<b>Coal Liquefaction</b>			
		Federal Republic of Germany	R&D focuses on production of fuel oil from coal: hydrogenation of coal to produce heavy heating oil that is environmentally clean. Additional hydrogenation of coal is being studied to produce middle distillates (heating and diesel oil).
Japan	A synthetic natural gas (SNG) plant to produce 50,000 cubic meters per day. Basic research will be conducted in gasification methods, equipment and safety, and maintenance techniques. Coal gasification power generation in the 2,000 ton/day class (in terms of treatment capacity). A gas turbine/steam turbine compound cycle power generating system in the 200-megawatt class. Basic research will be conducted using an experimental 2-megawatt plasma gasification furnace.	Japan	The feasibility of coal liquefaction will be ascertained and a 30-ton/day pilot plant for manufacturing solvent-refined coal will be developed. In addition, small-scale test plants for direct hydrogenation will be designed, built and operated experimentally.
		United Kingdom	R&D on extraction of liquids from coal with component gases near their critical temperature (laboratory scale) and on extraction with a coal-based liquid solvent (small pilot-plant scale). Coal liquefaction focuses on the extraction of liquids from coal gases under pressure and on the extraction of liquids with a coal-based liquid solvent, which is being tested on a pilot-plant scale. Other research focuses on the production of fuel from coal through coal hydrogenation to produce environmentally clean heavy heating oil.
Netherlands	Gasification of coal and heavy fuel oil.	<b>Transportation</b>	
Poland	Coal firms have initiated research in coal liquefaction and gasification and mining techniques. A jointly funded \$60 million, seven-year research project on coal was agreed upon by the United States and Poland in 1974. (U.S. funds are PL480 local currency accounts.)	Canada	Investigations of coal transportation systems: coal-water-slurry or coal-oil-slurry pipelines, and unit train concepts for large-scale coal movements.
United Kingdom	Preparation for low-Btu gas: R&D on fluidized bed gasification using air/steam as gasifying medium. High-Btu gas: COGAS—pilot plant for gasification of char from		

## ELECTRICITY

### Hydroelectric Power

Iceland	Hydrological, topographical and geological investigations of potential hydropower sites. Engineering planning.	Switzerland	Research on curvature of water turbine blading.
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## ELECTRICITY

### Power Plant Improvement

Belgium	Various studies connected with the improvement of power plant efficiency.
France	Regulation and control of power plants; heat exchange; auxiliary equipment in power plants; behavior of turbo-alternators. Studies on the various components of power plants: reliability, corrosion, etc.
Ireland	Transient studies of electrical machines.
Switzerland	Research on composition of fuel oils and combustion gases for conventional power stations. Design of components: burners, boilers, stacks, etc.

### Turbines and Combined Cycles

Belgium	Research on steam turbines and their components.
France	Research on steam and gas turbines.
Federal Republic of Germany	Combined cycles for utilization of reject heat.
Netherlands	Feasibility study on combined cycles. Higher efficiency of gas turbines.
Sweden	Development of a high-efficiency gas turbine which is suitable for peaking power but can also be provided with exhaust gas boilers driving steam turbines.

### Storage

Belgium	Studies of electrolytes.
France	Monitoring of the various methods of storage. Design of a 200 MW storage plant using compressed air. Studies on hydraulic storage. Research aiming at increasing the specific energy of batteries.
Federal Republic of Germany	Research on batteries and on methods for storage, such as flywheel storage.
Netherlands	Primary and secondary batteries.
Sweden	Iron-air battery.

United Kingdom	Development of advanced batteries for buses and light commercial vehicles.
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### Transmission

Austria	Research on high voltages, high-intensity currents, ac-dc conversion and superconducting cables.
Belgium	Research on networks, conductors, and automatic control of electric transport and distribution systems. Research on superconductors.
France	Research on electrical and mechanical properties of insulators to be used in superconducting cables.
Federal Republic of Germany	Transmission lines and very high voltages for dc and ac. Cool-end underground transmission lines. Superconducting lines.
Ireland	Study of control systems for high-voltage dc transmission schemes.
Japan	Development of high transmission capacity superconducting lines; main R&D areas: electrical behavior; superconducting environment; thyristor valves for ac-dc conversion, superconducting transformers, cooling systems; compatibility with present transmission systems.
Netherlands	High-pressure and gas-insulated cables.
Norway	High voltages.
Sweden	Ultrahigh voltage transmission. High-voltage dc transmission. Interconnection of power systems.
Switzerland	Superconducting cables.
United Kingdom	Research on ultrahigh voltage transmission design of various types of cables, including superconducting cables.
USSR	Operated long-distance power lines at higher voltages and over longer distances than any other nation. Under scientific exchange agreements, some Soviet technology is being shared with the United States, although apparently only a limited amount so far. Specific agreements concern ultrahigh voltage (UHV) transmission technology and

## ELECTRICITY

USSR (cont'd)	high-voltage direct-current (HVDC) transmission system experience and design, electric power system planning and dispatching and superconducting transmission technology.	Japan	Study of the environmental effect of thermal water from power stations: first stage (1972-74)—evaluation of physical effects; second stage (1975 onwards)—evaluation of biological effects.
<b>Reduction of Thermal Pollution</b>		Sweden	Environmental effects of the outlet of cooling water.
France	Problems connected with cooling in rivers, lakes and estuaries: cooling capacity, heat dissipation, ecology of sites. Dry and wet cooling towers.	Switzerland	Studies on wet and dry cooling towers. Climatic effects associated with cooling towers.
Ireland	Fundamental research on packing ratios in cooling towers.		

## FUEL CELLS

Canada	Work on portable hydrazine air systems (300w and 60w). Engineering evaluation of a 70 kw installation.	Federal Republic of Germany	Research on fuel cell technology for construction of small power plants situated close to the users.
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## GEOHERMAL ENERGY

Austria	Research on geothermal energy underway in the framework of geoscientific and geotechnical programs.	Iceland (cont'd)	formed. This program is carried out simultaneously with investigations on hydro-power potential.
Canada	Practical use and exploitation of geothermal energy. Study of hot springs and fumaroles in western Canada. Participation in NATO's CCMS Task Force for the improvement of information exchange and nonelectrical uses of geothermal energy.	Indonesia	A geothermal project in central Java, scheduled for completion in 1978, should generate 30 MW and to provide fresh water and raw materials for the chemical and mineral industries. Some lessons in the use of geothermal energy for multiple applications may be learned from this project.
France	Research on geothermal high-temperature reservoirs including expansion and vaporization mechanisms in rocks, clefts, and wells. Research on geothermal low-temperature reservoirs including: geology, mathematical models of reservoir evolution, heat exchangers, and pumps.	Italy	The world's oldest geothermal power station is in operation in central Italy near Lardarello. With over 60 years of experience, Italy has an outstanding collection of data on worldwide geothermal operations. Research and development is being conducted on various types of hot water and natural steam systems. Italy has 10 geothermal electric stations, with four more under construction. These are hot-water or low-temperature systems. Two types of turbines are used: direct intake exhausting to the atmosphere, and direct intake condensation. Total power generated in 1972
Federal Republic of Germany	Investigations on prospects of geothermal energy utilization in volcanic regions.		
Iceland	Exploration of thermal areas by geological, geophysical, and geochemical methods. Drilling and hydrological studies being per-		

## GEOTHERMAL

Italy (cont'd)	equaled 2,582 GW from an installed capacity of close to 400 MW.	Japan (cont'd)	will be undertaken on long distance transportation of geothermal fluids and other subjects related to the multipurpose utilization of geothermal energy. Research and investigation will be conducted on the effects on the natural environment, including changes in hot water systems associated with the extraction of geothermal fluids to clarify the impact of geothermal utilization on the environment.
Japan	Development of technology of steam production used for large-scale electric power plant in the five year program 1972-1976. Total expenditures amount to Yen 759 million. As part of the "Sunshine Project," research on geothermal energy includes: survey of geothermal resources, study of mechanisms of natural steam and hot water reservoirs, development of binary cycles and power plants, and large-scale test facilities. Japan has three geoelectric plants in operation and three more under construction. All are turbine-condenser facilities. The combined capacity of the plants in operation or under construction is 170 MW. Current Japanese geothermal research and development includes methods of ascertaining reserves of geothermal resources; improving technology for exploring and extracting geothermal energy; researching technology for high-accuracy exploration and analyzing geothermal resources; and developing measuring equipment needed for exploration. A drilling system suitable for use in a geothermal environment of 250° C will be developed. A 10-MW binary-cycle power generation system utilizing hot water will be developed. Corrosion-resistant materials, high-efficiency heat exchange techniques, etc., will be developed for this system. Design studies for a 50-MW natural steam, low-enthalpy, combined cycle will be developed. A 10-MW volcanic power generation system will be developed. Technology for fracturing hot rock necessary for artificially extracting geothermal energy from volcanoes and hot dry rock will be developed. Research	Mexico	Work is in progress to exploit the geothermal resources in northern Baja California. A plant for electric power generation and the recovery of chemical by-products is planned. Installed electrical capacity should approach 200 MW before 1980. Studies are underway for 23 other sites in Mexico. Total R&D is running approximately \$3 million a year including investigation and construction of a low-pressure turbine generator unit using natural steam.
		New Zealand	Existing operational geothermal plant producing 192 MW, built in 1958; steam is separated from hot water at the well head and piped to the turbine. A study was conducted to determine the best way to utilize the remaining thermal energy at Waikei Field where the current plant is operating. (The study was completed in 1972.) Other geothermal sites have been surveyed and further plants may be built in the future.
		Philippines	Four geothermal projects are planned in the Philippines. Studies and planning are underway and construction on two sites should begin in the near future. These geothermal operations involve subsurface hot water sources.

## MAGNETOHYDRODYNAMICS (MHD)

Japan	Research on long-term operation, heat exchanger, seed recovery, heat-proof materials, superconducting magnets; this work is centered on a 1,000 KW MHD test plan.	USSR	The Soviet MHD project, probably the largest in the world, is the first U.S.-USSR cooperative energy project. The AVCO Corporation is building large channeling elements for the Soviet MHD generators under the cooperative agreement sponsored by ERDA. Soviet interest also has been expressed in U.S. instrumentation, super-cooled magnets and electrodes. The Soviet system is based on a once-through plasma
Sweden	Exploratory work on open-cycle MHD systems.		
Switzerland	Direct conversion into electricity by closed-cycle process.		

## MHD

USSR  
(cont'd)

technique. The USSR has operated a pilot plant for 12 years and plans to initiate

commercial scale operations within 5 or 6 years.

## NATURAL GAS

### Production

France Studies to make gas interchangeable in domestic, commercial, and industrial equipment.

United Kingdom

R&D on pipes, components, fracture behavior of large pipelines, stress corrosion, inspection devices in high-pressure systems.

### Storage

### Transportation

Canada R&D on engineering economics and environmental impact of a pipeline system across the Arctic and Sub-Arctic, in permafrost conditions. R&D on underwater pipelines between the Arctic Islands, at depths of 300 meters. Marine surveys, ecological studies. Other concepts studied: icebreaker LNG tankers, giant aircraft, electricity transmission.

Austria

Underground storage of gas.

France

R&D on rock mechanics and cavity stability in salt, nuclear and natural cavities. R&D on storage of gas in aquifers. R&D on storage of gas in karst-cavities. R&D on storage of gas in cavities created by nuclear explosions near sea coasts.

Switzerland

Study of storing oil and gas in Swiss geological formations. Seismic surveys and drilling.

France Materials R&D for cryogenic hulls in LNG ships.

United Kingdom

Economics and safety on high-pressure storage in pressure vessels and pipelines, salt cavern storage, LNG storage.

Federal Republic of Germany Storage and transport of LNG.

## NUCLEAR ENERGY

### Uranium Enrichment

Australia Ultracentrifuge process.

Sweden

Gaseous diffusion. Minor effort on gas centrifugation.

Belgium Gaseous diffusion.

United Kingdom

R&D on centrifuge. Collaboration with Federal Republic of Germany and Holland in ultracentrifuge process.

France Gaseous diffusion and ultracentrifuge process.

### Light Water Reactors

Federal Republic of Germany Ultracentrifuge process.

Belgium

Improvement of equipment and fuel.

Finland

Development of a computer program system for the fuel management in LWRs.

Japan Centrifuge process. Gaseous diffusion process.

France

Improvement of PWRs and BWRs.

Netherlands Ultracentrifuge process. Isotope separation by fast rotating plasmas.

Federal Republic of Germany

Nuclear research tied in with that in France and in Italy. Several light water plants have been built, often using U.S. technology.



## NUCLEAR

FRG  
(cont'd) Building a 300-MW experimental reactor in addition to collaboration with French on a 1200-MW reactor.

Japan Japan has the world's most ambitious program to convert its electric power generation to nuclear. Much of the technology involved has been borrowed, but the Japanese are experimenting with a high-temperature gas-turbine reactor, with breeder reactors, and with fuel enrichment. The scope of the Japanese R&D effort can be measured by budget figures for FY 1974. The fast breeder and the light water reactor each had R&D budgets of \$40 million. Fusion was assigned \$2.6 million and all nonnuclear energy R&D, \$8 million. Time required for the construction of nuclear plants in Japan is approximately one-half that required in the United States.

Norway Experimental fuel performance studies. Computer-based control and supervision systems. Computer program system for fuel management. Development of zircaloy alloys and canning tubes.

Sweden Among the various projects involved, three have unique features: 50 MW R2 materials testing reactor; zero-power high-temperature reactor KRITZ; prestressed concrete pressure vessels for LWR. Improvement of ASEA-ATOM boiling water reactors. Computer programs for the calculation of power dissipation and burnout, and of void and temperature distribution in LWRs; hazard analysis in PWR and BWR stations; water chemistry and corrosion in LWRs.

### High-Temperature Gas-Cooled Reactors

Belgium Study of helium technology and of new irradiation means. Research on fuels, core physics and safety.

Federal Republic of Germany Three main projects: (1) THTR 300—high-temperature reactor 280 MWe power plant. Total cost: 885 million DM. (2) HHT—specifications for the construction of a 300-MWe power plant using helium turbines in direct loops. Total cost: 251 million DM. (3) Direct use of nuclear process heat in various industrial processes.

Japan Multipurpose utilization.

Switzerland HHT program: specifications for construction of a 300-MWe power station with direct-cycle helium turbines. Swiss contribution amounts to 10 percent of the German HHT project.

United Kingdom Research on problems relating to fuels and behavior of materials. Includes work on "Dragon."

### Liquid Metal Fast Breeder Reactors

Belgium Participation in the West German SNR 300 project.

France France is operating a liquid metal fast breeder reactor, the Phenix, which went critical on August 31, 1973, and has now achieved full operating power of 233 MW. The French program is also supported by Germany and Italy and will lead to fast breeder power plants being built in those countries as well. Under this program, construction of a 1200 MW fast breeder is already underway in France. It is expected to begin operation in 1979 or 1980.

Federal Republic of Germany Construction of a 300 MWe prototype SNR300. Total cost: 1,700 million DM.

Japan Construction of a prototype 200-300 MWe FBR based on an experimental 50 MWe reactor started in 1969.

Netherlands Participation in the German SNR300 project.

Sweden Study of fuel and material problems, reactor physics and neutron data.

United Kingdom The British fast breeder reactor would have gone critical before the French reactor if an accident had not delayed it. It appears to be similar to the French reactor. The British reactor has a 20-year fuel doubling time, a relatively long period, but perhaps a useful trade-off in view of the lead time necessary in building fast breeder plants; 250 MWe prototype fast reactor PFR ready to run up to power. Commercial fast breeder reactor (CFR) being planned. The De-

## NUCLEAR

UK (cont'd)      partment of Energy has approved capital investment for 4000 MWe steamer program.

USSR      The Soviet Union has built several experimental liquid metal fast breeder reactors. The most ambitious of these, located in the desert of Central Asia near the shores of the Caspian Sea, has been critical for some time, but still has not achieved full power. It was designed as a desalinization plant that would also produce major amounts of electricity. So far, according to U.S. sources, it has not yet started to produce power. A serious accident with the secondary liquid sodium coils occurred in fall 1973. Apparently, radiation did not escape, but some kind of fire must have occurred. The Soviets have so far been reticent about the incident. (The Soviet approach to atomic power generation is likely to have little attraction for western countries because of the markedly lower safety standards. Soviet reactors, for instance, do not use containment vessels and, despite this absence, are often placed significantly closer to major population centers than is permitted in the United States or western Europe.)

### Other Reactors

Canada      Canada has produced a commercially feasible heavy water reactor, the CANDU, which it has exported to several countries. The CANDU requires much less fuel enrichment than U.S. light water reactors, and permits easier recovery of plutonium from the spent fuel.

India      Relying largely on its own resources for design and construction but still using Canadian-manufactured components, India has built two heavy-water plants derived from the Canadian CANDU system. The plants were constructed by Canadians.

Japan      Construction of 200 MWe prototype ATR, heavy-water-moderated, boiling-light-water cooled and fueled with slightly enriched uranium and plutonium mixed oxide.

Netherlands      KSTR (KEMA suspension test reactor).

Switzerland      Gas-cooled fast reactors.

United Kingdom      Includes work on advanced gas-cooled reactor (AGR) SGHWR and supporting research.

### Safety

Belgium      Development of measurement techniques and elaboration of control methods consistent with the nonproliferation treaty.

Finland      Safety of nuclear reactors. Reliability of nuclear reactors. Environmental effects on nuclear energy.

France      Cooperation with Federal Republic of Germany for the safety of fast breeder reactors. Main work on PWR safety. New programs on BWR safety. Research on health and environmental effects of radiations.

Federal Republic of Germany      Work on the various aspects of reactor safety. Radiation protection and environmental effects of energy transformation.

Japan      In addition to research concerning the safety of the various types of reactors, a nuclear safety research reactor is being built. Biological aspects of nuclear safety.

Norway      Computer program for safety analysis of LW reactors. Analysis of radioactivity dispersion in the environment.

Sweden      Full scale LWR safety experiments at the Marviken reactor station. Projects on short-term safety problems facing industry.

Switzerland      Studies connected with the licensing of nuclear plants.

### Radioactive Waste Management

Australia      Work on treatment processes for wastes from mining and milling operations.

Austria      Research on storage of radioactive waste.

Belgium      Study and improvement of processing of effluents with either low or high radioactivity. Development of new incineration technique to burn plutonium-contaminated solid waste.

## NUCLEAR

Canada	Studies on storage in salt beds and rock formations.	France	Main emphasis on the creation, confinement and heating of plasmas with magnetic machines such as Tokamak and other machines under construction.
France	Work on vitrification of solid waste as well as on liquid and gaseous radioactive waste.	Federal Republic of Germany	Magnetic confinement.
Federal Republic of Germany	Special attention on the treatment (calcination and vitrification) of highly radioactive waste. Investigation of storage in salt mines.	Ireland	Submillimeter diagnostics of ionized plasmas.
Japan	Solidification technology of high- or middle-level radioactive wastes.	Japan	Magnetic confinement.
Norway	Development of absorption materials and methods for retention of gases. Methods for treatment and disposal of radioactive waste.	Netherlands	Fusion reactors.
Sweden	Main areas: separation of plutonium and other transuranium elements, solidification and stabilization of liquid waste, sites for ultimate disposal. Fixation of long-lived radioactive waste products in minerals. Actinide chemistry. Waste disposal at nuclear power stations.	Sweden	Plasma confinement in internal ring systems. Chemical problems in fusion technology.
Switzerland	Storage of low-activity wastes in geological formations. Processing and incineration of low-activity wastes within operating budget.	Switzerland	Plasma physics, confinement and dynamic stabilization of plasmas.
United Kingdom	Covers treatment and disposal as well as transportation of waste material.	United Kingdom	Work on a large new experimental Tokamak type assembly. This work is part of the joint EURATOM program.
<b>Thermonuclear Fusion</b>		USSR	Soviet research in fusion techniques has been extensive and comparable in achievement to the best programs in the west. The Tokamak and other devices have contributed to fusion research everywhere. The Deputy Chairman of the State Committee for Science and Technology recently claimed that the Soviet Union may be producing power from a fusion process by 1990. "The fact is," he said, "we are far ahead in this field." Fusion technology is on the list for scientific exchanges between the United States and Russia.
Belgium	Study of plasmas and magnetic confinement.		
Canada	Feasibility study for a Canadian program on controlled thermonuclear fusion.		

## OCEAN SOURCES

<b>Tidal Energy</b>		United Kingdom	Prospects being reassessed by CEEB and some universities.
Canada	Physical survey for potential use of Bay of Fundy tides for generating electric power.	<b>Ocean Thermal Gradients</b>	
France	Major 240-KW tidal energy facility at La Rance.	France	Feasibility studies on exploitation.
South Korea	Studies are being made to determine the feasibility of using tidal energy for electrical power generation, using a reversible, bulb-type turbine.	<b>Wave Energy</b>	
		United Kingdom	Studies of feasibility by the National Engineering Laboratory.

## PETROLEUM

### Production

Australia Development of geophysical equipment and techniques. Reservoir geochemistry.

Canada Offshore petroleum production systems; steam cracking of crude; pipeline materials evaluation.

France Development of floating, dynamically anchored drilling rigs (ship *Pelican*); geophysical equipment; Arctic zone oil equipment; exploration R&D in deep seas; development of drilling, well-head, and production equipment to a ocean depth of 1,000 meters; laying and repairing deep-sea oil pipelines.

Federal Republic of Germany Improved exploration for oil and gas by seismic and geochemical methods; emphasis on deep-drilling and offshore technologies.

Japan Development of remote-controlled undersea oil-drilling rigs: automatic digging machine linked to surface power supply device, other devices for mud water circulation and cementing, transportation and communication.

Netherlands Development of drilling platforms. Improving exploration (mainly seismic) techniques, extraction and offshore engineering technologies.

Norway

Deep seismic exploration technologies, geological and bottom mapping, oceanography pollution problems, marine technology and instrumentation.

United Kingdom

Marine technologies.

### Transportation

Canada Arctic railway studies; oil and gas pipeline technology.

Netherlands Oil transportation from offshore wellheads.

### Storage

France R&D to create underground cavity through nuclear explosions for storage of liquid fuels.

Japan Storage of oil on the sea bed in large-scale vessels.

Sweden Storage stability of fuel oil. Corrosion in fuel oil tanks; development of corrosion inhibitors.

Switzerland Study of the possibilities of storing oil and gas in Swiss geological formations. Seismic surveys and drilling.

## SOLAR ENERGY

Australia Australia vies with Israel as the leader in applied solar energy systems. Research and development is largely sponsored by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Melbourne. Although no Australian research and development projects represent major breakthroughs in solar techniques, the practical experience that the Australians have acquired should be of use by other countries. The most widespread use of solar energy in Australia is for heating domestic water to about 60° C (140° F). Research is

Australia  
(cont'd)

now attempting to extend this work to industrial applications aimed at attaining temperatures above 90° C. An experimental four-stage installation designed to heat water to 95° C is in operation at the Griffith Field Station. An experimental solar kiln for timber drying is also in operation there and appears to be a practical and economical application. Testing of solar stills for structural reliability and economics of construction is also underway. Varieties of solar water heaters for domestic use are being tested. Research in high-

## SOLAR

Australia (cont'd)	temperature industrial applications is being carried on. Various designs for solar distillation are also being developed. The Australians have noted that the unchecked formation of reflecting layers of salt on the base, liner and water surface of a solar still can reduce output by as much as 50 percent. Research to establish reliable cost figures for various energy systems is also underway.	France (cont'd)	systems of solar energy storage is underway at SAFT. French funds available for solar research and development for 1975 total more than 13 million francs. France also has developed a number of solar heating systems for houses that have been demonstrated in models located in the Pyrenees Mountains and in the north of France. Although these dwellings do not appear to have advanced the state-of-the-art, they are successful both in meeting design requirements and cost limitations. Other major centers of solar research in France include the Laboratory of Solar Physics (heliophysique) at the University of Provence in Marseille, the Delegation Grenoble de la Recherche Scientifique et Technique (DGRST), Commission on Atomic Energy (CEA), Centre National D'Etudes Spatiales (CNES), Centre Scientifique et Technique du Bâtiment (CSTB).
Belgium	Study of solar batteries and heat transformers.		
Denmark	The research program includes heating and cooling of buildings and development of solar central stations.		
France	The United States and France are cooperating on international solar research and development projects, primarily concerning the exchange of information. Zero energy houses using solar collectors and insulation are in research and development in France and other European countries. France pioneered the use of solar arrays to provide high temperatures for research in metallurgy. The solar furnace at Odeillo, France, is the leading installation of this type in the world. Research to develop solar furnaces for industrial applications has been underway there for some time. The National Center for Scientific Research, which operates the Odeillo furnace, also has undertaken research in solar refrigeration and water purification by solar radiation. These experiments have included field work in the deserts of Chile. France is now engaged in a solar heating project through the civilian sector of NATO. Experimental space heating units have been installed in Paris. French manufacturers produce silicon photovoltaic cells on a commercial basis and have conducted extensive and successful research on cadmium sulfide cells. Photovoltaic cells with an installed capacity of 4-5 KW for various specialized uses have already been manufactured. French devices are in use in six countries: France, the United Kingdom, Niger, Saudi Arabia, Chile, and Peru. Two French companies, SAT and RTC, manufacture photovoltaic cells. Research and development is conducted in laboratories in Toulouse, Grenoble, Limeil-Bravennes, Paris, Montpellier, Nancy, Marseille, and Bellevue. Research on	Federal Republic of Germany	Main emphasis on R&D for heating and cooling of buildings.
		Greece	Solar distillation systems that supply the entire fresh water needs of six sparsely populated islands. These plants have been designed and built by the Hellenic Industrial Development Bank in cooperation with the Democritus Nuclear Center.
		India	Solar energy is being used for evaporation to recover salt and chemicals, for heating water, for desalinization, and for drying agricultural products. No advanced research and development projects are known.
		Israel	Israeli research and development and application of solar energy has a long tradition. Until 1973, however, interest in solar energy has been decreasing for a decade because of the availability of cheaper energy sources derived from oil and gas. Nevertheless, more than 100,000 domestic solar water heaters are in use. Research on solar refrigeration was stopped when it became apparent that it would be much more expensive than conventional refrigeration. A satisfactory design was established for solar cookers, but the market until 1973, at any rate, was limited. Both in Israel and in developing countries, people either had enough money to afford the slightly more

## SOLAR

Israel  
(cont'd)

expensive and much more convenient kerosene stove or they lacked even enough money to buy a solar cooker. Israeli research on silicon photovoltaic (PV) cells continues as well as on other PV systems. However, a reduction in production costs has not been large enough to permit commercial production. Israeli research and development of solar ponds has been particularly significant. Experiments have produced relatively cheap electricity and high-quality salt as a by-product. The solar ponds, however, were not competitive in Israel, and research has declined because of the costs of moving toward a large-scale demonstration program when economically attractive domestic applications appear to be lacking. The Israeli solar pond system should generate approximately 5 MW for one square kilometer of pond surface. Such a plant should also produce about 50,000 tons of salt a year or provide heat equivalent to that generated by 45,000 tons of fuel oil. A solar pond can also produce distilled water as a by-product—approximately 500,000 cubic meters (130 million gallons) per year from a one-kilometer square pond. If the operation is devoted entirely to desalinization, a far larger quantity of fresh water can be obtained. An outstanding Israeli solar development is the organic vapor Rankine-type turbine that was designed to operate at the relatively low temperatures that could be obtained from solar collectors and that requires virtually zero maintenance. This turbine is now in production and sold all over the world, but no one uses solar power to operate it. Its fuel-fired version, however, is in great demand.

Japan

Japanese research and development has produced a variety of solar applications that are now being used commercially in Japan and at least 14 other countries. Much of this development has been conducted by the Sharp Company and includes photovoltaic devices for buoys, navigational lights, railroad signals, remote weather stations and radio relay equipment. Japan's joint governmental and industrial "Project Sunshine" was funded at \$7.5 million for 1974 (and probably more for 1975) to develop further solar applications. Results so far have been disappointing. Solar water

Japan  
(cont'd)

heaters went into use in Japan over 25 years ago. By the mid-1960s, more than 2 million solar water heaters were in use, but the number had decreased by 1973, because of the relatively cheap price of oil and the installation of central heating systems. A number of high-temperature solar furnaces are also in use. The main center for research is the Solar Research Laboratory of the Government Industrial Research Institute at Nagoya. A blue ribbon panel is surveying all U.S.-Japan bilateral S&T cooperative activities. The U.S.-Japan Energy R&D Agreement is the most recent contribution to these activities. Specific projects planned for development between 1974 and 1980 include a solar thermal power generation system to develop a peak output of about 1 MW to explore the technical and economic feasibility of a solar thermal power generation system. A parallel conceptual design for a 10-MW system will be undertaken. Additional R&D will be undertaken into techniques for utilizing high-temperature heat. The technical feasibility for manufacturing a photovoltaic conversion system at approximately 1 percent of current costs will be studied. Research will be conducted on solar heat electric power generation as well as space power generation. Solar heating and cooling and hot water supply systems will be developed. Individual items of equipment and materials needed for systems in individual houses, apartments and large buildings will be developed. Basic research will be conducted on new methods of utilizing solar energy. Meteorological investigations will be undertaken to clarify the relationship between solar energy technology and the economic, social, and natural environment.

Niger

In relation to the size of its resources, Niger has one of the largest solar energy research efforts in the world. Although locally feasible systems appear to be under development there, the use of Niger's solar energy systems for other countries outside of tropical Africa is probably quite limited. Studies on the optics of concentration, testing and operation of a solar-powered water pump, and the development, manufacture and installation of water heaters have been undertaken.

## SOLAR

USSR	The Soviet Union has long maintained a research and development program in solar energy, primarily in southern parts of the Soviet Union. This work has concentrated on solar stills, water heaters, dryers and cookers, and other domestic applications. Large-scale use of solar energy, however, was recently described by a Soviet energy economist visiting in the United States as "science fiction." Research centers in solar energy in the Soviet Union include Krzh-	USSR (cont'd)	izhanovsky Institute of Power Energy in Moscow, the All-Union Institute for Research in Solar Technology, and the Academies of Science of Uzbekistan and Kazakhstan. Silicon PV cells are commercially produced in the Soviet Union. The Soviet Union also produces gallium arsenic PV cells, apparently in monocrystalline form, for space exploration. The high cost of this system appears, even for the Soviets, to rule out terrestrial applications.
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## WIND ENERGY

Denmark	Investigations on wind energy carried out in cooperation with industry.	Uruguay	Among the more ambitious wind energy programs is that of Uruguay, which is planning to build aeroelectric generators with capacities from 100 to 200 KW each to a total of 20 MW. It is planned to tie the generator into the national power grid and to develop an industry for the manufacture and export of aeroelectric generators.
Netherlands	A study on the utilization of winds is ready to start.		
Sweden	Wind power investigations. Construction of lower power units.		
United Kingdom	Prospects being reassessed by ETSU (Department of Energy).		

## OTHER ENERGY SOURCES

Hydrogen		United Kingdom	Assessment studies and a small amount of experimental work.
France	Production of hydrogen through thermochemical dissociation of water in high temperature nuclear reactors. Storage of hydrogen as hydrides.	Methanol	
Federal Republic of Germany	Use of process heat for hydrogen and hydrocarbon production.	Netherlands	Feasibility studies on the use of methanol as a fuel for automotive power systems and for fuel cells.
Japan	Hydrogen production by electrolysis or thermochemical and thermal decomposition techniques. Transportation and storage of hydrogen. Hydrogen liquefaction. Applications of hydrogen. This activity is part of the "Sunshine Project."	Oil Shale	
Netherlands	Hydrogen storage as intermetallic compounds.	USSR	Commercial plant that produces energy from shale oil from deposits in Estonian Republic, south of Leningrad. The primary use of this oil shale is as a fuel in power plants where it is consumed directly without extraction of oil. This process, which appears to be of marginal value in the Soviet Union, is of no commercial interest in the United States.
Switzerland	Research on hydrogen storage.		

## OTHER

### Solid Wastes

France      For several years, France has operated a power plant near Paris largely fueled with solid wastes. Although the extent of organ-

France  
(cont'd)

ized research and development in this field is not known, French experience derived from this installation and others is considerable.



CHAPTER V

PETROLEUM

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## INTRODUCTION

Petroleum and petroleum products contribute about 44 percent to the worldwide demand for energy, nearly as much as natural gas and coal combined (Figure V-1). In the United States, petroleum and petroleum products contribute about 45 percent of energy demand (Table V-1).

Because oil is the world's primary energy source, energy problems are basically oil problems. These problems have resulted because the principal oil consumers are not the major oil producers and world oil supplies are dwindling.

Table V-1

### PETROLEUM FACTS SHEET

Energy Content <sup>1</sup>	5.8 million Btu per barrel
Proven U.S. Reserves <sup>2</sup> (1976)	31.3 billion barrels (including 10 billion barrels in Alaska)
Ultimate U.S. Resources <sup>3</sup>	113 billion barrels of petroleum liquids as ultimately recoverable resources
U.S. Production (1976) <sup>4</sup>	10.1 million barrels/day (including 8.1 million barrels/day of crude oil)
Imports (1976) <sup>4</sup>	7.2 million barrels/day (42% of consumption)
U.S. Consumption (1976) <sup>4</sup>	17.3 million barrels/day
Contribution to Demand <sup>5</sup>	Petroleum supplied 45.3% of the 1975 U.S. energy demand

<sup>1</sup>"Domestic Oil and Gas Availability," *U.S. Energy Outlook*, National Petroleum Council, pages 57-133, December 1972.

<sup>2</sup>*Oil and Gas Journal*, page 105, December 27, 1976.

<sup>3</sup>National Academy of Sciences, February 12, 1975.

<sup>4</sup>U.S. Bureau of Mines, January 19, 1977.

<sup>5</sup>Federal Energy Administration.

## STRATEGIC OIL DEPENDENCIES

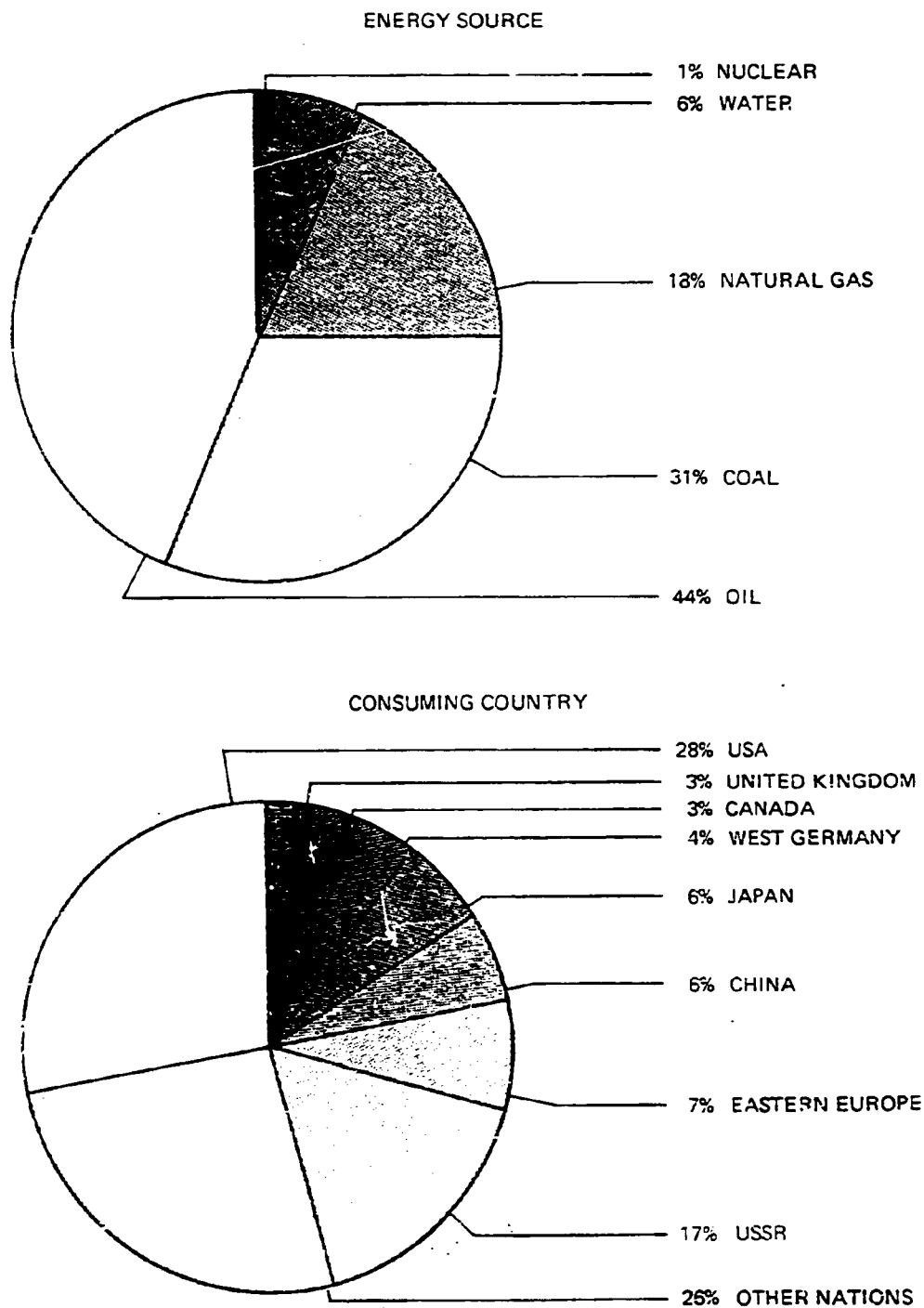
Figure V-2 shows the major oil consumers and producers. The heavy users are the highly industrialized nations. The United States alone accounts for approximately 6 billion barrels (33 percent) of the world total consumption of 18 billion barrels annually.

The third-world nations are the predominant oil producers (Table V-2). The Middle East and Africa account for nearly 50 percent of total world oil production. Oil production in the United States represents only 16 percent of the world's total. (Domestic oil production peaked in 1970 and has been declining steadily since, although there will be a resurgence when Alaskan oil begins flowing in 1977.)

The imbalance between the world's major oil consumers and its producers is likely to continue in the mid- and far-term, given the distribution of proved crude oil

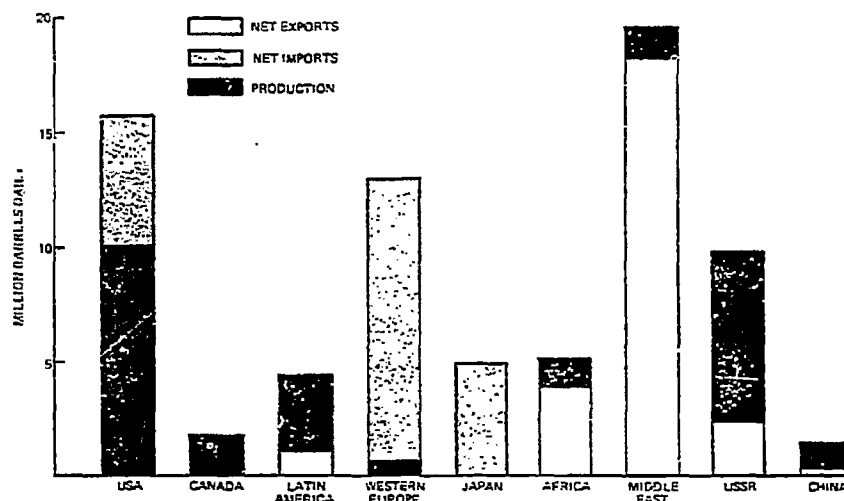
reserves—those that have been discovered, measured, and are ultimately recoverable. As shown in Table V-3 and Figure V-3, more than one-half of the world's crude oil reserves are in the Middle East and Africa, and only about 5 percent are in the United States.

The near-, mid-, and far-term imbalance places the United States, as an oil-dependent nation, in a precarious position. Today, U.S. imports of petroleum and petroleum products account for 42 percent of its consumption. Of this amount, 68 percent is imported from the Organization of Arab Petroleum Exporting Countries (OAPEC) (Table V-4). Another OAPEC embargo would have serious implications for the United States. Little can be done to reduce U.S. dependence on foreign oil in the near-term, other than to reduce oil consumption.



Source: British Petroleum Statistical Review of the World Oil Industry, 1975.

Figure V-1. WORLD ENERGY CONSUMPTION, 1974



Source: British Petroleum Statistical Review of the World Oil Industry, 1975.

Figure V-2. OIL PRODUCTION, CONSUMPTION, AND TRADE (January 1975)

Table V-2

DISTRIBUTION OF WORLD CRUDE OIL PRODUCTION, 1976

Area/Country	Production (millions of bbls/day)	Percent of World Total
North America	10.26	17.9
United States	8.11	14.2
Canada	1.30	2.3
Mexico	0.85	1.5
South America and Caribbean	3.54	6.2
Middle East	21.88	38.2
Iran	5.88	10.3
Saudi Arabia	8.57	15.0
Kuwait	1.82	3.2
Iraq	2.07	3.6
Abu Dhabi	1.59	2.8
Other	1.95	3.4
Europe	0.90	1.6
Africa	5.60	9.8
Libya	1.90	3.3
Nigeria	2.02	3.5
Other	1.68	2.9
Asia-Pacific	2.67	4.7
Communist Countries	12.36	21.6
World Total Production	57.21	100.0

Source: *Oil and Gas Journal*, December 27, 1976, pp. 104, 105.

Table V-3

## DISTRIBUTION OF WORLD OIL RESERVES, JANUARY 1, 1977

Area/Country	Reserves (millions of bbls)	Percent of World Reserves
North America	44,500	7.4
United States	31,300	5.2
Canada	6,200	1.0
Mexico	7,000	1.2
South America and Caribbean	22,608	3.8
Middle East	326,281	54.5
Saudi Arabia	110,000	18.4
Iran	63,000	10.5
Kuwait	67,400	11.3
Iraq	34,000	5.7
Abu Dhabi	29,000	4.8
Other	22,881	3.8
Europe	24,539	4.1
Africa	60,570	10.1
Libya	25,500	4.3
Nigeria	19,500	3.3
Other	15,570	2.6
Communist Countries	101,100	16.9
U.S.S.R.	78,100	13.0
China	20,000	3.3
Other	3,000	0.5
Asia-Pacific	19,391	3.2
World Total	598,990	100.0

Source: "Worldwide Oil at a Glance," *Oil and Gas Journal*, December 27, 1976, pp. 104, 105.

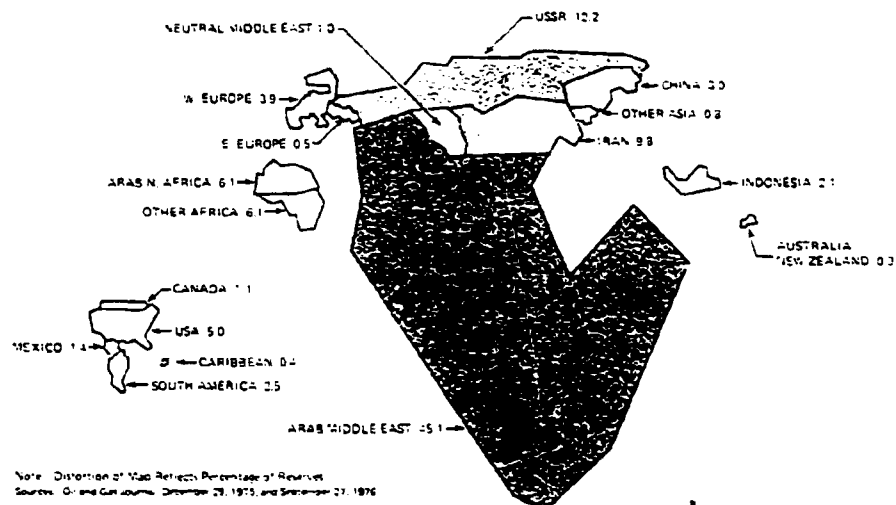


Figure V-3. WORLD PROVED RESERVES OF CRUDE OIL (PERCENT)

Table V-4

**U.S. CRUDE IMPORTS 1970-1976**  
(Thousands of barrels per day)

Country of Origin	1976 <sup>a</sup>	1975	1974	1973	1972	1971	1970
Bolivia	3	5	7	2	...	2	2
Chile	...	...	...	...	...	1	...
Colombia	...	...	...	2	5	9	20
Ecuador	48	37	42	47	...	...	...
Mexico	87	70	2	1	...	...	...
Trinidad	139	115	63	60	24	...	...
Venezuela	214	395	319	345	256	303	268
<b>Latin America total</b>	<b>491</b>	<b>642</b>	<b>433</b>	<b>457</b>	<b>285</b>	<b>315</b>	<b>290</b>
Algeria	438	264	180	120	87	13	6
Angola	10	71	48	48	16	4	...
Congo	9	...	2	...	...	...	...
Egypt	18	5	9	15	8	19	21
Gabon	25	27	23	...	...	...	...
Libya	423	223	4	133	110	53	47
Nigeria	964	746	698	448	244	95	48
Tunisia	12	2	12	18	7	...	...
Zaire	20	...	...	...	...	...	...
<b>Africa total</b>	<b>1,925</b>	<b>1,338</b>	<b>976</b>	<b>782</b>	<b>472</b>	<b>184</b>	<b>122</b>
Kuwait	6	4	5	42	36	29	33
Saudi Arabia	1,215	702	438	462	174	115	17
Neutral Zone	...	...	...	...	...	...	23
Iran	322	278	463	216	136	106	33
Iraq	9	2	...	4	4	11	...
Qatar	33	18	17	7	3	...	...
Israel	5	...	...	1	...	...	...
United Arab Emirates	222	117	69	71	74	80	63
<b>Middle East total</b>	<b>1,812</b>	<b>1,121</b>	<b>992</b>	<b>803</b>	<b>427</b>	<b>341</b>	<b>169</b>
Canada	395	600	791	1,001	856	721	672
Far East	535	384	285	201	167	117	70
Europe	50	17	...	...	...	...	...
<b>Total U.S. crude imports</b>	<b>5,208</b>	<b>4,102</b>	<b>3,477</b>	<b>3,244</b>	<b>2,207</b>	<b>1,678</b>	<b>1,323</b>

<sup>a</sup>Preliminary.Source: *Oil and Gas Journal*, December 27, 1976.**WORLD OIL DEPLETION**

Estimates show that the world crude oil production will probably peak about 1990. Estimates of world oil wealth depend on economic and technical feasibility of extracting oil, methods used to estimate reserves, and the degree of uncertainty assigned to the estimates. Much of the confusion over estimates of the world's oil resources and reserves has come from using different assumptions when incorporating these three factors into the estimates. As a result, there appears to be at least as many estimates of reserves and resources as there are estimators. Rather than favoring any

single estimate, the implications of a broad range of estimates must be related to the energy situation.

Theoretical world oil exhaustion dates are calculated for the resource boundaries as a proxy for depletion dates. The ultimate depletion date, which is the time when the available resource is below the amount necessary to maintain current consumption patterns, will be determined by several interrelated and often unquantifiable factors. Specifically, the depletion dates, or transition periods, are determined by world oil production, consumption, and

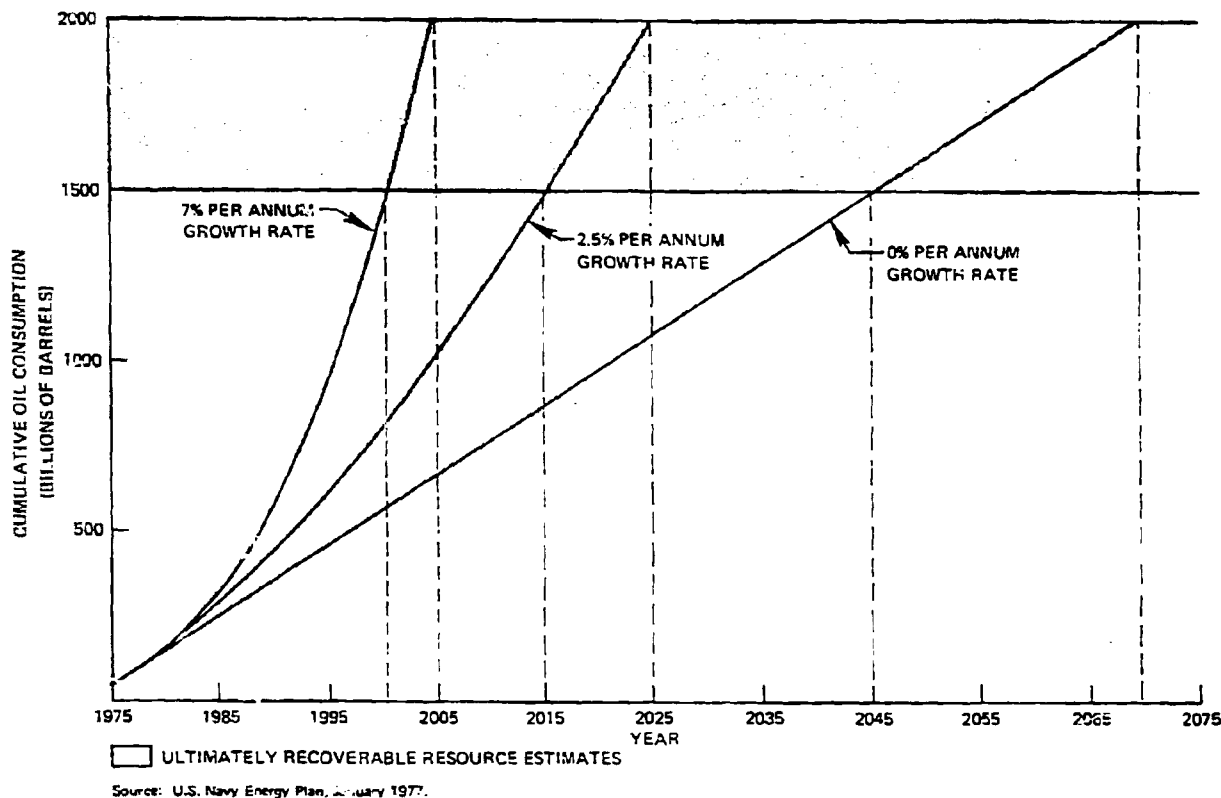


Figure V-4. PROJECTED WORLD OIL EXHAUSTION DATES

pricing policies and, ultimately, discovered recoverable oil. The exhaustion date is when the cumulative consumption of oil exceeds the total ultimately recoverable reserves. The calculation assumes that sufficient oil is produced and available to meet the demand. In actual practice, production will decline as the reserves are used and delay the actual exhaustion date, creating a supply shortfall (that is, depletion). Calculating theoretical exhaustion dates indicates the length of time current production and consumption trends could continue until oil supplies are exhausted.

Three alternative oil consumption growth rates have been used to project world exhaustion dates (See Figure V-4). The conservative 2.5 percent annual consumption growth rate projects that, between 2015 and 2025, the entire estimated range of recoverable resources will be exhausted. If an historical growth rate of 7 percent is assumed, exhaustion will occur sometime between 2000 and 2005. In the unrealistic, but most optimistic, case of no increase in consumption, exhaustion will occur no later than 2070.

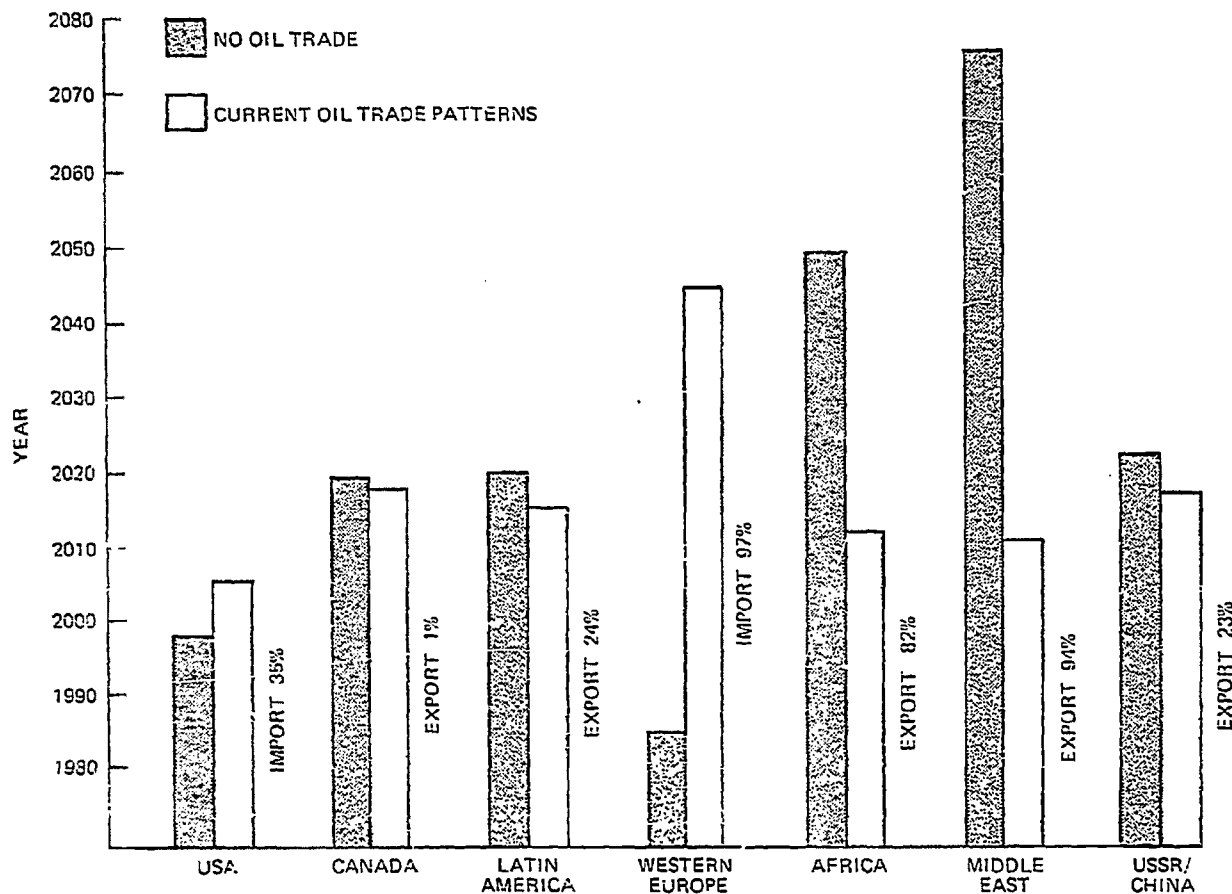
The proximity of the exhaustion date for the historical growth rate and the relative insignificance of the actual

reserve estimate, except under the no-growth case, are significant. The low-growth alternative could stretch available recoverable oil by about 25 years.

Theoretical exhaustion dates for world areas will vary significantly because of the location of oil bearing formations, local production and consumption patterns, and different trade policies. Figure V-5 gives the exhaustion dates for world regions, assuming oil consumption will have an average annual increase of 4 percent and there is no oil trade. The proximity of Western Europe's exhaustion date relates directly to its heavy dependence on foreign oil sources. Likewise, the United States is destined to face greater dependence on oil imports as its oil resources are depleted. The Soviet Union, on the other hand, has at least 20 more years of available oil than the United States.

Many countries are extending their exhaustion date by substituting foreign oil for domestic oil. Figure V-5 also depicts the exhaustion dates of these regions' domestic supplies when current import patterns are projected for the future. Figure V-6 shows, in detail, the projected oil exhaustion dates for the United States (excluding imports and alternative production policies). To extend available





Note: Assumes 4 Percent Annual Growth in Oil Consumption.  
 Source: U.S. Navy Energy Plan, January 1977.

Figure V-5. REGIONAL OIL EXHAUSTION DATES

domestic oil resources, many countries, in choosing an alternative, will still depend on foreign oil. Since Western Europe relies heavily on foreign sources, their exhaustion date can be postponed to about 2040, but this region will

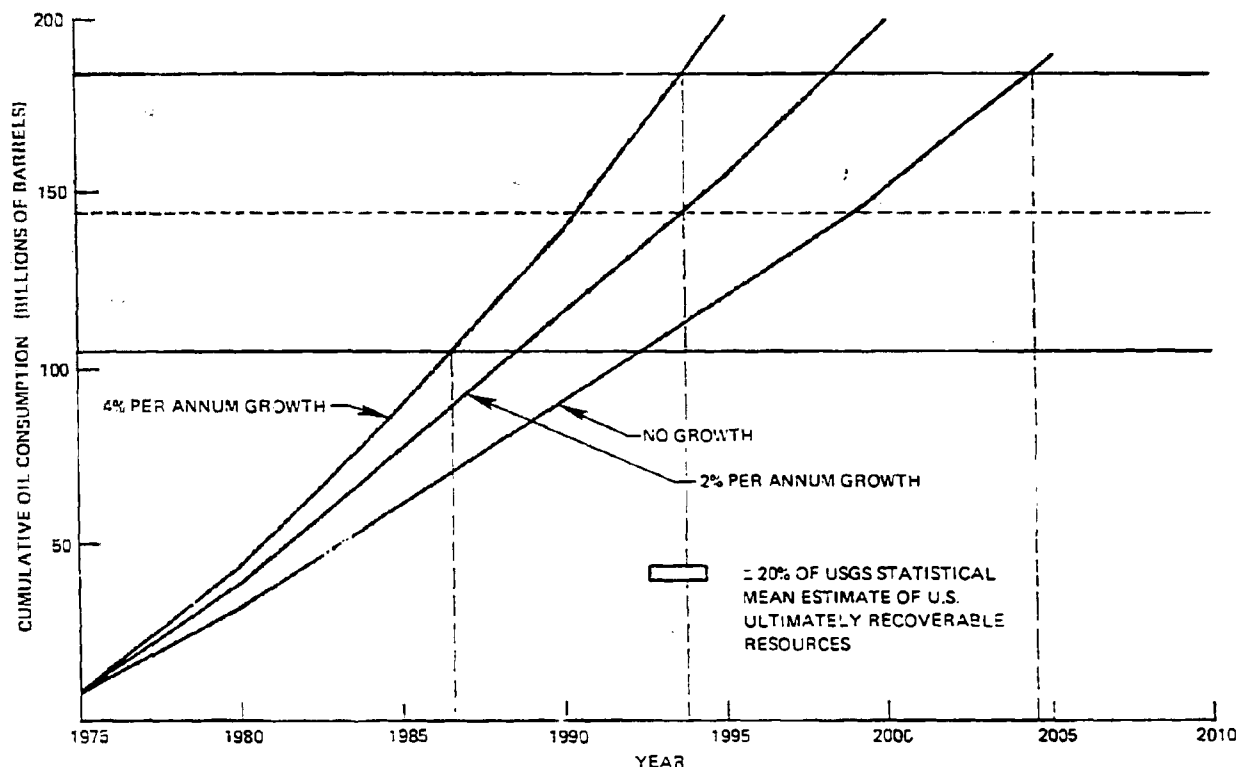
still substantially rely on foreign sources. For the United States, heavy dependence on oil imports will only delay the exhaustion date by about six years.

## SECONDARY AND TERTIARY OIL-RECOVERY TECHNOLOGY

Most of the 434 billion barrels of original-oil-in-place discovered in the United States is still in the ground: approximately 290 billion barrels of domestic oil have not been recovered, giving a past recovery factor of about 32 percent.

Recent increases in the price per barrel of oil, and the realization that the United States may have to depend more

fully on the utilization of its own resources in the near future, have encouraged both government and industry to renew interests in oil-recovery techniques not widely used in the past, such as those for augmenting the natural energy of a petroleum reservoir once the primary and, in some cases, the secondary stages of recovery have been completed. It has been estimated by various sources that 50 to



Note: Projections Exclude Imports and Alternative Production Policies

Source: U.S. Navy Energy Plan, January 1977.

Figure V-6. PROJECTED U.S. OIL EXHAUSTION DATES

60 billion barrels of oil could be recovered in the U.S. using these techniques. (Bureau of Mines estimates a 4-billion barrel annual production by 1980.<sup>1</sup>)

These methods, referred to as secondary and tertiary oil recovery, may have the potential of increasing domestic oil production in less time than that required for development of other fuel sources, assuming that the price of oil is high enough to cover the added cost of these methods.

Secondary oil recovery is generally held to mean waterflooding, although gas injection is used in some areas, such as California. Secondary recovery methods have been profitable in some reservoirs, i.e., additional cost per barrel of oil produced by these methods has not exceeded the market price per barrel. This is usually the case, since water is cheap in certain areas (or gas, if natural methane is being produced in the area) and since the methods use investments already made for drilling and well equipment.

Tertiary recovery normally refers to recovering part of the oil left after waterflooding. There are several methods that come under this classification, many of which have been studied for over two decades by industry. These

techniques have not been widely applied in large reservoirs although they may, in some cases, be technically feasible, they have not been economically feasible.

The most promising tertiary oil recovery methods involve injecting a slug, or a small bank, of solvent and driving the slug through the reservoir with either a liquid or a gas. The active ingredient, i.e., the solvent, can be an alcohol, a ketone, a number of refined hydrocarbons, a condensed petroleum gas, carbon dioxide, liquefied natural gas or even various exhaust gases;<sup>2</sup> its objective is to mobilize and push forward the oil that remains in pore spaces.<sup>1</sup> This, in turn, is propelled from injection wells to production wells by drive fluid, which is water or a selected gas. These methods are also termed as "miscible flooding," one of the most popular types being micellar-polymer flooding. (Micellar flooding has also been termed in t

<sup>1</sup> Energy Research Program of the U.S. Department of Interior, prepared by Office of Research and Development, March 1974.

<sup>2</sup> Secondary and Tertiary Oil Recovery Processes, Interstate Oil Compact Commission, Oklahoma City, Oklahoma, September 1974.

Table V-5

## ERDA OIL-RECOVERY CONTRACTS

ERDA Contractor	Total Project Cost (Government Award)	Title	Test/Research Site
Cities Service Oil Co. Tulsa, Oklahoma	\$7,098,394 (\$3,002,117)	Improved oil recovery by micellar-polymer flooding	Butler County, Kansas
Phillips Petroleum Co., Bartlesville, Oklahoma	\$9,764,514 (\$3,402,042)	Improved oil recovery by micellar-polymer flooding	North Burbank Unit, Oklahoma
Keweenaw Oil Co., Tulsa, Oklahoma	\$3,884,899 (\$1,150,752)	Improved oil recovery by controlled waterflooding	Stanley Stringer Field, Oklahoma
Shell Oil Co., Houston, Texas	\$7,374,872 (\$2,168,206)	Oil recovery by polymer flooding	East Coalings Field, Fresno County, California
Penn Grade Crude Oil Assoc., Bradford, Pennsylvania	\$4,444,000 (\$2,222,000)	Bradford micellar-polymer flood	Bradford Field, McKean County, Pennsylvania
Husky Oil Company, Cody, Wyoming	\$6,791,800 (\$2,000,000)	Oil recovery by combination thermal drive	Paris Valley, Field, Monterey County, California
Columbia Gas System Service Corp., Columbus, Ohio	\$4,255,025 (\$2,014,155)	Massive hydraulic fracturing in the Devonian shale	Wayne and Lincoln Counties, West Virginia

Source: "Contracts and Grants for Cooperative Research on Enhancement of Oil and Gas," *Progress Review No. 4*, Energy Research and Development Administration, October 1975.

literature as "surfactant flooding" or "microemulsion flooding.")

A well-known commercial example of miscellar-polymer flooding is the Maraflood process, developed first in the 1960's by the Marathon Oil Company. This method, available under license to other companies, produces oil under both secondary and tertiary conditions. Unless there has been previous experience with the Maraflood process, approximately one year is required for evaluation before a large project can be started in a particular area. The process is most effective in sandstone reservoirs and at less than 200° F. The Maraflood process has been successfully applied in the Pennsylvania Bradford field, where it was shown to be economically favorable at the price of crude oil in January 1974.<sup>1</sup>

Other predominant methods for tertiary recovery of oil include:

- Thermal recovery, which uses heat to decrease the viscosity of oil, making it flow more easily (e.g., the COFCAW—Combination of Forward Combustion and Waterflooding—which can be used to recover any API gravity oil that could be or has been waterflooded.<sup>2</sup>
- Hydrocarbon miscible flooding, which uses solvents to decrease the attractive forces between oil and other fluids in the reservoir.

- Carbon dioxide flooding, where CO<sub>2</sub> acts as the solvent.

The different methods vary as much in estimated cost (for the additional chemicals and equipment) as they do in theory. Rough estimates by industry for the additional cost per barrel of oil recovered by tertiary methods, for example, run from \$0.75 to \$2.00 per barrel. Oil recovered by secondary or tertiary methods is regulated by the "old" price per barrel of crude oil (\$5.25). Attempts are being made by the Interior Department and FEA to plan a detailed program for removing price controls on oil extracted by the more expensive secondary and tertiary techniques.<sup>3</sup> If this oil were salable at the "new" oil price per barrel (about \$10.00), tertiary oil recovery would probably be profitable.

Improved Oil Recovery symposiums, sponsored by the Society of Petroleum Engineers, were held in 1972 and 1974 to provide a forum for information exchange between the companies that collectively have undertaken hundreds

<sup>1</sup> *Proceedings of the SPE Symposium on Improved Oil Recovery*, Tulsa, Oklahoma, April 22-24, 1974.

<sup>2</sup> Ted M. Geffen, "Oil Production to Expect from Known Technology," *The Oil and Gas Journal*, May 7, 1973, pp. 66-76.

<sup>3</sup> *Energy Users Report*, October 31, 1974.

of projects to study secondary and tertiary oil-recovery techniques.

The Interstate Oil Compact Commission (IOCC) has been monitoring the "new theories and improvement" for years, and a September 1974 IOCC publication summarizes the technical status of various methods.<sup>1</sup>

In addition to a small amount of in-house research in enhanced oil recovery in the past, the Bureau of Mines, Department of Interior, established a research and development program for the stimulation of oil and gas production, which included provisions for contracts with private firms for pilot testing on a cost-share basis and with engineering

schools to do either basic or applied research. The program was designed as a possible vehicle for cooperative effort, not only between government and industry, but also to ensure public dissemination of research results that might otherwise be prevented because of antitrust implication and private economic concerns. The program, now called "Enhancement of Recovery of Oil and Gas," was absorbed by ERDA. Some of the larger contracts are listed in Table V-5.

<sup>1</sup>*Secondary and Tertiary Oil Recovery Processes*, Interstate Oil Compact Commission, Oklahoma City, Oklahoma, September 1974.

CHAPTER VI

OIL SHALE

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## INTRODUCTION

Synthetic crude from oil shale is obtained by heating oil shale—a sedimentary rock containing an organic material called kerogen—to approximately 900° F. USGS Circular 523 projects that resources of about 2.2 trillion barrels exist in the United States; of this, about 80 billion barrels are considered recoverable reserves, using existing technology. (See Table VI-1.)

Shale oil products were first obtained in France in 1838 by retorting oil shale. Other countries, including China and USSR, have successfully exploited oil shale; a plant in Manchuria was a source of fuel for the Japanese navy during World War II. Successful exploitation, how-

ever, has depended almost entirely upon economic factors.

Oil shale developments have been undertaken by both industry and the U.S. Bureau of Mines. Technology has been developed and the first-generation processes are well in hand. Successful commercial development depends entirely on the ability of industry to obtain an adequate price for its products. Uncertainties in the "price" of crude oil are inhibiting commercialization. DOD efforts are directed toward providing and encouraging appropriate government incentives, and testing of the resulting fuels for operational use as they become available.

Table VI-1

### SHALE OIL FACT SHEET

Gross energy content of shale oil <sup>1</sup>	18,330 — 18,680 Btu/lb
Recoverable reserves <sup>2</sup>	80 billion barrels
U.S. resources (known) <sup>2</sup>	2,200 billion BOE <sup>a</sup>
U.S. resources (total) <sup>2</sup>	140,000 billion BOE <sup>a</sup>
Concentration <sup>1</sup>	10.5—75 gallons/ton

<sup>a</sup>BOE = Barrel oil equivalent

Sources: 1. *Synthetic Fuels Data Handbook*, Cameron Engineers, 1975.

2. USGS Circular 523, 1966.

## OIL SHALE RESOURCES

The quantity of oil shale in the world represents a large energy resource. As with other energy sources, however, the estimates of the magnitude vary widely. Consequently, any estimate needs to be used with a good deal of caution, and there is significant variation between estimates. The resource estimates presented at the 1974 World Energy Conference are used in this summary, and they appear in Table VI-2. This reference shows that the

bulk of the oil shale in the world is found in the U.S. The magnitude of the U.S. deposits reported generally agrees with other estimates. Detailed breakdowns of U.S. resources (USGS Circular 523) and an estimate of the recoverable reserves contained in the Green River Formation in Colorado, Utah, and Wyoming appear in Table VI-3.

Table VI-2  
WORLD OIL SHALE RESOURCES

Location	Resource (Megatonnes)	Resource (million bbl)	Location	Resource (Megatonnes)	Resource (million bbl)
Argentina	45	330	Jordan	7	50
Brazil	497	3,645	Luxembourg	109	795
Bulgaria	19	140	New Zealand	224	1,640
Burma & Thailand	217	1,590	Spain	6	45
Canada	24,860	182,225	Sweden	880	6,450
Chile	25	185	Turkey	2	15
China (Peoples Republic)	21,000	153,930	United Kingdom	298	2,185
Czechoslovakia	1	7	United States	145,000	1,062,850
France	237	1,740	USSR	3,388	24,835
Germany (Federal Rep.)	311	2,280	Yugoslavia	128	940
Israel	20	145	Zaire	1,550	11,360
Italy	1,087	7,965	TOTAL	199,311	1,465,347

Source: 1974 World Energy Conference.

Table VI-3  
U.S. OIL SHALE RESOURCES  
(Billions of barrels)

Deposits	Known Resources				Order of Magnitude of Possible Extensions of Known Resources			Order of Magnitude of Undiscovered and Unappraised Resources			Order of Magnitude of Total Resources		
	Recoverable Under Present Conditions	Marginal and Submarginal			Marginal and Submarginal			Marginal and Submarginal			Oil Equivalent in Deposits		
Range in grade: oil yield, in gallons per ton of shale	25-100	25-100	10-25	5-10	25-100	10-25	5-10	25-100	10-25	5-10	25-100	10-25	5-10
Green River Formation, Colorado, Utah, and Wyoming	80	520	1,400	2,000	600	1,400	2,000	---	---	---	1,200	2,800	4,000
Devonian and Mississippian shale, Central and Eastern United States	None	None	200	200	None	800	1,800	---	---	---	---	1,000	2,000
Marine shale, Alaska	Small	Small	Small	Small	250	200	Large	---	---	---	250	200	Large
Shale associated with coal	Small	Small	"	"	Small	Large	Large	60	250	210	60	250	210
Other shale deposits	Small	Small	Small	"	"	"	"	500	22,000	134,000	500	22,000	134,000
Total	80	520	1,600	2,200	850	2,400	3,800	550	22,000	134,000	2,000	26,000	140,000

\*No estimate. Estimates and totals rounded.

Oil shale resource estimates include shale zones of the Green River Formation 10 feet or more thick yielding as little as 10 gallons of oil per ton.

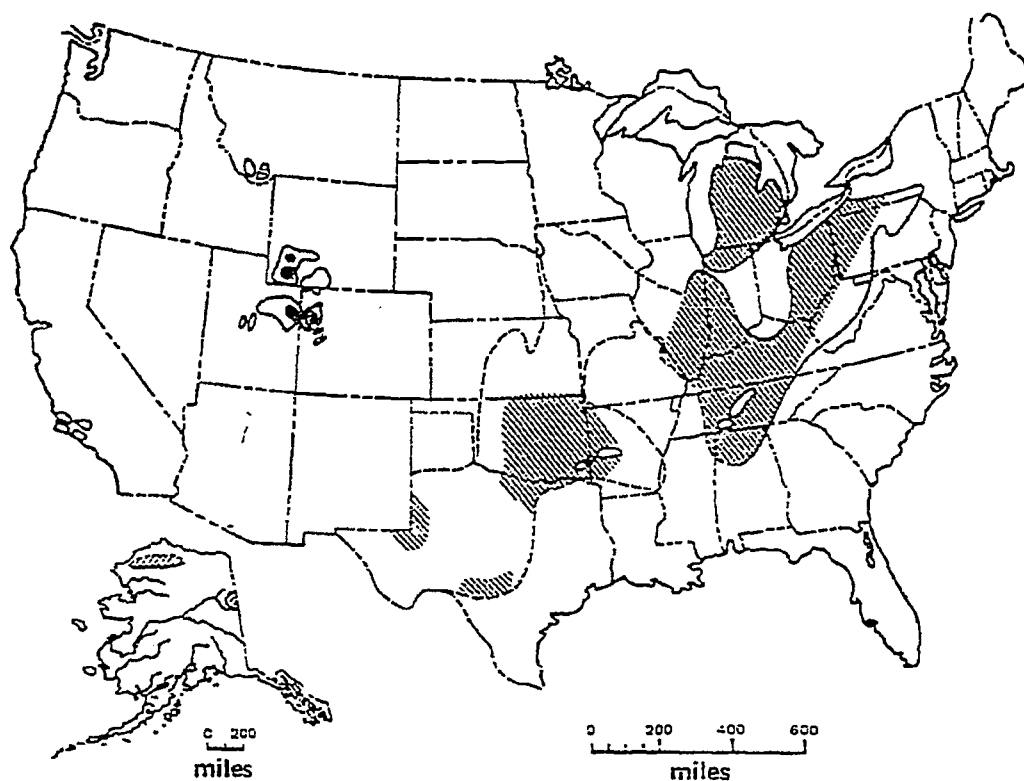
Source: USGS Circular 523, 1965




## LOCATION OF U.S. OIL SHALE RESOURCES



Oil shale deposits in the U.S. are shown in Figure VI-1. The eastern and midwestern deposits are of minor importance as fuel source, however. The major U.S. oil shale


resource is contained in the Green River Formation in Colorado, Utah, and Wyoming. (See Figure VI-2.) Table VI-4 shows the composition of the various shales.



### EXPLANATION

 Tertiary deposits  
Green River Formation  
in Colorado, Utah, and  
Wyoming; Monterey  
Formation, California;  
middle Tertiary deposits  
in Montana. Black areas  
are known high-grade de-  
posits

 Mesozoic deposits  
Marine shale in Alaska  
 Permian deposits  
Phosphoria Formation,  
Montana

 Devonian and Mississippian  
deposits (resource esti-  
mates included for  
hachured areas only  
in Geological Survey  
Circular 523). Boundary  
dashed where concealed or  
where location is uncertain.

Source: *Final Environmental Statement for the Prototype Oil Shale Leasing Program*, U.S.D.O.I. 1973, Vol. 1, p. 11-5.

Figure VI-1. MAP OF PRINCIPAL REPORTED OIL SHALE DEPOSITS OF THE UNITED STATES

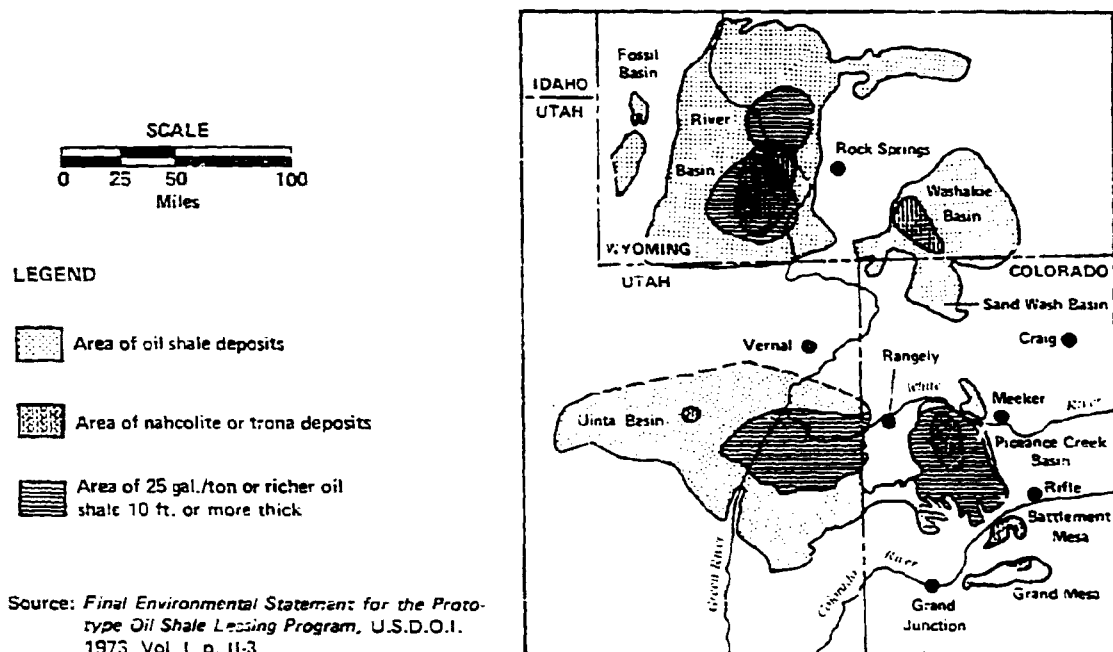


Figure VI-2. LOCATION OF OIL SHALE RESOURCES  
IN THE GREEN RIVER FORMATION

Table VI-4

TYPICAL OIL SHALE COMPOSITION

ORGANIC MATTER (13.7% by weight)		MINERAL MATTER (86.3% by weight)		AVERAGE MAHOGANY ZONE OIL SHALE COMPOSITION		
	% weight		% weight		% weight	1 ton yields
Carbon	80.5	Carbonates	50.0	Oil	10.9	26.4 gallons
Hydrogen	10.3	Feldspars	19.0	Water	0.8	1.9 gallons
Nitrogen	2.4	Illite	15.0	Gas and Losses	2.0	400 scf
Sulfur	1.0	Quartz	10.0	Spent shale	86.3	1726 pounds
Oxygen	5.8	Analcite	5.0			
Pyrite	1.0					

Source: *Mineral Facts and Problems*, U.S. Department of Interior Bulletin 650-1970.

## OIL SHALE RETORTING

### Surface Retorting

The surface approach for converting the kerogen in oil shale into synthetic crude requires that the shale be mined in either a surface or underground mine; be transported to the processing plant; and be crushed and fed into a retort heated to approximately 900° F where the kerogen is converted from a solid waxy material into a liquid. The liquid hydrocarbon is collected, hydro-treated to pipeline quality, and piped to a refinery for further processing. The spent shale is deposited in landfills. Several of the more promising processing schemes are illustrated in Figures VI-3 through VI-11.

### In Situ Retorting

The various in situ techniques, although not as well developed, require that a portion of the shale seam be fractured. A flame zone is then passed through the fractured material that retorts the shale in place. The liquid shale oil is collected and further processed in the same manner as in the surface technique. Problems inherent in the in situ technique include obtaining uniform fracturing, obtaining uniform heating as the flame zone moves through the fracture zone, and self-healing of the fractures. Several organizations have attempted to process shale in situ, including USBM, Sinclair Oil Co., Equity Oil Co., and Occidental Oil Co. Currently, ERDA and Occidental Oil Co. have development programs in progress. The Occidental approach is shown in Figures VI-12 and VI-13.

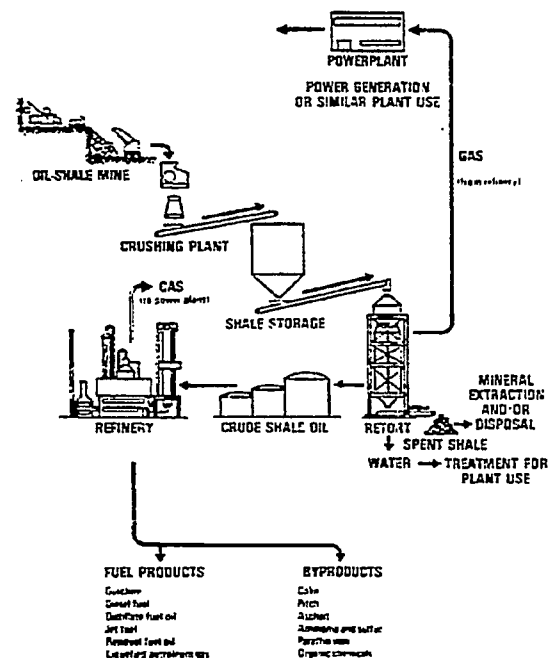
### Multimineral Recovery

Multimineral concepts, such as the Superior Oil Process, recover not only the oil from the oil shale but also recover the nahcolite, alumina, soda ash, and water. Only the spent shale is returned to the mine. The raw shale is crushed, pressed, screened and then is partially calcined in a kiln where a white film is deposited on the nahcolite particles. The shale and nahcolite particles are then passed through a feeder onto a belt conveyor where the particles are scanned with a computer-controlled laser scanner with an air blast separator. As the particles leave the conveyor belt the air blast is directed toward the nahcolite particles, changing their trajectory and separating the shale from the nahcolite.

The crushed shale is placed in a circular grate retort where it is indirectly heated. A diagram of the cross section of the circular grate retort is presented in Figure VI-14.

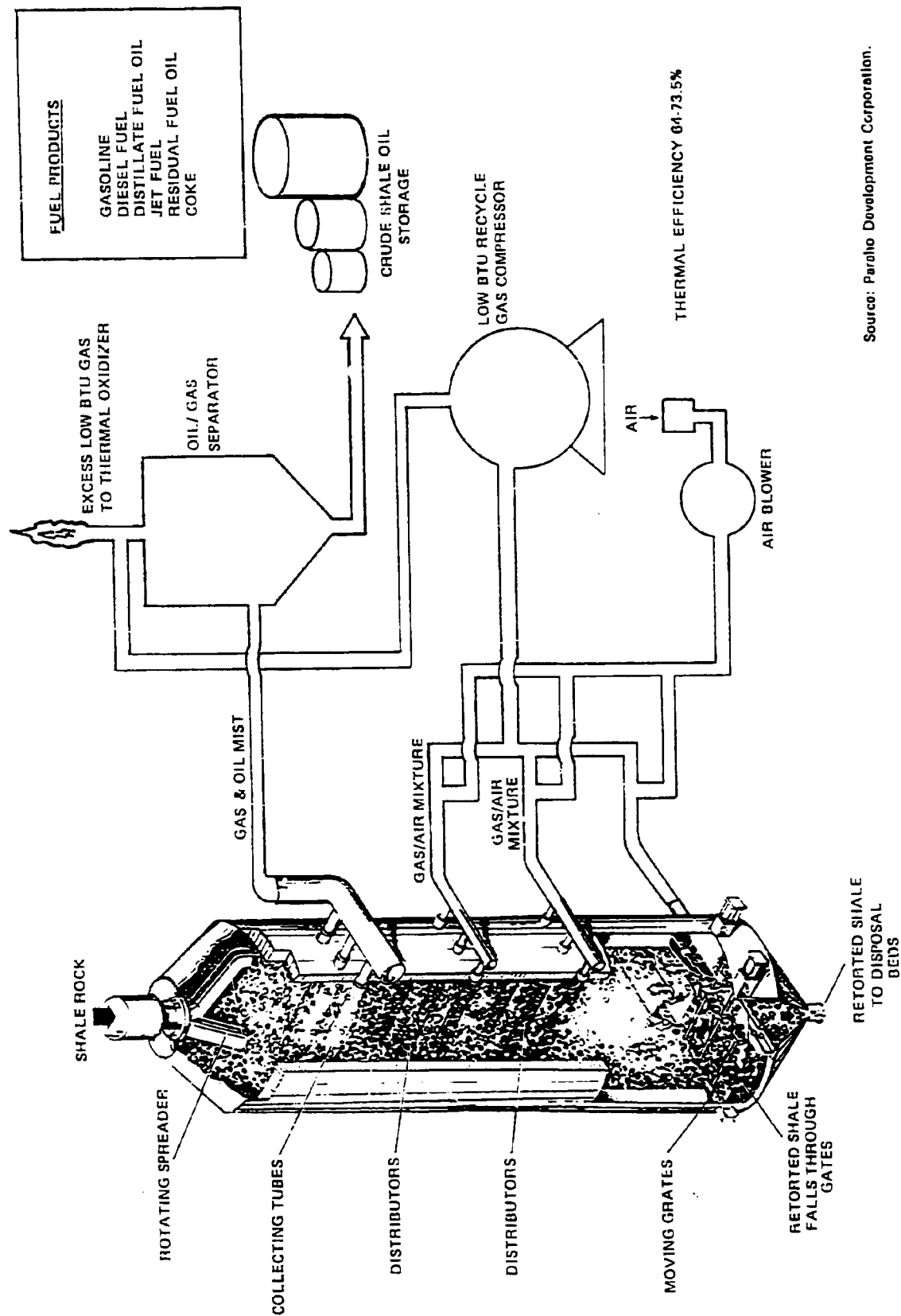
The spent shale from the retort is processed to remove the alumina and soda ash ( $\text{Na}_2\text{CO}_3$ ). This process is diagrammed in Figure VI-15.

The major variation in surface oil shale processing is how the shale is retorted. The properties of several shale crudes are compared with petroleum crudes in Table VI-5.



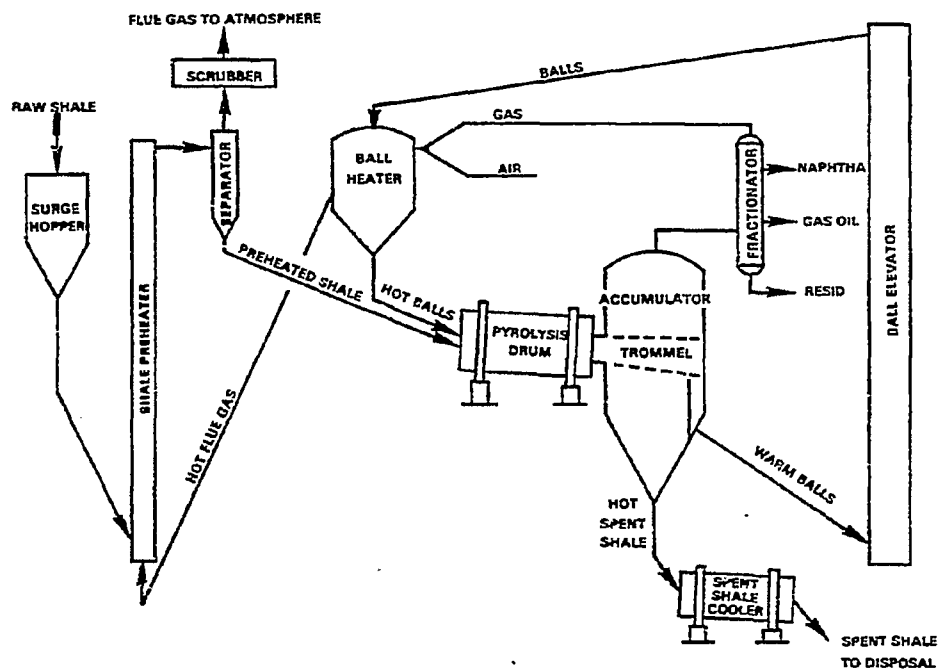
Source: *Final Environmental Statement for the Prototype Oil Shale Leasing Program*, U.S.D.O.I. 1973.

Figure VI-3. SCHEMATIC DIAGRAM OF OIL SHALE SURFACE PROCESSING



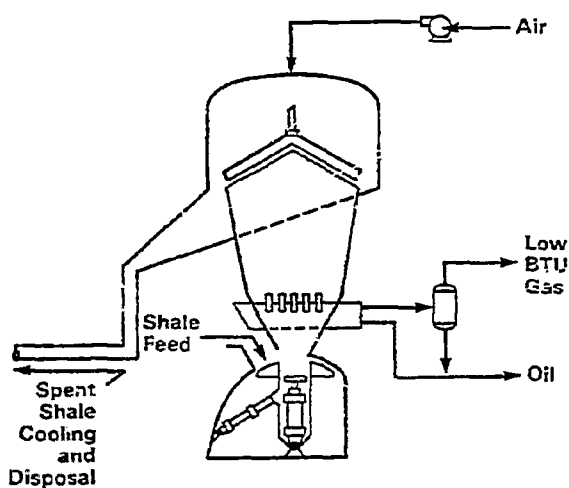
Source: Paraho Development Corporation.

Figure VI-4. SCHEMATIC OF PARAHO OIL SHALE PROCESS



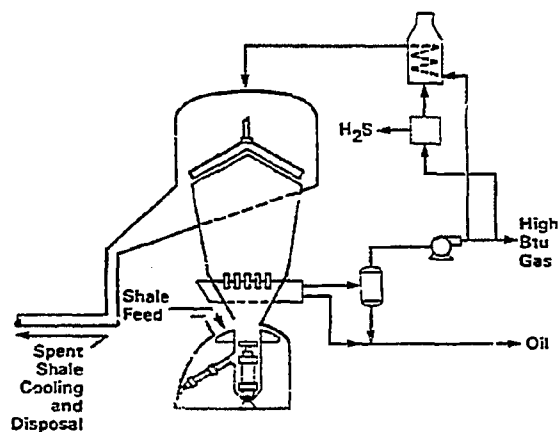
Adapted from: Albert F. Lenhart, "The TOSCO Process—Economic Sensitivity to the Variables of Production," Proceedings of the American Petroleum Institute, Refining Division, 1969.

Figure VI-5. TOSCO II OIL SHALE PLANT



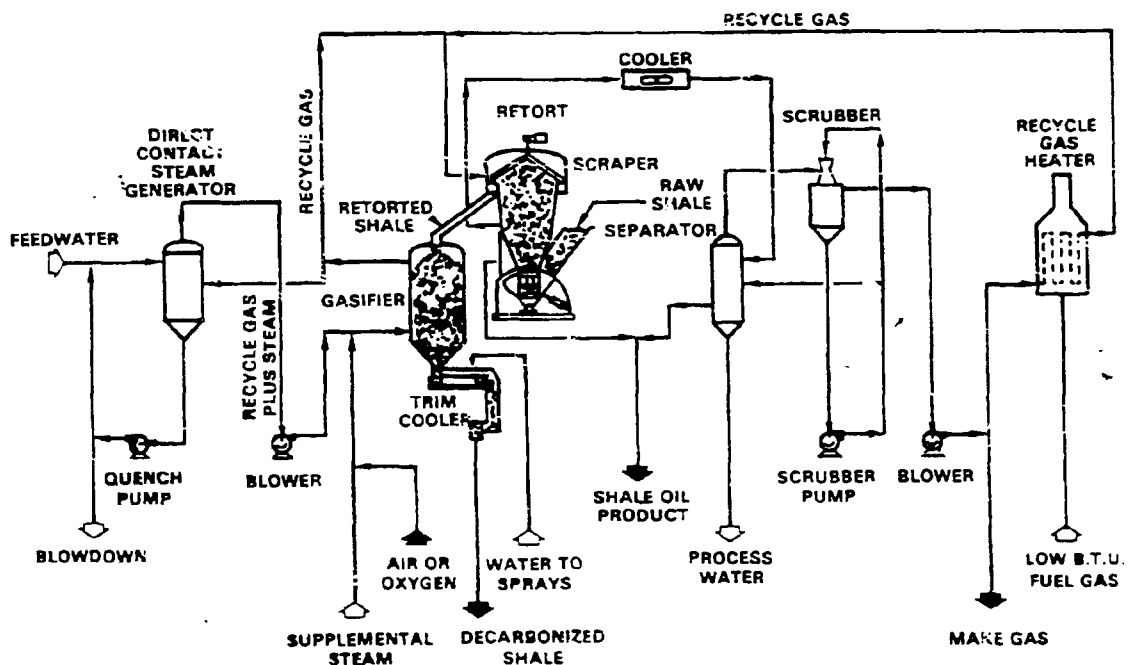
83% Thermal Efficiency  
(40% Low BTU Gas, 60% Crude Oil)  
Demonstrated in 1956-58 at up to  
1200 Tons/Day

Figure VI-6. UNION OIL—OIL SHALE  
RETORT A



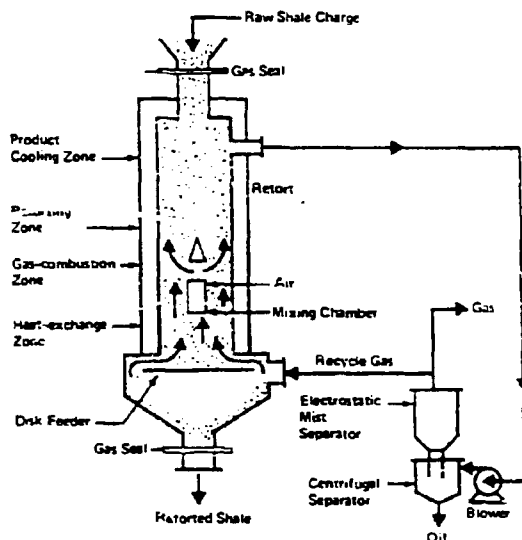
69% Thermal Efficiency

Figure VI-7. UNION OIL—OIL SHALE  
RETORT B



Adapted from: Fred L. Hartley, "Oil Shale: Another Source of Oil for the United States," Oil Daily's Third Annual Synthetic Energy Forum, New York, New York, June 10, 1974.

Figure VI-8. UNION OIL SGR OIL SHALE PLANT

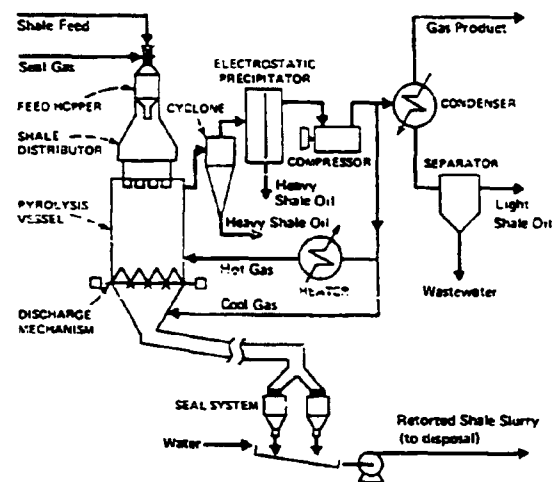


Recycle gas is mixed with air and burned within the retort. Gases flow upward and shale moves downward.

Size: 360 tons/day Efficiency, % of Assay: 82-87

Source: Final Environmental Statement for the Prototype Oil Shale Leasing Program, U.S.D.O.I. 1973, Vol. 1, p. 1-13.

Figure VI-9. USBM GAS COMBUSTION RETORT



Size: 2200 tons/day

Efficiency % of Assay: Unknown

Source: "Shale Oil-Process Choices," Chemical Engineering, May 13, 1974.

Figure VI-10. PETROSIX OIL SHALE PROCESS

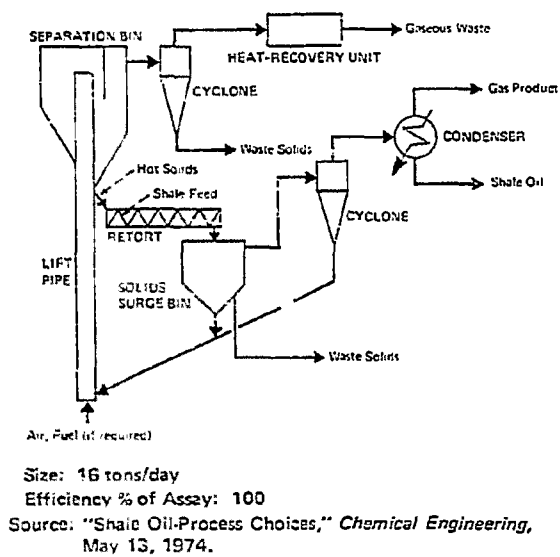


Figure VI-11. LURGI-RUHRGAS OIL SHALE PROCESS

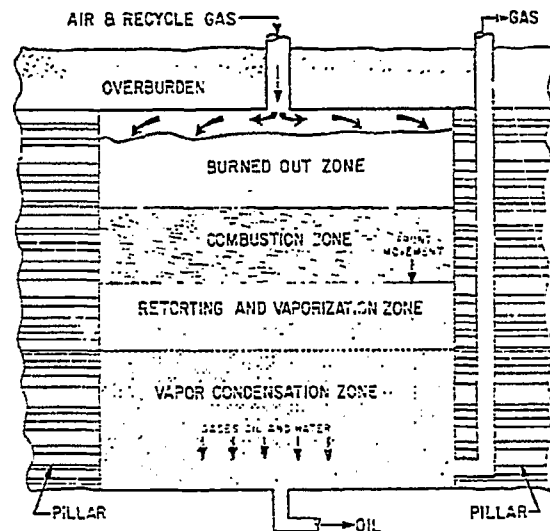


Figure VI-13. OCCIDENTAL IN SITU OIL SHALE RETORTING

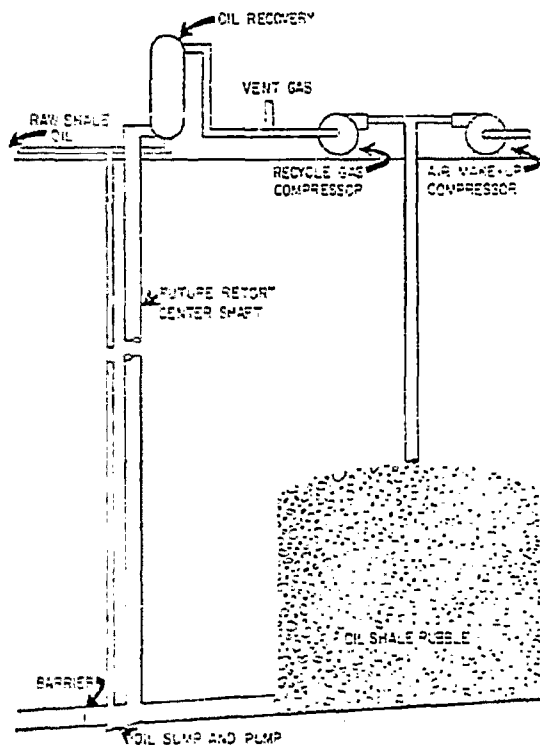


Figure VI-12. OCCIDENTAL IN SITU OIL SHALE PROCESS

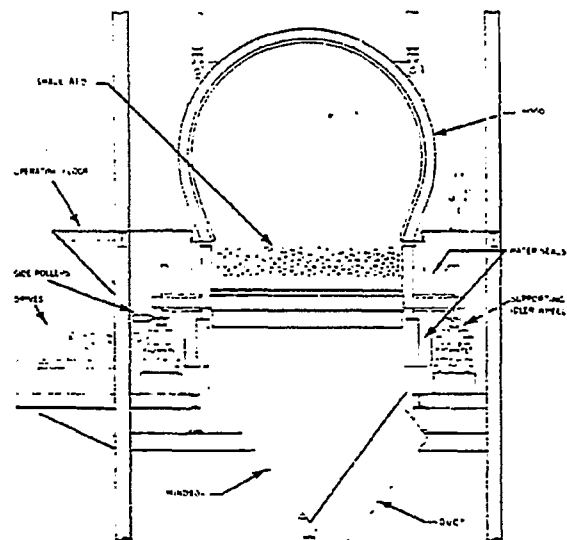


Figure VI-14. CROSS-SECTION OF SUPERIOR OIL COMPANY CIRCULAR RETORT

Table VI-5

## TYPICAL SHALE OIL CRUDE PROPERTIES

Property	Crude Shale Oil						
	TOSCO <sup>a</sup>	Paraho <sup>b</sup>	Union A <sup>a</sup>	LERC <sup>a</sup> Gas Combustion Retort	LERC <sup>a</sup> In-situ	U.S. Crude Petroleum Black Bay, <sup>c</sup> Westfield Louisiana	Imported Petroleum Crude <sup>d</sup> Saudi Arabia
Gravity (° API)	28	19.3	19.7	19.5	28.4	34.4	30.8
Pour Point (° F)	75	85.0	85	80	10	< 5	+ 5
Sulphur (wt %)	0.8	0.61	1.0	0.60	0.60	0.19	2.4
Nitrogen (wt %)	1.7	2.19	1.8	2.16	1.69		
Oxygen (wt %)		1.40			0.80		
Viscosity (SUS at 100° F)	120			543	45	< 5	
C/H (wt/wt)	~ 7.50	7.38			7.06		
Carbon (wt %)	~84.7	84.90			84.88		
Hydrogen (wt %)	~11.3	11.50			12.02		

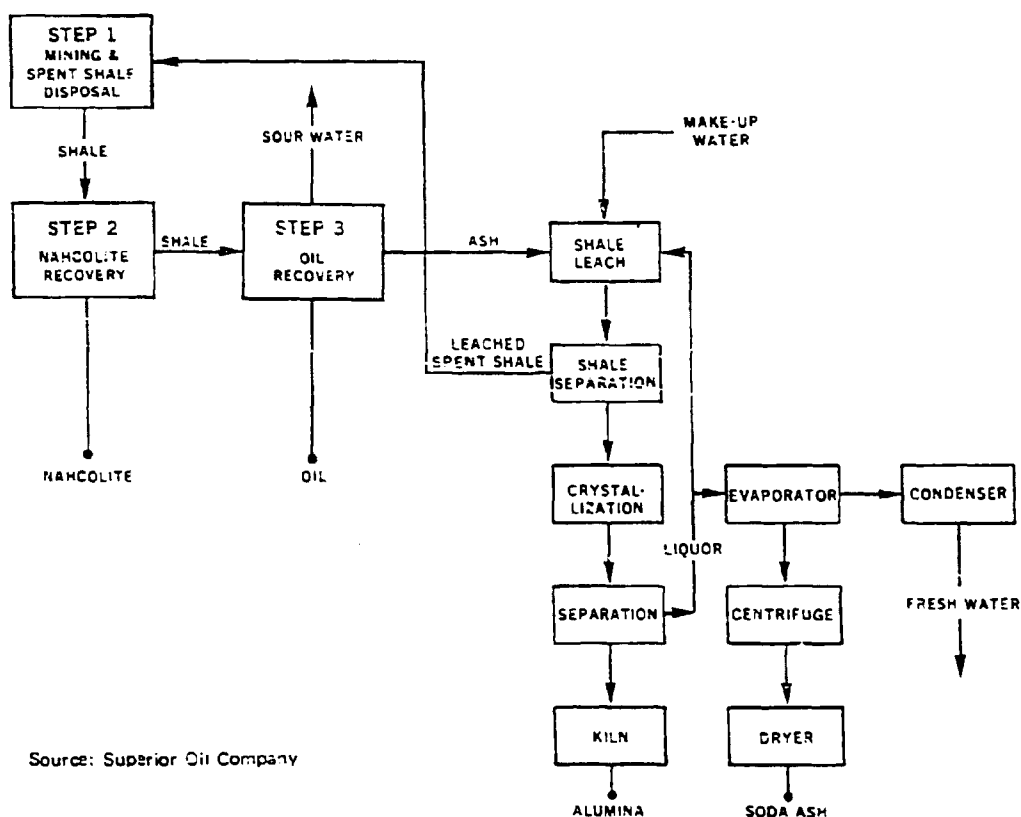
LERC = Laramie Energy Research Center.

<sup>a</sup>Evaluation of Methods to Produce Aviation Turbine Fuels from Synthetic Crudes, Part I (AFAPL-TR-75-10, March 1975).

<sup>b</sup>The Production and Refining of Crude Shale Oil into Military Fuels, August 1975.

<sup>c</sup>Petroleum Refining, Vol. 5, 1975.

<sup>d</sup>Oil and Gas Journal, 29 March 1976.



Source: Superior Oil Company

Figure VI-15. SUPERIOR OIL PROCESS



## CURRENT AND PLANNED PROJECTS

There was substantial industrial enthusiasm for commercial oil shale operations in early 1975. By year end, however, all major commercial projects had been cancelled or delayed. Uncertainties in production economics and product price, and uncertainties regarding future government policy were the reasons for the slippage and cancellation.

In late 1974, the Department of Interior (DOI) estimated that a one million bbl/day shale industry could be in

operation by 1985. The Synthetic Fuels Commercialization task force, an interagency group convened by the President during 1975, concluded in its July 1975 report, however, that government incentives approaching \$6 billion would have to be provided to achieve a 350,000 bbl/day commercial capacity from all synthetic crude sources by 1985. Tables VI-6 and VI-7 present the status of some selected projects.

Table VI-6  
U.S. OIL SHALE PROJECTS

Project	Location	Operational Dates	Capacity (bbl/day)
Bureau of Mines	Anvil Points	1947-1956	-
Union Oil	Parachute Creek	1956-1958	720
Colony (TOSCO II)	Parachute Creek	1965-1972	600
Paraho	Anvil Points	1974-1976	150
Occidental	Logan Wash	1975-1976	300
Union Oil (SGR)	Parachute Creek	Suspended	1,350
Arco, et.al. (TOSCO II)	Parachute Creek	1978 (suspended)	50,000
Union Oil	Parachute Creek	1980	50,000
Amoco/Gulf	Colorado-A	19 ?	100,000
Arco, et.al.	Colorado-B	19 ?	50,000
Sun, Phillips	Utah-A	19 ?	100,000 (Combined Project)
Sohio, Phillips, Sun	Utah-B	19 ?	

## NAVY, DEPARTMENT OF DEFENSE, AND INDUSTRY JOINT SHALE OIL PROJECT

Paraho Development Corporation operates a 2.5-ft pilot retort at Anvil Points, Colorado, that has produced 300 barrels of synthetic crude from oil shale, and an 8.5-ft semiworks retort, which has produced 10,000 barrels. Paraho supplied 9,936 barrels to the Navy for refining in March 1975. The refinery produced 5,756 barrels of refined products and 5,107 barrels were shipped to various government agencies and industry.

Fuel Type	Produced (bbl)	Shipped (bbl)
Motor gasoline	725	644
JP-4	454	347
JP-5	650	666
DFM/DF-2	1167	1030
Heavy fuel oil	2760	2520

Note: The discrepancies between the amounts produced and shipped occurred because of heels in the tanks.

Table VI-7

## PRESENT AND PROJECTED ERDA OIL SHALE PROJECTS

Program Element	FY 1977 Funding (millions of dollars)	Performer	Location
<u>Oil Production</u>			
In-house	2.95	Laramie Energy Research Center	Laramie, WY
	2.30	Lawrence Livermore Laboratory	Livermore, CA
	2.20	Sandia Laboratory	Albuquerque, NM
University	0.55	Los Alamos Scientific Laboratory	Los Alamos, NM
	0.16	Universities	—
Industry			
True in situ		Tally Frac	
Modified horizontal:		Geokinetics	
Surface up-lift			
Modified horizontal:	8.04	Equity Oil	
Solution mining		Occidental Petroleum	
Modified vertical			
<u>Gas Production</u>			
In-house	0.45	Laramie Energy Research Center	Laramie, WY
Industry			
Gasification of			
Antrim Shale	3.15	Dow Chemical Company	Midland, MI
<u>Environmental</u>			
In-house	0.68	Laramie Energy Research Center	Laramie, WY
	0.02	Lawrence Berkeley Laboratory	Berkeley, CA
University/Other	0.47	Universities	—
<u>Supporting Research</u>			
In-house	1.25	Laramie Energy Research Center	Laramie, WY
Universities	0.06	Universities	—
Total	22.20		

Source: Dr. Philip White, Statement on ERDA's R&D Program in Oil Shale, before the Subcommittee on Minerals, Materials, and Fuels of the Senate Committee on Interior and Insular Affairs on November 30, 1976.

The Air Force Aero Propulsion Laboratory (AFAPL) reported that the synthetic JP-4 it received met all military specifications after clay treatment and exceeded natural JP-4 in lubricity performance. The Air Force flew a T-39 from Wright-Patterson AFB to Carswell AFB on the synthetic JP-4. The JP-4 was also tested in a single T56 combustor and a J85 combustor with an afterburner. There

was no noticeable difference from natural JP-4 except for higher NO<sub>x</sub> emissions.

The Naval Ship Research and Development Center (NSRDC), Annapolis, reported on investigations of the wax content and corrosion in both crude and refined Paraho shale oil. Corrosion in the worst case was rated as mild. Synthetic JP-5 was found to have an excellent cetane

number, probably in part because of the abundance of aromatics, but its accelerated stability index was almost four times higher than military specifications. NSRDC tests indicated that the jet fuel fraction was in need of upgrading, the lubricant fraction was not acceptable by specification standards, and the residual fraction was too waxy for use as a fuel.

The Navy Research Laboratory (NRL) Fuel Chemistry Division and the Naval Air Propulsion Test Center (NAPTC) investigated physical characteristics of JP-5 and Jet-A fuels derived from oil shale crude. They found the n-paraffin content of these fuels to be 38.6 percent. The synthetic JP-5 was found to be almost similar to natural JP-5 with antistatic additives.

The Naval Ship Engineering Command (NAVSEC), Philadelphia, tested DFM from shale oil in a test boiler and a diesel engine (GM 3-71). The boiler test showed that burner lightoff was satisfactory, and combustion performance indicated increased air requirements for the synthetic DFM in the test configuration. Changes to the burner settings might correct this problem. Capacity characteristics were acceptable and coking at low rates of fuel usage was not a problem. In the preliminary diesel tests, higher soot deposits were experienced, as was some atomizer fouling and sluggish fuel oil control valve operation. Overall, however, the shale-oil derived fuel was acceptable, but had a very high bottom sediment and water (BSW) content. The fuel was centrifuged to relieve this problem.

After 50 hours of operation, the test engine was disassembled. Examination of the engine components showed fouled injectors and sticking and worn rings, possibly caused by high wax content in the fuel.

The Naval Air Propulsion Test Center (NAPTC) found synthetic JP-5 to have low thermal stability, high gum content, high freeze point, and high solid content. Upon standing for two weeks, however, the solids content dropped by 80 percent. Engine tests performed by NAPTC in a TF34 engine indicated that synthetic JP-5 performance did not differ significantly from natural JP-5. However, nozzle blockage did exceed acceptable limits by substantial margins. Distillation of the synthetic JP-5 improved all problems except the freeze point and nitrogen. Sulfuric acid treatment reduced the nitrogen problem, and urea extraction improved the freeze point and viscosity by removing the high molecular weight n-paraffins.

The Army, in tests conducted in an L-141 jeep engine, found no significant differences in the NATO gasoline derived from shale oil and petroleum gasoline. This sample was supplied by MERDC from its portion of the Paraho fuel.

Industry test results from Pratt and Whitney and Allison Division of Detroit Diesel generally agreed with DOD results. They found that the synthetic diesel fuels had higher  $\text{NO}_x$  emissions, but all other combustion characteristics were essentially the same for both synthetic and natural fuels.

## 1976 DOD/ERDA OIL SHALE PROGRAM

In September 1976, the Navy awarded a \$411,187 contract to renovate the Anvil Points Oil Shale Research Facility to Development Engineering, Inc. (DEI), a subsidiary of Paraho Development Corporation. The renovation of the facility is the first step in a proposed joint DOD/ERDA plan for an oil-shale production run at the site in 1977. The oil produced will be refined for additional DOD testing and evaluation of military specification fuels. The project's goal is to produce about 80,000 barrels of crude shale oil. When added to the 20,000 barrels of crude shale oil now being stored at Anvil Points, about 100,000 barrels of feedstock will be available for the refining phase of the proposed program.

A contract to refine the crude oil into military specification fuels will probably be let sometime in 1978.

When the refining phase has been finished, the fuel products will be distributed to various government and contractor facilities for test and evaluation.

This project is part of a planned joint DOD/ERDA program to assess the suitability of synthetic fuels for military and commercial uses. ERDA's role in this joint project is to develop and extend technology for producing synthetic fuels, as well as to demonstrate the potential of the refining technology for commercial use. DOD's main concerns are to ensure that synthetic fuels can be used with existing and future energy systems and to be prepared to use and logistically support synthetic fuels for military use.

ERDA will provide technical support and R&D direction to DOD, as DOD's agent for synthetic fuels, is the contracting agency.

Table VI-8

## OIL SHALE ENVIRONMENTAL RD&amp;D ACTIVITIES SUMMARY

Environmental R&D Needs	RD&D Projects	Environmental Category	Primary Pollutants	Planned Accomplishments
<b>Oil Shale Subprogram</b> - Overall characterization of pollutants - Data for control technology development - Baseline data for environmental impact assessments - Water resource requirements, effects and conservation	- Environmental monitoring of field operations at Rock Springs Site 9. (Laramie Energy Research Center)	- Air and water	- Overall pollution assessment	- Characterize water produced as a result of oil shale retorting. - Characterize quality of natural waters and quantify usage - Identify and define flare gas constituents - Perform thermographic analysis to evaluate postburn surface effects
	- Environmental baseline monitoring at selected White Mountain and Green River sites (Laramie Energy Research Center)	- Air, water, and land	- Ambient quality	- Monitor site meteorological aspects - Characterize site physiographic, geologic, and soil features - Monitor groundwater and surface water quality and quantity - Identify and define biological, historical, and scientific resources - Complete environmental impact assessment for White Mountain site
	- Biological degradation of retort water (University of Southern California)	- Water	- Organic material	- Continue studies to develop a practical method to decompose soluble organic pollutants in retort water
	- Conservation of water with in situ oil shale development. (Lawrence Berkeley Laboratory)	- Water	- Trace elements	- Provide plans for continuous allocation of water - Provide strategy for real-time monitoring of water quality - Identify methods for treatment of combustion gas scrubbing water - Identify control methods for in situ combustion retorting - Complete report presenting data and results of study
	- In situ spent shale leaching rate study (Texas Technological University)	- Solid waste	- Trace elements	- Continue studies to determine selected inorganic chemical parameters of environmental significance in retorted oil shale leachings.

Source: Dr. Philip White, Statement on ERDA's R&D Program in Oil Shale, before the Subcommittee on Minerals, Materials, and Fuels of the Senate Committee on Interior and Insular Affairs on November 30, 1976.

## CALIFORNIA EDISON EXPERIMENT

The Paraho oil-shale program shipped 3,668 barrels of synthetic crude to California Edison's Highgrove electric power generating plant near Los Angeles in July 1976. The synthetic crude was processed from oil shale at the project's facility at the Naval Oil Shale Reserves near Rifle, Colorado, and are being used by California Edison in

combustion tests in a commercial boiler. These tests are part of an effort to find the best method of using unrefined shale oil. The program is sponsored by Paraho, the Rio Blanco Oil Shale Project, the White River Shale Project, and Southern California Edison.

## ENVIRONMENTAL ISSUES AND ACTIVITIES

In situ oil shale processing poses environmental problems that must be solved before shale can be used commercially. These problems include disposal of in situ water, migration of fluids during and after in situ processing, surface thermal

problems, and identification of materials leached from in situ processed spent shales. Specific studies of these environmental concerns are being funded; they are summarized in Table VI-8.

## ECONOMICS OF OIL SHALE SYNTHETIC CRUDE TECHNOLOGY

The economics of the various synthetic fuels are clouded by uncertainties in technology, legal and regulatory factors, environmental considerations, government energy policy (or lack of policy), and very rapid inflation in key industries. These uncertainties have forced the abandonment or delay of oil shale projects in the U.S. and tar sands projects in Canada.

The rapid changes in equipment and manpower costs make even the most carefully prepared economic analyses of the synthetic fuels projects very tenuous. Nevertheless, it

is necessary to make such analyses in order to determine on a rough estimate basis whether synthetic fuel processes are feasible or not. Care must be exercised when using any of these estimates, however.

Synthetic fuel plants based on various oil shale processes have been designed and evaluated over the past several years. Recent estimates made by ERDA are felt to be fairly representative of the economics of the oil shale industry. These estimates appear in Table VI-9 and Figure VI-16.

Table VI-9

### ESTIMATED OIL SHALE PRODUCTION COST<sup>a</sup>

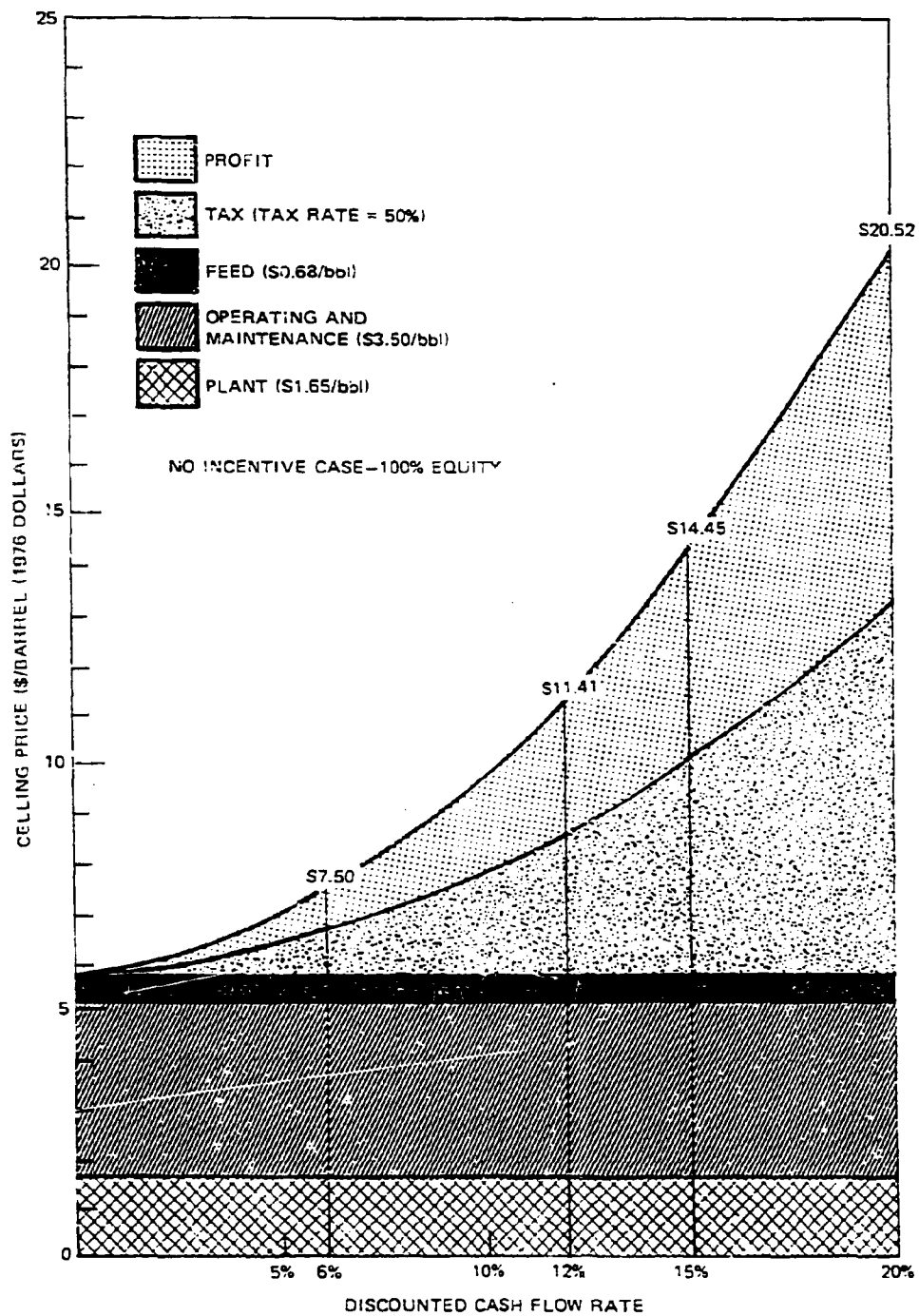
Process	Investment Cost (dollars/barrel/day)	Operating Cost (dollars/barrel)	Selling Price (15% CDF, <sup>c</sup> 100% Equity) (dollars/barrel)
Modified in situ	5,000-7,000	3.50-5.00	8.00-11.00
Surface retorting	14,000-23,000	4.00-5.00	16.00-25.00
Multimineral <sup>b</sup>	7,000-9,000	2.75-4.00	9.00-12.00

<sup>a</sup>The oil produced by these methods may be pre-refined to a quality comparable with Arabian crudes for an additional \$1 to \$4 per barrel.

<sup>b</sup>Superior Oil Process is an example of multimineral shale treatment. (See Figures VI-14 and VI-15)

<sup>c</sup>See Figure VI-16 for selling prices at different discounted cash flow (DCF) rates.

Source: Dr. Philip White Statement on ERDA's R&D Program in Oil Shale, before the Subcommittee on Minerals, Materials, and Fuels of the Senate Committee on Interior and Insular Affairs on November 30, 1976.



Source: *Proposed Synthetic Fuels Commercial Demonstration Program Fact Book*,  
ERDA, March 1976.

Figure VI-16. REQUIRED SHALE OIL SELLING PRICE AS FUNCTION OF  
DISCOUNTED CASH FLOW

**CHAPTER VII**

**TAR SANDS**

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## INTRODUCTION

The terms tar sands, oil sands, bitumen-bearing rocks, oil impregnated rocks, and bituminous sands are used interchangeably to describe unique hydrocarbon-bearing deposits. The bitumen occurs in both consolidated and unconsolidated rocks, varies from viscous to solid; for practical purposes it is immobile to fluid displacement, and it cannot be recovered by primary petroleum produc-

tion methods. A summary of tar sands data is presented in Table VII-1.

Early development work occurred principally in Canada. Recently efforts have been initiated to develop resources in the western United States. A comparison of United States and Canadian tar sands properties is shown in Table VII-6.

Table VII-1

### U.S. TAR SANDS FACT SHEET

Energy content <sup>1</sup>	18,000 Btu per pound <sup>2</sup>
Proven reserves <sup>2</sup>	27 billion barrels
Resources <sup>3</sup>	29 billion barrels (estimated)
Bitumen saturation <sup>3</sup>	53 percent of pore volume
Bitumen in tar sand <sup>4</sup>	Percent by weight
	Utah
	Tar Sand Triangle 5
	Circle Cliffs 5
	Sunnyside 8-9
	Hill Creek 8-9
	Asphalt Ridge 8-9
	P.R. Spring 6
	Canada
	Athabasca 12-13

<sup>1</sup>Bitumen in tar sands.

Sources: 1. T. F. Yen, *Shale Oil, Tar Sands, and Related Fuel Sources*, ACS Series 151, 1976.

2. *Assessment of U.S. Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems and Cameron Engineers, Inc., May 15, 1976, Contract N00014-76-C-0427.

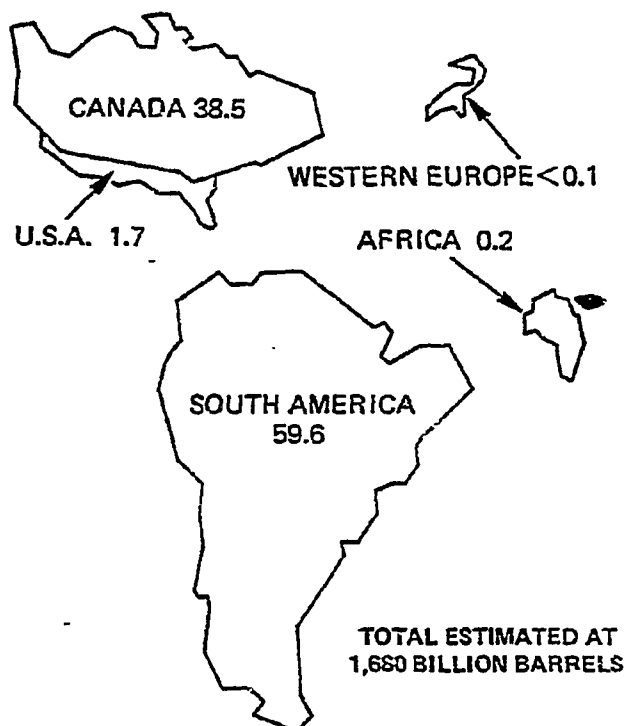
3. Cecil Cupps, et al., "Field Experiment of In-Situ Oil Recovery from Utah Tar Sand by Reverse Combustion," AICHE Symposium Series No. 155, 1976.

4. Alex G. Oblad, et al., "Recovery of Bitumen from Oil-impregnated Sandstone Deposits of Utah," AICHE Symposium Series No. 155, 1976.

## WORLD RESOURCES

Tar sands are found on every continent except Australia and Antarctica and in 22 of the United States. An estimate of known resources for nine countries is shown in Table VII-2. The best defined deposits in the world are those of northern Alberta, Canada, and the "tar belt" of Venezuela. World tar sands deposits contain fuel sources

equal to 65 percent of all the crude oil known and produced in the world since the discovery of petroleum. World resources of oil bearing bituminous sands are shown in Figure VII-1. (The map has been distorted to show each country's relative proportion of world tar sands deposits.)



Source: 1974 World Energy Conference

Figure VII-1. WORLD RESOURCE  
OF TAR SANDS (PERCENT)

### Canada

Canadian oil sands extend over some 19,000 square miles of northeastern Alberta. (See Figure VII-2.) Near the Athabasca River, the oil sands are located at or close to ground level. However, most of the deposits are below an overburden of muskeg, glacial till, cretaceous bedrock, and lean oil sand varying in depth from 150 to 2,500 feet. The thickness and quality of the deposits vary considerably.

Table VII-3 summarizes the Alberta Energy Resources Conservation Board's most recent estimates by major deposit.

### United States

There are approximately 27 billion barrels of oil in U.S. tar sands deposits. While 22 states contain tar sands, only six contain deposits which could be extracted commercially:

State	Millions of barrels
Alabama	1,180
California	294
Kentucky	149
New Mexico	57
Texas	130
Utah	25,100

Table VII-2

### ESTIMATE OF WORLD RESOURCES FOR OIL FROM BITUMINOUS SANDS<sup>a</sup> (Billions of barrels)

North America		Africa	
Canada	895.0 <sup>1</sup>	Malagasy Republic	1.7 <sup>3</sup>
Trinidad and Tobago	68.0 <sup>3</sup>		
United States	27.0 <sup>2</sup>	Europe	
		Albania	0.4 <sup>3</sup>
South America		Rumania	0.03 <sup>3</sup>
Colombia	1139.1 <sup>3</sup>	USSR	0.03 <sup>3</sup>
Venezuela	74.3 <sup>3</sup>		

<sup>a</sup>Care should be taken in comparing resources among nations, since the data provided to World Energy Conference was based on different economic considerations as well as different degrees of mapping and exploration.

Sources: 1. Alberta Energy Resource Conservation Board.

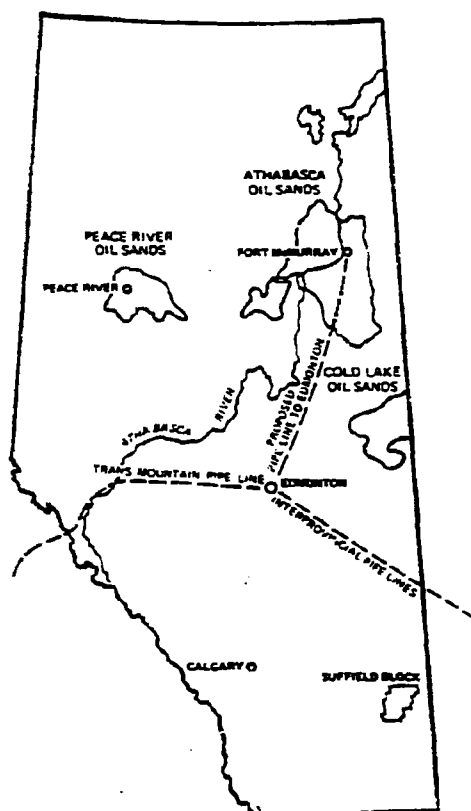
2. *Assessment of U.S. Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems and Cameron Engineers, Inc., May 15, 1976, Contract N00014-76-C-0427.

3. *Survey of Energy Resources*, World Energy Conference, 1974.

Table VII-3  
ESTIMATE OF ALBERTA TAR SANDS RESOURCE  
BY MAJOR DEPOSITS

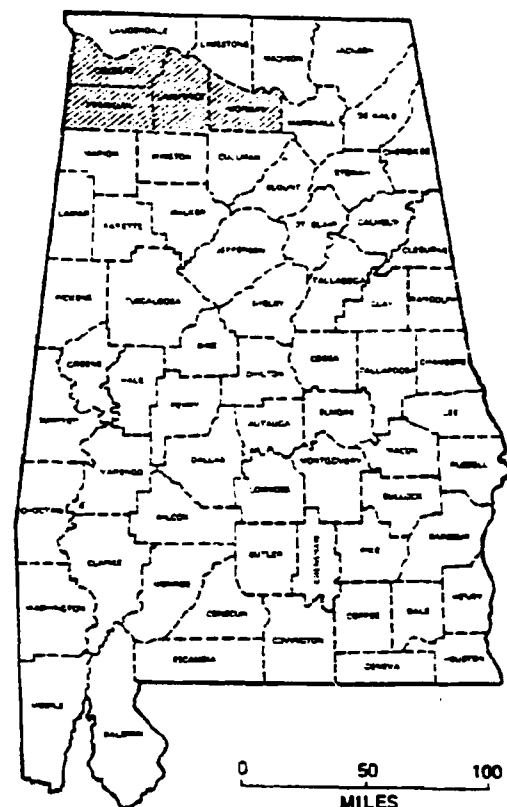
Deposit	Overburden Depth (feet)	Areal Extent (M acres)	Crude Bitumen In-Place (billions of barrels)
Athabasca	0-150	490	74
	150-2000	5,260	552
Cold Lake A	1000-2000	1,800	118
Cold Lake B	1000-2000	650	33
Cold Lake C	1000-2000	710	14
Buffalo Head Hills	500-2500	152	1
Peace River	1000-2500	1,180	50
Wabasca A	200-2000	764	30
Wabasca B	1000-2500	1,000	23
		12,013	895

Source: Alberta Energy Resources Conservation Board.



Source: *The Alberta Oil Sands Story*, Alberta Federal Intergovernmental Affairs, January 1974.

Figure VII-2. LOCATION OF ALBERTA OIL SANDS DEPOSITS



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-3. TAR SANDS DEPOSITS IN ALABAMA

The location of the Alabama deposits are shown in Figure VII-3, California in Figure VII-4, and Utah in Figure VII-5. Table VII-4 presents the characteristics of the tar sands deposits in Alabama, California, Kentucky, New Mexico, and Texas, and Table VII-5 lists the characteristics of the tar sands deposits in Utah.

The tar sands resource of Utah has been described in detail in a survey compiled by Howard R. Ritzma in 1973.<sup>1</sup> There are about 97 tar sand deposits in Utah

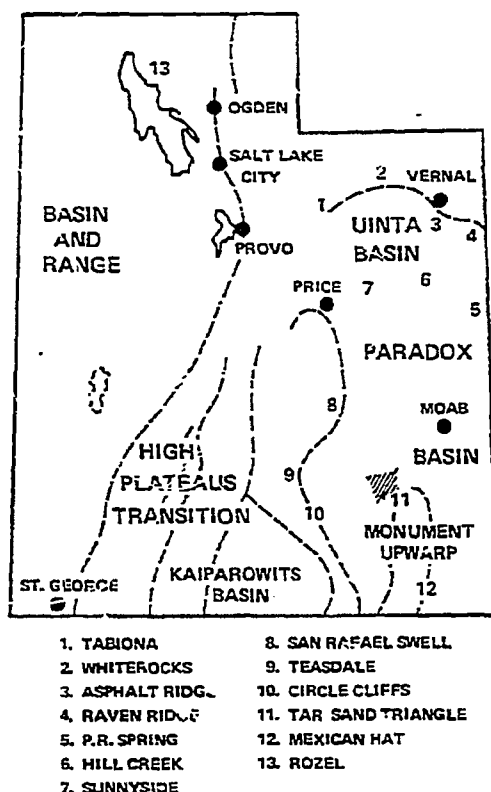
which total 25.1 billion barrels of oil, about 93 percent of the known resources in the United States. The sulfur content of Utah tar sand bitumen varies. In the Uinta Basin, the sulfur content averages 0.56 percent by weight while those in the central southeast region averaged 3.1 percent by weight (see Table VII-5).

<sup>1</sup>Howard R. Ritzma, *Utah Geological and Mineralogical Survey Map 33, Sheet 2, April 1973.*



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-4. TAR SANDS DEPOSITS IN CALIFORNIA



Source: *The U.S. Energy Problem—Appendix S Technology of Alternative Fuels*, Interotechnology Corporation, November 1971.

Figure VII-5. TAR SANDS DEPOSITS IN UTAH

Table VII-4

## U.S. TAR SAND DEPOSITS

	Oil (million of barrels)	Average Overburden (feet)		Oil (million of barrels)	Average Overburden (feet)
Alabama Hartselle Sandstone	1,180	225	Kentucky Edmonson County Davis-Dismal Creek	32.7	15
California Casmalia			Bee Spring	7.6	30
North	0.5-40	None	Kyrook	18.4	15
South	46.4	0 to 40	Ollie School	7.4	15
Edna	150	0 to thin	Asphalt	47.6 <sup>a</sup>	0 to thin
McKittrick	4.85-9	Up to 100	Logan County Russellville	35.3	0 to thin
Point Arena	1.2	Several hundred	Total	149.0	
Santa Cruz	10	0 to 100	New Mexico Santa Rosa	57.2	0 to thin
Sisquoc	36.9	15	Texas Uvalde	154	18
Total	293.3				

<sup>a</sup>200 million tons of sandstone. Assuming a bitumen content of 10 gallons per ton, this would equal a reserve of 47.6 million barrels.

Source: *Assessment of U.S. Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems and Cameron Engineers, Inc., May 15, 1976, Contract N0C014-76-C-0427.

## RECOVERY TECHNIQUES

There are two basic techniques for mining tar sands: the raw materials are mined and the bitumen processed above ground or the bitumen is recovered from the sand in-situ.

## Surface Mining

The only commercial tar sands plant in operation is the Great Canadian Oil Sands (GCOS) plant, located north of Edmonton, Alberta, Canada. The facility began operations in 1967 and now produces roughly 50,000 barrels per calendar day of high quality synthetic crude oil from 130,000 tons per day of tar sands feed. Huge bucketwheel excavators strip the tar sands from the Athabasca deposit into terraces 70 feet high.

Synchrude Canada, Ltd., is building a plant in the Athabasca deposit. Surface mining with large electric draglines will be employed.

As in recovering coal, surface mining is an economical recovery technique for deposits lying close to the surface with little or no overburden. But the cost of mining one cubic yard of overburden is about the same as mining one cubic yard of high grade ore. A general rule of thumb used for Canadian operations is that the ratio of overburden thickness to ore body thickness should not exceed 1. Factors such as ore grade, overburden characteristics, and ultimate product market value can affect this ratio.

Surface mining cleanup operations are accomplished with bulldozers, scrapers, and front-end loaders. In addition to the disposal of overburden and waste sand from

the separation process, large amounts of waste water from above ground extraction facilities must be handled. The GCOS facility pumps approximately 24,000 gpm of slurry into holding ponds. Some of this water may be recycled, but much of it contains clay and sand which remain in suspension indefinitely.

## Underground Mining

Very little experience has been gained in underground mining of tar sands, primarily because of the abundance of surface accessible deposits in Alberta. Conventional hardrock mining is not feasible, because of the structural makeup of tar sands deposits. It may be possible to modify conventional longwall mining techniques to recover tar sands.

On the other hand, hydraulic mining might be used. The technique has been used quite successfully for underground mining of uranium ore, and is now being tested with tar sands in southern California. Figure VII-6 illustrates operation of the process. A capsule containing a high pressure nozzle, a slurry pump, and piping is lowered through a casing into a shaft drilled through the tar sands zone into the underlying formation. The nozzle directs a stream of water against the tar sands deposit, breaking the material into small pieces which are then entrained in the waste water as a slurry. The slurry drains into the sump in the underlying zone and from there it is pumped to the surface for above-ground processing.

Table VII-5

## CHARACTERISTICS OF UTAH TAR SANDS DEPOSITS

Deposit	Area (square miles)	Number of Principal Pay Zone	Gross Thick- ness of Pay, Range (feet)	Overburden Thickness, Range (feet)	Oil (barrels)
Uinta Basin					
Argyle Canyon	7-15	3 to 6	15-85	0-500+	100-125 million
Asphalt Ridge	20-25	2 to 5	10-135	0-500+	1,048 billion
Asphalt Ridge, NW	0.15-0.20	1 to 3	20-300	0-275	10-15 million
Chapita Wells	0.35-1.0	1 to 3	5-30	0-300	7.5-8.0 million
Cow Wash	0.08-0.10	1	5-25	0-200	1.0-1.2 million
Hill Creek	115-125	1 to 3	5-35	0-500+	1.16 billion
Lake Fork	0.3-0.5	1 to 3	5-70	0-450	6.5-10.0 million
Littlewater Hills	0.5-1.75	1 or 2	5-90	0-500+	10-12 million
Minnie Maud Creek	0.5-3.5	1 to 4	5-20	0-500+	30-50 million
Pariette	1.2-1.4	1 or 2	5-32	0-300	12-15 million
P.R. Spring	240-270	2 to 6	10-80	0-500+	4.0-4.5 billion
Raven Ridge	20-25	1 to 7	5-48	0-500+	125-150 million
Rim Rock	2.5-3.5	1 to 4	5-95	0-500+	30-35 million
Spring Branch	0.1-0.2	1	5-250	0-350	1.5-2.0 million
Sunnyside	35-90	3 to 12	15-550	0-500+	3.5-4.0 billion
Tabiona	0.15	1 to 3	5-150	0-400	4.6 million
Whiterocks	0.6-0.75	1	1,000	0-500	65-125 million
Central Southeast					
Circle Cliffs, East Flank	21.1	1 to 3	5-260	0-500+	860 million
Circle Cliffs, West Flank	6.6	1 or 2	5-310	0-500+	447 million
Cottonwood Draw	10.5-12.0	1 to 3	5-65	0-500+	75-80 million
Poison Spring Canyon	0.6-0.8	1 or 3	5-24	0-500+	1.0-1.2 million
Tar Sand Triangle	200-230	1 or 2	5-300+	0-500+	16 billion
Ten Mile Wash	5.0-6.5	1 to 4	5-30	0-500+	6.0 million
White Canyon Flat	0.3-0.4	1	5-21	0-220	2.8 million

Notes: 24 deposits have been mapped and sampled in sufficient detail to provide the above information relative to possible development.

Area is generally given as a range, the minimum figure being the measured areal extent, the maximum being the indicated extent.

Number of pay zones is the number of oil-impregnated rock units five or more feet thick likely to be encountered at any one location within the measured or indicated areal extent of the deposit.

Gross thickness of pay is the total thickness of the combined pay zones likely to be encountered at any one location within the measured or indicated areal extent of the deposit. Minimum pay zone is five feet thick.

Overburden thickness is from outcrop to 1,320 feet (0.25 mile) from outcrop. Variations shown emphasize importance of topography in evaluation of these deposits.

Source: Howard R. Ritzma, *Utah Geological and Mineralogical Survey Map 33, Sheet 2*, April 1973.

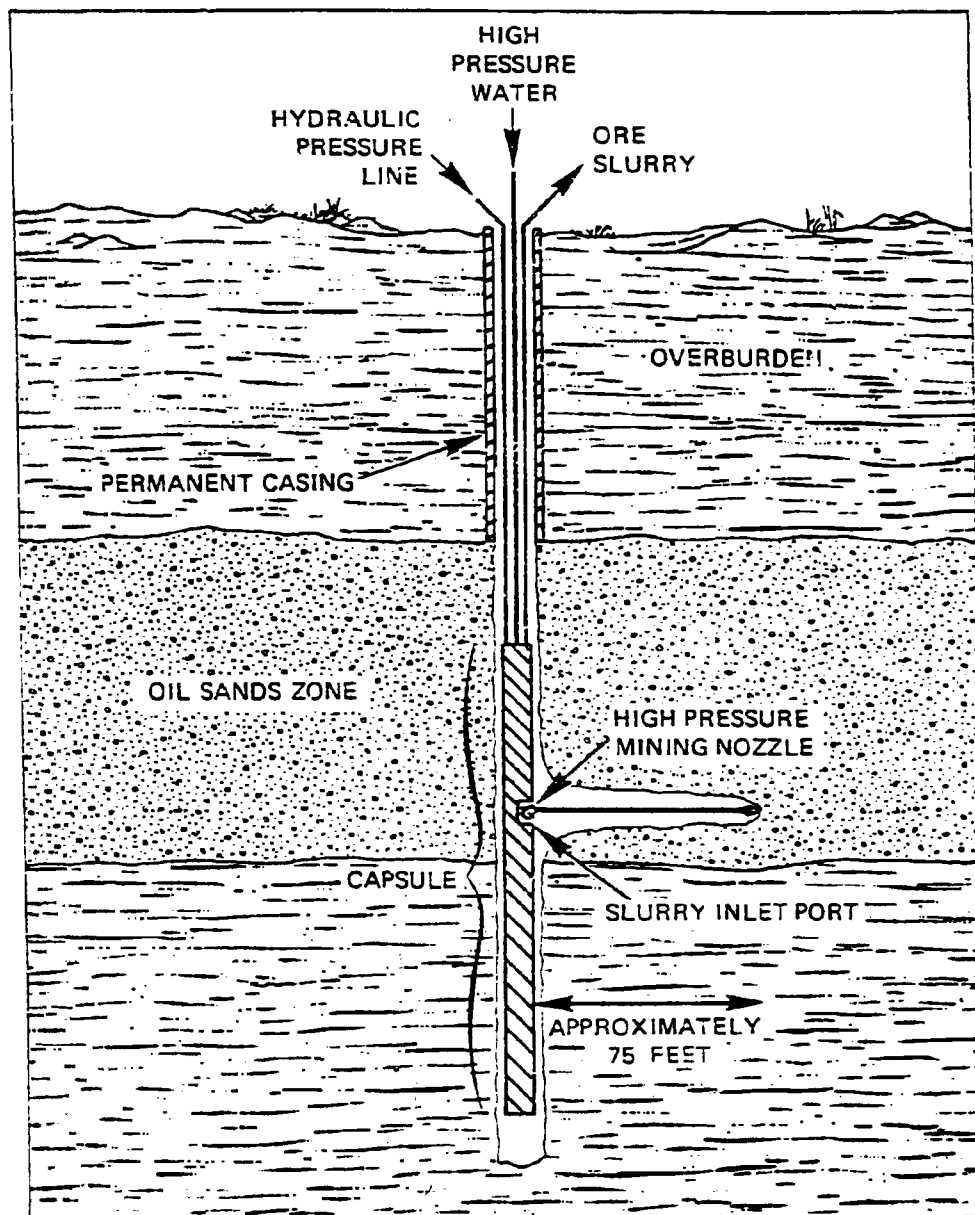
## EXTRACTION PROCESSES

## Hot Water Processes

Even though the hydrocarbon constituent of tar sand is visible and may even seep from the sand matrix at elevated temperatures, recovery of the oil product is not a simple or inexpensive process.

The only commercial above-ground extraction process actually in use is the K. A. Clark hot water process used by GCOS. A flow diagram of this technique is shown in

Figure VII-7. In the first step of the process, referred to as conditioning, the tar sands feed is heated and mixed with water to form a pulp of 60 to 85 percent solids at 180°-200° F. In the second step of the conditioning process, the pulp is mixed mechanically and reacted with sodium hydroxide. These steps take place in rotating conditioning drums. Upon leaving the drum, the conditioned slurry is screened to remove oversize lumps and water is added to form a pulp with the proper consist-



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-6. HYDRAULIC SLURRY MINING TECHNIQUE

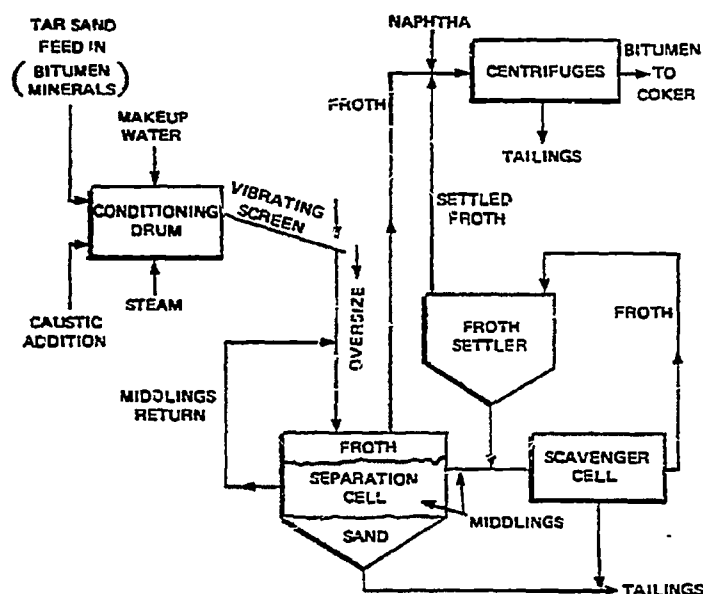
cy for the next processing steps.

The conditioned slurry is separated in a quiescent settling tank in which the sand settles to the bottom and the bitumen floats to the top. Wiper arms on the surface of the tank push the bitumen into overflow launders for collection while mechanical rakes in the bottom of the

tank move the sand outward for discharge. The Clark hot water extraction process has a recovery efficiency of 91 percent.

Another hot water extraction process is being tested in pilot facilities by Arizona Fuels Corporation/Burmah Oil at Vernal, Utah. A schematic of this process is shown in





Source: Schurr, S. H., "Energy Research Needs," Resources for the Future, Inc., October 1971.

Figure VII-7. GREAT CANADIAN OIL SANDS, LTD. (GCOS) PROCESS FOR BITUMEN RECOVERY FROM TAR SANDS

Figure VII-8. Tar sands feed is preheated in a furnace fired with No. 4 fuel oil or butane and then fed into the top of a 51-foot high tower. As it enters the tower, the ore mixes with hot recycle oil that breaks up agglomerated particles. Passing down through the column, the feed meets hot water flowing upward in the column. The bitumen is stripped from the sand and rises to the top of the water column where it is collected. The sand continues to settle to the bottom of the tower and is removed. While only a limited amount of shearing action is encountered by the tar sands feed, residence time in the tall column is long enough to cause separation.

#### Cold Water Processes

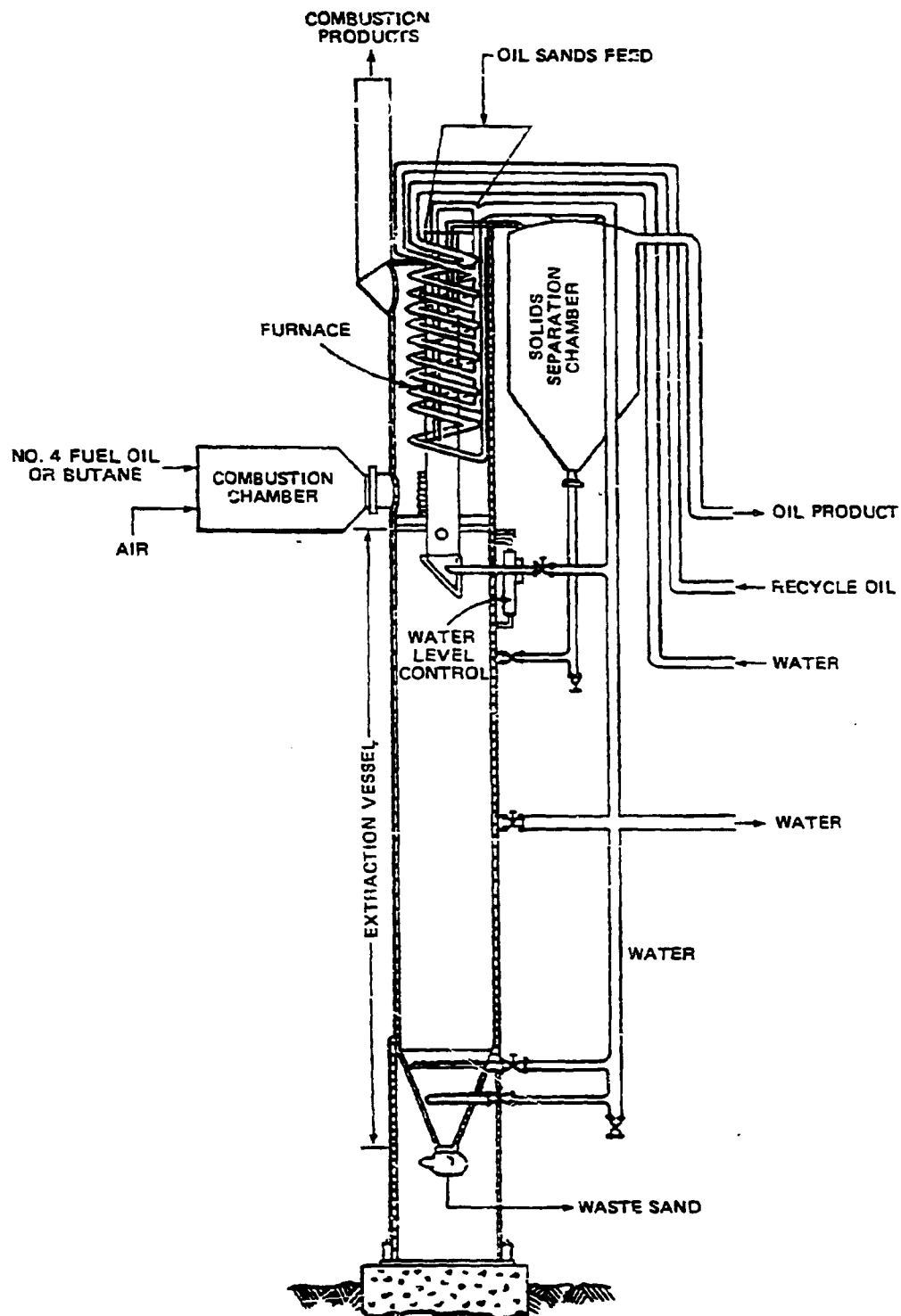
Because of the large energy required for hot water processes, much research has been performed on cold water separation techniques. One process, devised by the Mines Branch of the Canadian Department of Mines and Technical Surveys in 1949-50, uses both cold water and solvent, and was tested in a 200 pound per hour continuous pilot plant. This technique is shown schematically in Figure VII-9.

In the first stage, the tar sands feed is mixed with kerosene, water, soda ash, and a wetting agent in a pebble

mill containing roughly one-half pound of pebbles for each pound per hour of feed. The effluent from the pebble mill is then fed to an agitator, mixed with more water, and the bitumen is separated from the sand by shearing action. The bitumen and sand mixture is then separated further in a rake classifier, with the overflow from this unit further concentrated in a series of thickeners.

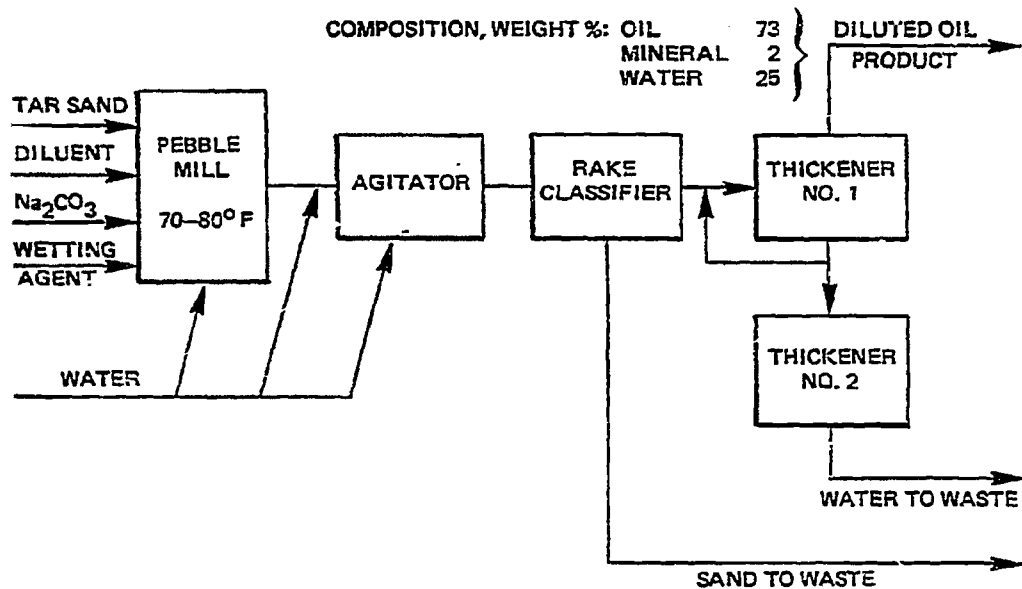
A second type of cold water process was developed by Imperial Oil Enterprises, Ltd., (Exxon). This technique is called the sand reduction process and uses cold water only, rather than water and a solvent. The primary objective of the process is not to produce a pure bitumen product but a bitumen-rich feed suitable for fluid coking operations. The sand reduction process is shown in Figure VII-10.

In the first step the tar sands feed is mixed with water in the ratio of about 0.75 ton water/ton tar sand. The mixture is then discharged to a 20-mesh rotary drum screen submerged in a water-filled vessel. The bitumen forms agglomerates which are returned by the screen and are collected from the bottom of the vessel. Meanwhile, the sand grains pass through the screen and are withdrawn as a waste stream. A third stream, primarily water and suspended minerals, is removed from the vessel and



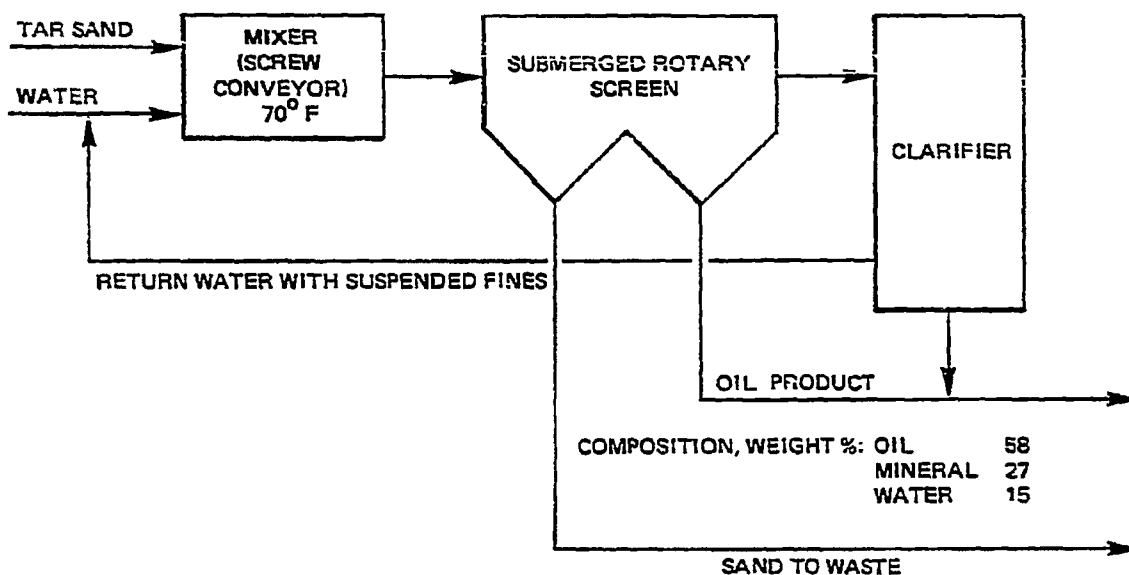
Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*,  
Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-8. ARIZONA FUELS EXTRACTION PROCESS



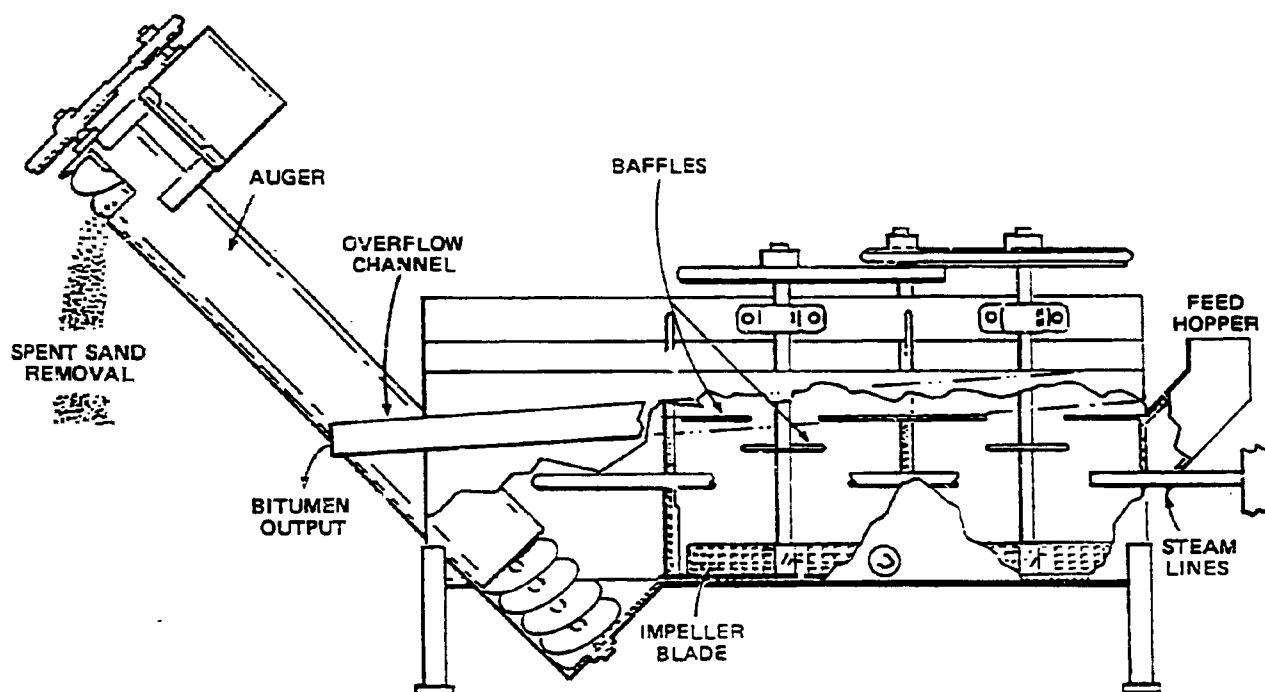
Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*,  
Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-9. COLD WATER SOLVENT RECOVERY PROCESS



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*,  
Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-10. SAND REDUCTION PROCESS



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems Corporation and Cameron Engineers, Inc. May 15, 1976.

Figure VII-11. MAJOR OIL COMPANY EXTRACTION PROCESS

further treated in a clarifier for additional bitumen recovery.

#### Solvent Extraction Processes

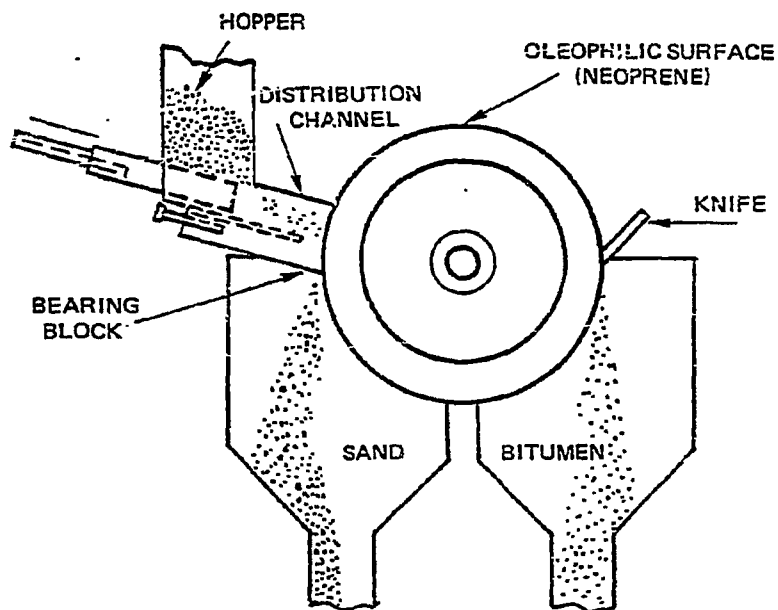
Many researchers have suggested bitumen extraction processes using light distillate solvents. Unlike the kerogen in oil shale, tar sands bitumen is soluble in light hydrocarbons such as benzene and diesel fuel, making solvent extraction a feasible mechanism. Indeed, bitumen recovery is usually very good, but solvent recovery presents a problem. Because solvents are usually valuable products in themselves, the loss of relatively small amounts of these materials in the waste sand can very likely offset the gains of recovering large quantities of raw bitumen. For this reason, the solvent recovery step is the key to the economic success of any solvent extraction process. Furthermore, disposal of waste sand containing hydrocarbons causes very serious environmental problems.

Some of the first work in solvent extraction was conducted by Cities Service Athabasca, Ltd., during 1959-61. The countercurrent solvent wash technique used by Cities Service demonstrated that if the solvent was reclaimed by steam stripping the waste sand, energy requirements were

excessive. If this step were not taken, however, solvent losses were so great as to reduce net bitumen recovery to only 19 percent (assuming product bitumen were used to generate makeup solvent).

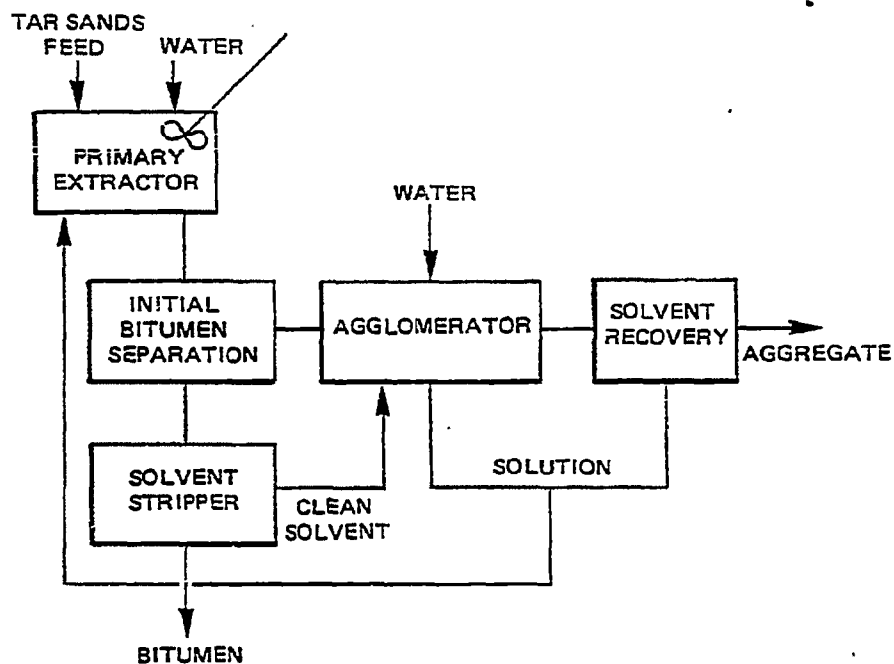
More recently, a solvent extraction process was pilot tested by Major Oil Company on tar sands from the Asphalt Ridge deposit near Vernal, Utah. The apparatus used in this test is shown in Figure VII-11. The pilot test was conducted in 1969 using a tank roughly eight feet long, divided into three chambers. The first two cells were separation cells and the third was a settling unit. Tar sands feed was mixed with a diluent such as kerosene, preheated to about 212° F, and fed into the bottom of the first separation cell. The feed was agitated with rotating impellers which also pushed the material into the second zone. Here it was agitated a second time and propelled into the quiescent settling zone. The bitumen was allowed to rise and was skimmed off. The clean sand was then withdrawn from the vessel by an auger. No allowance was made for solvent recovery from the waste sand.

Another solvent extraction process has been proposed by Guardian Chemical Corporation of Hauppauge, New York. The chemical known as Polycomplex A-11 produced by this firm for use in treating oil spills in water is



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-12. GRAY MECHANICAL SEPARATION PROCESS



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-13. SPHERICAL AGGLOMERATION PROCESS

used in the extraction process. Upon contact with oil, Polycomplex A-11 gradually diffuses into the oil and forms an intermolecular complex that is lighter than water, chemically stable, and considerably hydrophilic, or water attracting.

A low-concentrate solution of a modified form of Polycomplex A-11 is used in the tar sands extraction process. The solution is mixed with the raw sand and agitated at about 140° F. The mixture is then transferred to a settling zone. Because there is not enough Polycomplex to convert all the oil, the oil rises to the top of the tank and the sand drops out. The resulting water/Polycomplex solution is then recycled for extraction. Recovery efficiency of 95 percent is attainable from sands having 11.5 percent by weight bitumen content.

### Mechanical Extraction Processes

The only research that has been done on mechanical separation techniques has been conceptual; in some cases bench-scale processes have been tested.

One mechanical separation process has been patented by Frank and John Gray of Canada. Figure VII-12 illustrates the equipment and its operation. Tar sands feed is first transferred by a plunger mechanism from the feed hopper into a distribution channel. At the end of this channel, the tar sands contact a rotating drum having a surface composed of an oleophilic (oil-attracting) material.

The rotating surface picks up a thin layer of the feed material, the thickness of which is determined by the spacing between the drum and the distribution channel. Immediately below the feed outlet is an incised bearing block of neoprene rubber. The use of this block increases separation efficiency.

Wetted sand particles are continuously discharged from the mass on the rotating drum into the waste hopper. The bitumen-rich residue clings to the surface until it is scraped off by a knife and allowed to fall into the second hopper. The bench-scale apparatus which has been tested had a 5-inch diameter drum, which rotated at 2,500 rpm.

One of the most critical factors in the separation process is the consistency of the feed material. Not only must the mixture of sand, bitumen, clay, and water be uniform, but it must be of a consistency that will compact itself against the oleophilic surface. On a commercial scale, uniformity would be a very difficult constraint to meet, especially when working with U.S. tar sands.

### Spherical Agglomeration Extraction Process

Attention has been directed toward an extraction technique known as spherical agglomeration. The process, developed by Dr. Ira Puddington of the Research Council of Canada, is a combination chemical-mechanical treatment for the recovery of finely divided and suspended solids. The technique applied to tar sands processing is shown in Figure VII-13.

In the first step, raw tar sands is agitated in a tank containing kerosene. The hydrocarbons (bitumen) dissolve in the kerosene while the sand and other hydrophilic materials remain in suspension. The rotating system is then sprayed with water to preferentially wet the surfaces of the hydrophilic materials. When these particles collide during agitation, they adhere to one another due to the surface tension between the kerosene and the water. This repeated agglomeration leads to the formation of dense, spherical particle clusters. Once the spherical agglomerates reach the required size, they may be removed easily from the bitumen-rich solution.

## IN-SITU RECOVERY TECHNIQUES

A second technique for extracting the bitumen from tar sands is in-situ recovery, which completely processes the tar sands underground, removing only the valuable bitumen and leaving the sand matrix in place.

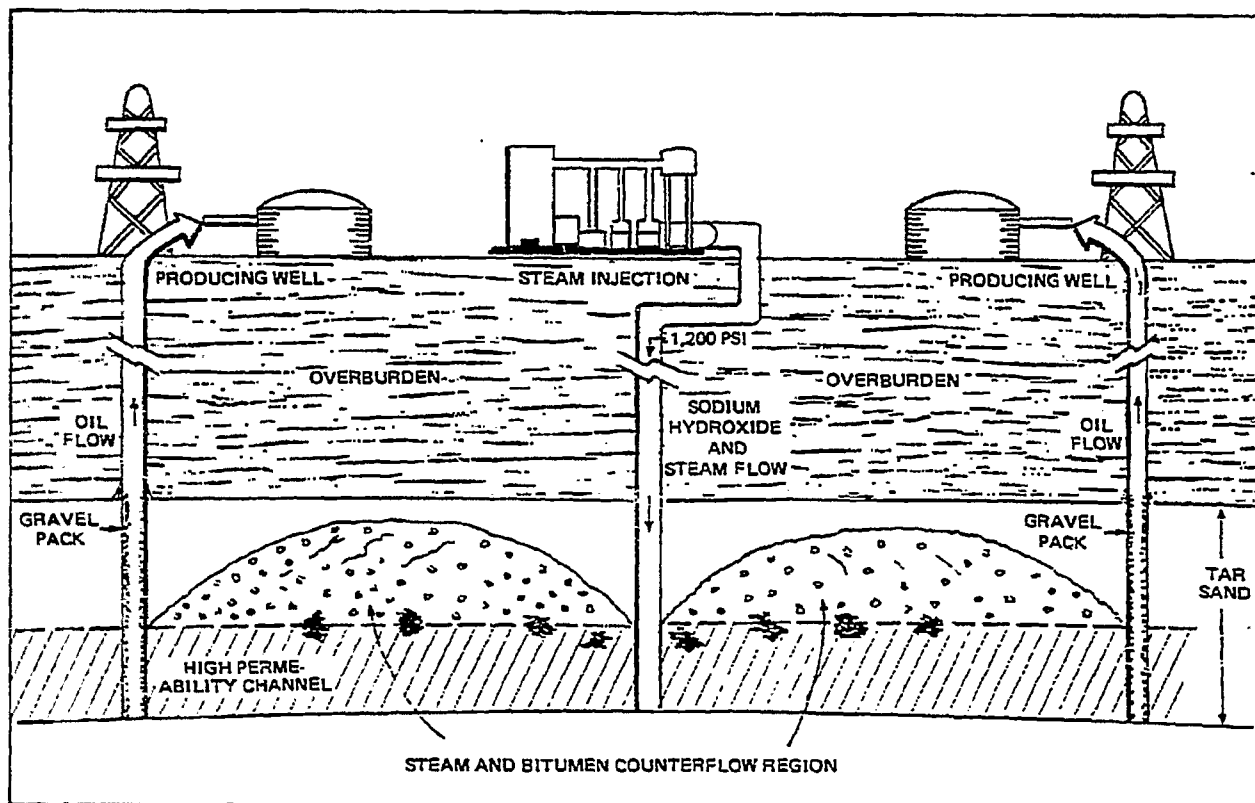
From a purely technical standpoint, in-situ recovery is a much more complex operation than above-ground processing. When the reactions take place far underground, monitoring and controlling them become monumental tasks. Even though handling of sand is eliminated, large quantities of recovery fluids must be pumped. Because

recovery rates are dependent on many unknown natural geologic characteristics, recovery efficiencies are usually much lower than those attainable above-ground where such conditions may be controlled. Therefore in-situ processing is unlikely to be any less expensive than above-ground processing.

From an environmental standpoint, the in-situ technique also has many drawbacks. Removal of bitumen can cause surface subsidence, and carcinogenic combustion by-products can eventually be leached into ground water and pollute water supplies. Using nuclear explosives for in-situ processing opens up more environmental dangers.

Even though in-situ processing is not any cheaper nor more environmentally acceptable than above-ground processing, in many instances it is the only recovery technique that can be used. Only 10 percent of U.S. and Canadian tar sands are recoverable by surface mining. Therefore, in order to make tar sands an important energy source, in-situ techniques or underground mining methods must be developed.

There are two types of in-situ processes: thermal stimulation and solvent extraction.



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*,  
Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1970.

Figure VII-14. SHELL CANADA IN-SITU RECOVERY PROCESS

### IN-SITU THERMAL STIMULATION

Thermal stimulation has been used by the conventional oil industry for many years as secondary and tertiary recovery methods in depleted oil reservoirs. The primary difference in tar sands applications is that the low gravity and high viscosity of bitumen require extremely high displacement pressures to initiate flow. Such processes are limited to deep deposits which have enough overburden to contain the high pressures.

#### Steam/Hot Water Process

Imperial Oil, Ltd. (Exxon) has investigated steam flooding, cyclic steam injection, gas injection, and in-situ combustion of Alberta tar sands.

In the cyclic steam injection technique, steam is periodically injected into the tar sands strata and oil is produced from the same well. As the steam is injected it lowers the viscosity of the bitumen around the well, thereby increasing the permeability. This increased permeability then allows the less viscous bitumen to be removed

from the well. Continued injection cycles expand the halo of permeability around each well until the halos of adjacent wells overlap and conventional steam flood may be used.

Great Plains Development Company (now a part of Norcen Resources, Ltd.) produced oil from Alberta oil sands during 1965 using the cyclic steam injection technique. The average porosity of the zone was 36 percent, with bitumen saturation of 65 percent of pore volume. The bitumen had an API gravity of 10 to 11 degrees. Injection of steam continued for six days at a rate of 1,400 barrels (as water) per day. Following a shut-in of 16 hours, production was maintained for five hours and then the well was pumped for 47 days yielding approximately 2,100 barrels of oil.

In a formation with communication established between adjacent wells, the steam flood process may be used. Steam is injected at one well site that forces bitumen ahead of it toward a production well. This process has been studied by Shell Canada at its Peace River test

site. Rather than using cyclic steam injection to achieve communication between wells, however, Shell used a steam soak process in which steam was constantly injected until breakthrough. This breakthrough required two years in a tar sands zone about 2,000 feet deep. While maintaining steam injection, backpressure was increased over a six-month period until the desired pressure of about 1,000 psi was obtained. The steam pressure was then maintained for about one and one-half years until the entire zone was heated. The pressure was then lowered to about 250-500 psi for a production period of about one and one-half years. Shell stated that this process was developed for use specifically in the geology in the Peace River deposit and would have to be changed if different geological conditions were encountered.

Tests using steam displacement, steam stimulation, and hot water injection have been conducted by BPOG Operations (British Petroleum) in the Cold Lake deposit of Alberta. The tests yielded about 44,000 barrels of bitumen, but required a water injection rate of 9.4 barrels of water per barrel of bitumen produced.

#### Steam and Bitumen Immiscible Process

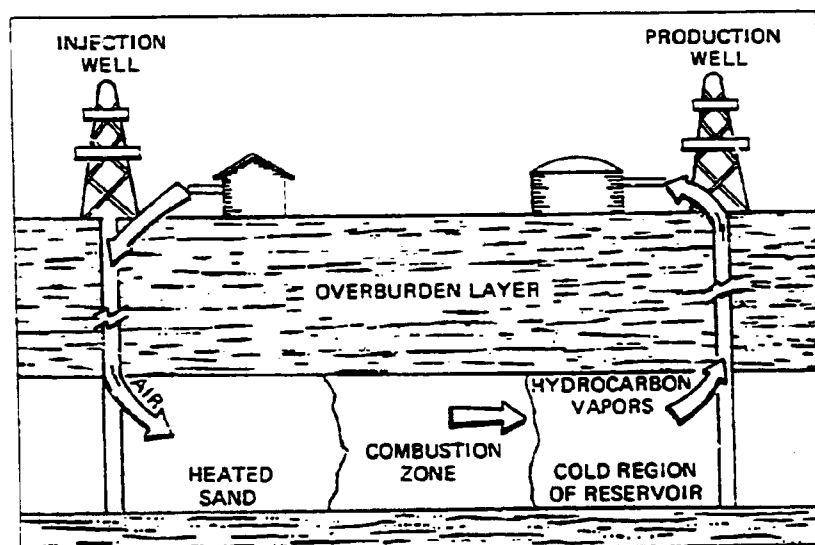
Between 1960 and 1962, Shell Canada conducted tar sands recovery tests in the Athabasca area based on injection of steam and sodium hydroxide. The tests showed

that horizontal fractures could be induced in the tar sands zone to create communication between injection and production wells. Once these fractures had been formed, emulsifying fluid was introduced into the formation. Figure VII-14 illustrates the process. According to Shell, 50-70 percent of the bitumen in place could be extracted with less than three barrels of water injected per barrel of bitumen produced.

The amount of steam injected per barrel of bitumen produced is very important. One barrel of water represents roughly 350,000 Btu as the latent heat of vaporization. Considering that raw bitumen has a heating value of only 6.24 million Btu per barrel, for Shell's 3:1 water to oil ratio, 17 percent of the heating value of the recovered bitumen would be required to heat the water for injection (assuming 100 percent efficiency of bitumen energy use).

#### Forward Combustion

In forward combustion some of the tar sands deposit is burned in order to recover the hydrocarbon product from the remainder. Figure VII-15 illustrates the technique. Combustion is started in the tar sands zone near the injection well and is maintained through continued injection of air. At first, bitumen is consumed in the combustion



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-15. FORWARD COMBUSTION PROCESS



tion process, but as the ore ahead of the combustion zone becomes heated, the bitumen will be driven toward the production well, leaving behind carbon residue and heavy ends as a fuel source for the combustion process.

This process is dependent on the natural permeability of the deposit to enable the vapors produced to be recovered at the production well. If this natural permeability is not adequate, it may be necessary to fracture the zone before ignition.

Regardless of the source of permeability, either natural or induced, it is vital that it be uniform throughout the vertical extent of the zone. If permeability is greater in one horizontal plane than another, the air injected will tend to create a path through that zone causing the combustion front to finger into the path rather than to progress uniformly through the zone.

Another problem with forward combustion is the plugging of pores as the hydrocarbon vapors pass through the cooler parts of the tar sands zone on the way to the production well. Even if the initial permeability of the zone were adequate to allow for the flow of vapors, condensing vapors may well plug these pathways and cause production to stop.

### Reverse Combustion

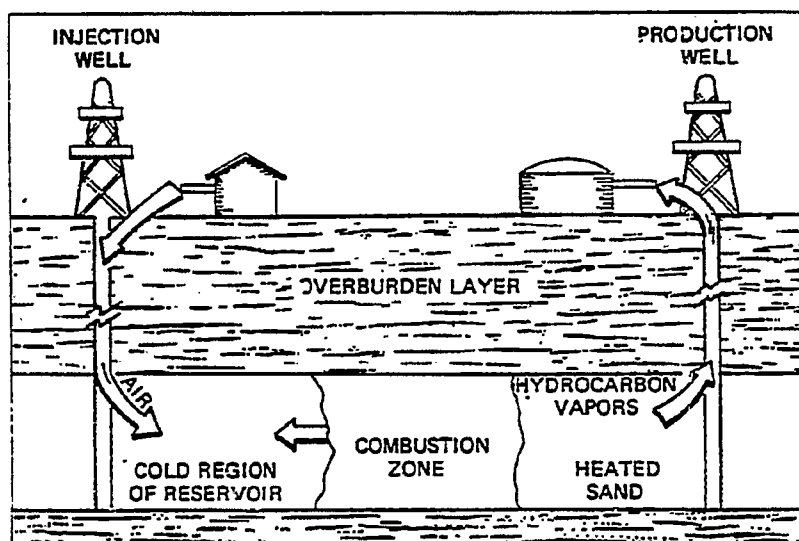
Reverse combustion is based on the same concept as forward combustion, except the combustion zone progresses from the production well to the injection well. Figure VII-16 illustrates this process. Because the hydrocarbon vapors which are produced pass through a heated

area on their way to the production well, plugging is minimized. Furthermore, some degree of thermal cracking occurs because of the high temperatures which the vapors encounter on the way to the production well, leading to the production of an upgraded product. The Laramie Energy Research Center (LERC) of ERDA recently conducted a pilot test of the reverse combustion process in the tar sands of Asphalt Ridge near Vernal, Utah.

### Combustion and Water Injection Combination Process

This combination in-situ process is commonly referred to as the COFCAW process (an acronym for Combination of Forward Combustion and Water-flood). This technique has been patented by Muskeg Oil Company, a Canadian subsidiary of Standard Oil of Indiana (Amoco).

The COFCAW process has been field tested by Amoco in the Gregoire Lake area of the Athabasca tar sands deposit. The first step in the process is fracturing of the formation to achieve communication between injection and production wells. Forward combustion is then started and maintained. After an initial heating period, water is injected along with the combustion air. As water vaporizes in the combustion zone it diffuses to the surrounding tar sands and heats them to approximately 200° F. At this temperature, the bitumen is less viscous and can be moved by the air-water drive to a production well. The Amoco tests indicated that if mechanical problems had not been encountered, recovery of in-place bitumen would have been close to 50 percent.



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-16. REVERSE COMBUSTION PROCESS

## IN-SITU SOLVENT EXTRACTION

Unlike kerogen, the hydrocarbon constituent in oil shale, the bitumen in tar sands is soluble in a variety of organic solvents. This property, along with the relatively high permeability of some zones, makes tar sands deposits targets for in-situ solvent extraction processes.

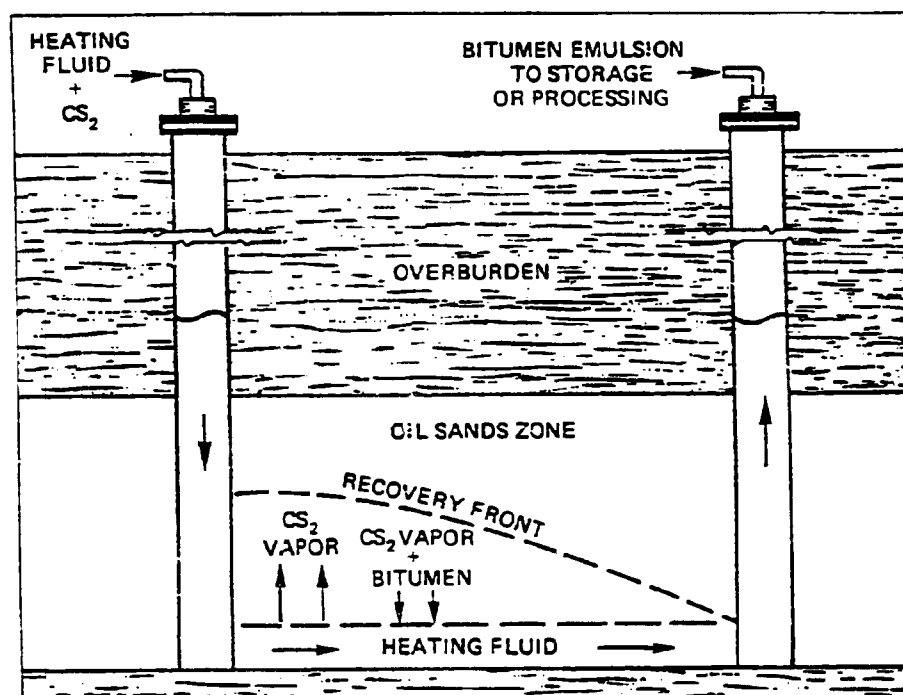
In in-situ solvent extraction processes, a solvent fluid is circulated through the impregnated zone. As bitumen is dissolved into the solvent, it is pumped to the surface. The permeability of the bitumen-free sand matrix then increases, providing passageways through which the solvent can flow to attack new areas of bitumen. Variations on this basic procedure may require heating the solvent or fracturing the impregnated zone.

Two of the many processes that have been devised for solvent extraction of tar sands were recently patented by Texaco. In the first process, two wells are drilled into the base of the tar sands zone, one an injection well and the other a production well. Communication between wells is established by fracturing. Hot water or steam is then injected and allowed to flow between the wells. A solvent such as carbon disulfide ( $\text{CS}_2$ ) is then injected along with the heating fluid. Since the boiling point of the  $\text{CS}_2$  is

less than the temperature of the heating fluid, the  $\text{CS}_2$  becomes vapor upon entering the impregnated zone, and diffuses into the tar sands zone, dissolving the bitumen. Once its temperature has been decreased, the  $\text{CS}_2$  condenses. As it drains back into the stream of heating fluid, it carries quantities of dissolved bitumen with it. Figure VII-17 illustrates this Texaco technique.

In another process patented by Texaco both surface mining and solvent extraction operations are used. After the overburden layer has been stripped off the tar sands zone, the pit is filled with water. Then carbon disulfide is injected into the tar sands zone immediately below the water. Carbon disulfide is used because it does not react with water and its density is greater than water.

As the solvent removes the bitumen from the sand matrix, the water from the pit above replaces it. As more  $\text{CS}_2$  is injected it contacts deeper levels of bitumen-rich sand. As the water level of the pond drops, more water is added to keep the cavity full. Once the bitumen has been removed, the cavity is pumped dry (except for the water remaining in the sand) and the pit is backfilled to minimize environmental damage.



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-17. SOLVENT EXTRACTION PROCESS  
PATENTED BY TEXACO

## BITUMEN PROCESSING

The bitumen extracted from tar sands is a very viscous black material having an API gravity between 4 and 15, a nitrogen content usually less than 1 percent by weight, and a sulfur content ranging from 0.3 to 5.5 percent by weight. A comparison of the properties of the bitumen extracted from U.S. tar sands and Canadian tar sands is presented in Table VII-6. An examination of this table indicates that the U.S. tar sands may have higher API gravities but less sulfur than Canadian tar sands. This heavy bitumen may be treated as a conventional heavy feedstock, allowing for the higher sulfur content.

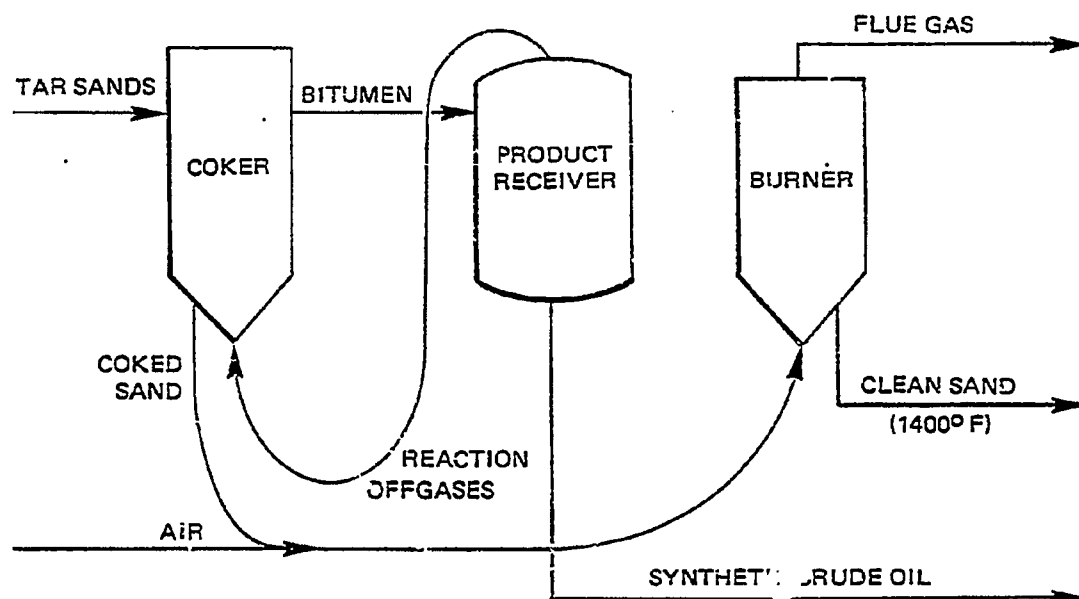
A summary of the status of leading tar sands projects appears in Table VII-7.

### Coking

Considerable research has been conducted on the feasibility of directly coking tar sands feed, a technology very similar to fluid catalytic cracking, already well proved in the conventional oil industry.

Tar sands are fed to a coker or still, operating at about 900° F. In the coker, the tar sands are heated by contact with a fluidized bed of clean sand from which the coke has been removed by burning. Volatile portions of the bitumen are distilled from the sand grains. Residual portions are thermally cracked, depositing a layer of coke around each sand grain. Coked solids are withdrawn from the coker down a standpipe, fluidized with air, and transferred to a second vessel.

This vessel, burner or regenerator, operates at about 1,400° F. In the regenerator most of the coke is burned from the sand grains, and the clean hot sand is withdrawn through a standpipe. Twenty to forty percent of the sand is rejected, and the rest is recirculated to the coker to provide heat for the coking reaction. Products leave the coker as a vapor, and are condensed in a product receiver. Reaction offgases from the receiver are recirculated to fluidize the clean, hot sand which is returned to the coker. Condensate from the product receiver forms heavy synthetic crude oil, the principal reaction product. (See Figure VII-18.)



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-18. PROCESS FOR DIRECT COKING OF TAR SANDS

Table VII-6  
PROPERTIES OF TAR SANDS

Property	United States	Canada
Porosity, percent	26-39	17-46
Permeability, air, md	10-3,800	0-600
Saturation, percent pore volume		
Oil	13-33	40-98
Water	23-82	1-39
Saturation, oil, weight percent	4-22	0-18
Viscosity, centipoise at formation temperature	$1.8 \times 10^3$ - $500 \times 10^3$	$3 \times 10^6$ - $600 \times 10^6$
Gravity, degree API	3.7-15.0	6-10
Sulfur, percent	0.5-4.2	3.7-5.0

Source: *The U.S. Energy Problem—Appendix S Technology of Alternative Fuels*, Intertechnology Corp., November 1971.

Table VII-7  
STATUS OF SELECTED TAR SANDS PROJECTS

Project/Company	Capacity (bbl/day)	Date Operational	Cost (dollars)	Status
Commercial				
AOP Group	122,500	Unknown	2 billion	ERCB approval granted
GCOS, Ltd.	50,000	Operational	—	\$3.5 million profit for last half of 1976
Home Oil/Alminex	103,000	1982	2.4 billion	Project shelved since 1974
Shell Canada, Ltd.	125,000	1980	—	Project shelved in 1976
Syncrude Canada, Ltd.	52,000	1980	2.048 billion	Plant 45 percent complete
	(initial)			
	104,000	1980		
	125,000	1980 + 16 mos.		
RD&D				
Arizona Fuels/Burmah Oil	200-1000	1976	3.0 million	Plant start-up
Amoco Canada/Aostr	8,000	Unknown	138 million	Unknown
Bingham Mechanical/Metal Products	2,500	1976	2.0 million	Production operations have started
Guardian Chemical Corp.	400 lb/hr	1976	1.0 million	100 tpd being conducted
Leming/Imperial Oil	5,000	1975	15 million	Unknown
Norcen Energy Resources	10,000	1981	20 million	Pre-production has started
NOMAC Oil and Gas	125,000	Unknown	20 million	Pre-production nearing completion
Shell Canada, Ltd.	Unknown	Unknown	58 million	Phase 1 only
Union Texas of Canada	1,000	Unknown	Unknown	Producing 200 B/D

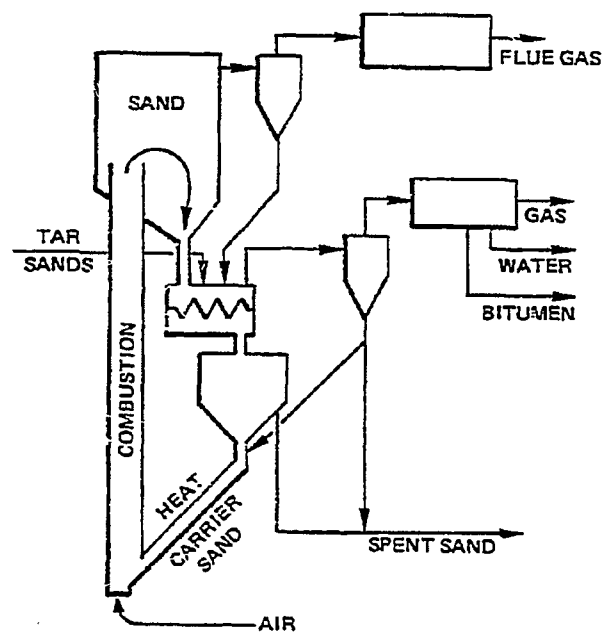
Source: *Synthetic Fuels*, September 1976.

American Lurgi has licensed the Lurgi-Ruhr gas process. A flow diagram of this direct coking process is shown in Figure VII-19. Tar sands feed is mixed with recycled sand in the screw mechanism. The gases given off by the decomposition reactions are sent to a separation system where water, gas, and bitumen products are collected. The waste sand is collected and some of it is recycled to a lift pipe in which the carbon residue is burned off and the sand is raised to a hopper for reinjection into the screw mechanism. All of the coke produced is consumed as a fuel, and in addition, some heavy ends from the product oil are used for energy.

### Hydrovisbreaking

Hydrovisbreaking is a term applied to a family of processes in which feed is heated, contacted with hydrogen, quenched, and distilled. Hydrovisbreaking is an extension of the visbreaking process in which heavy, long-chain hydrocarbon molecules are broken into shorter chains to produce a lighter material with a lower viscosity and pour point. This technique may be entirely thermal or a catalyst may be used.

Hydrovisbreaking adds hydrogen to the visbreaking process to saturate the broken chains. In addition, some degree of desulfurization is achieved by the chemical reaction between sulfur and hydrogen.



Source: *Assessment of Tar Sands as a Potential Source of Synthetic Military Fuels*, Applied Systems Corporation and Cameron Engineers, Inc., May 15, 1976.

Figure VII-19. LURGI-RUHRGAS PROCESS

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## INTRODUCTION

Natural gas is the cleanest of the fossil fuels and supplies roughly 30 percent of the nation's energy needs (Table VIII-1). Domestic natural gas production peaked in 1973 and has declined rapidly since then. U.S. natural gas production in 1976 averaged almost 10 percent less than three years ago. The finding rate (amount of gas dis-

covered versus number of feet drilled) has declined even faster. The United States produces 11.9 billion cubic feet per day, or about 43 percent of the world's and 57 percent of the free world's total production. U.S. reserves, however, represent only about 10 percent of the world's total.

Table VIII-1  
NATURAL GAS FACTS SHEET

Energy Content <sup>a</sup>	1032 Btu per cubic foot.
Proven U.S. Reserves (1976) <sup>b</sup>	220 trillion cubic feet (TCF). This stock constitutes a known inventory of natural gas stored underground against the time when the immediate needs of the industry require it to be brought to the surface.
Ultimate U.S. Resources <sup>c</sup>	530 TCF of ultimately discoverable resources.
U.S. Production (1976) <sup>d</sup>	20 TCF
Imports (1976) <sup>e</sup>	0.97 TCF (estimated)
U.S. Consumption (1976) <sup>e</sup>	19.5 TCF (estimated)
Contribution to Demand <sup>f</sup>	Natural gas supplied 28.4% of the 1976 U.S. energy demand.

<sup>a</sup>"Domestic Oil and Gas Availability", *U.S. Energy Outlook*, National Petroleum Council, pp. 57-133, December 1972.

<sup>b</sup>*Oil and Gas Journal*, 27 December 1976.

<sup>c</sup>National Academy of Sciences, 12 February 1975.

<sup>d</sup>*Oil and Gas Journal*, 24 January 1977.

<sup>e</sup>U.S. Bureau of Mines.

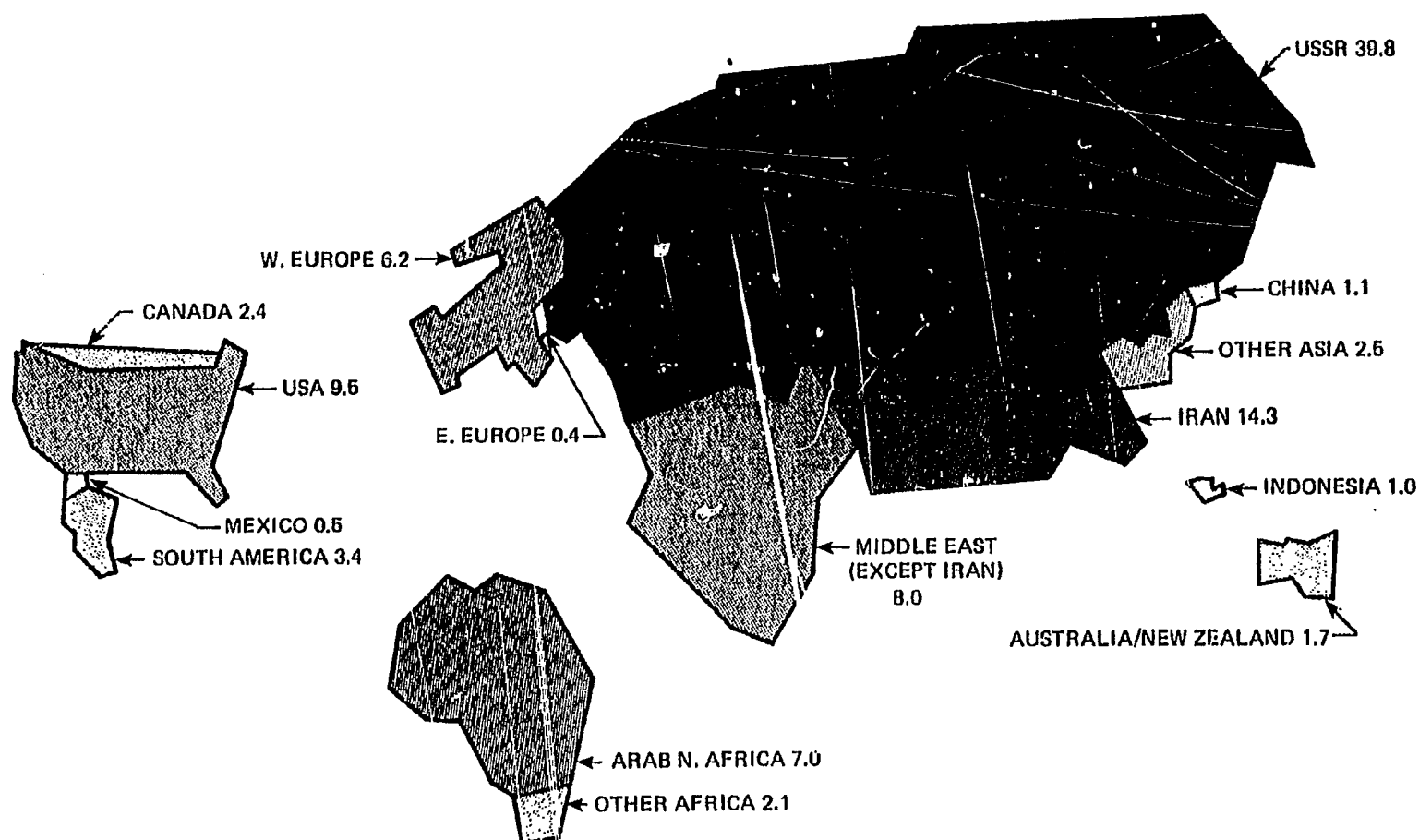
<sup>f</sup>Energy Research and Development Administration, 15 April 1976.

## WORLD SUPPLY OF NATURAL GAS

The world's natural gas reserves total an estimated 2,303.8 trillion cubic feet (TCF). The distribution of these reserves, by area and country, is shown in Table VIII-2 and Figure VII-1. The distribution of natural gas production is shown in Table VIII-3.

Estimates of ultimately recoverable natural gas resources, based on current technological and economic conditions, are given in Figure VII-2. Using these estimates and simplifying assumptions about consumption and production policies, theoretical gas exhaustion dates

can be calculated. Two possible consumption and production policies are shown on Figure VIII-3. The upper curve represents current production and consumption patterns and the lower curve represents a low-growth pattern where production and consumption are constrained. Figure VIII-3 indicates that exhaustion will take place between 2033 and 2075. If available resources prove to be only two-thirds of the estimate, then exhaustion will take place between 2022 and 2055.



World Aggregate: 409.6 Billion Barrels of Oil Equivalent

Note: Distortion of Map Reflects Percentage of Reserves.

Source: *Oil And Gas Journal*, December 27, 1978.

Figure VIII-1. WORLD PROVED NATURAL GAS RESERVES (PERCENT)



## U.S. CONSUMPTION AND SUPPLY OF NATURAL GAS

The United States consumes about 20 TCF of gas a year. Figure VIII-4 shows how this gas is used. The trend of annual consumption in the United States since 1900 is shown in Figure VIII-5.

Data on the U.S. natural gas supply and production for 1945 to 1976 are shown in Table VIII-4. Projections of the U.S. gas supply to 2000, developed by the U.S. Department of the Interior (DOI) and the National Petroleum Council, are given in Table VIII-5, and projections to 1990, developed by the Federal Power Commission

(FPC), are given in Table VIII-6.

DOI, the National Petroleum Council, and the FPC developed their projections, based on differing assumptions. DOI's forecast assumes that increasing prices paid for future imports of gas will result in substantial increases in the price of domestic gas. It is assumed that price increases sufficient to elicit the additional domestic supplies will be forthcoming and that these price increases will make supplemental supplies of LNG and synthetic gas economically feasible in some locations. Production of synthetic gas from coal depends on making certain mining techniques environmentally acceptable.

The National Petroleum Council developed its estimates for four cases:

- Case 1 (see Table VIII-5) assumes a high finding rate, a high growth in drilling rate, Alaskan North Slope production of gas by 1978, and an increase in average annual additions to reserves of 11 TCF/year to 26 TCF/year during the 1971-85 period.

Table VIII-2

**DISTRIBUTION OF WORLD  
NATURAL GAS RESERVES, 1976**

Area/ Country	Reserves (TCF)	Percent of World Total
North America	<u>288.0</u>	<u>12.5</u>
United States	220.0	9.5
Canada	56.0	2.4
Mexico	12.0	0.5
South America and Caribbean	<u>78.3</u>	<u>3.4</u>
Venezuela	40.7	1.8
Ecuador	12.0	0.5
Other	25.6	1.1
Middle East	<u>513.5</u>	<u>22.3</u>
Iran	330.0	14.3
Saudi Arabia	63.0	2.7
Iraq	27.0	1.2
Kuwait	31.7	1.4
Other	61.8	2.7
Europe	<u>141.9</u>	<u>6.2</u>
Netherlands	61.9	2.7
United Kingdom	30.0	1.3
Norway	18.5	0.8
Other	31.5	1.4
Africa	<u>209.1</u>	<u>9.1</u>
Algeria	125.8	5.5
Nigeria	44.0	1.9
Libya	25.8	1.1
Other	13.5	0.6
Asia-Pacific	<u>120.0</u>	<u>5.2</u>
Communist Countries	<u>953.0</u>	<u>41.4</u>
USSR	918.0	39.8
China	25.0	1.1
Other	10.0	0.4
World Total	<u>2,303.8</u>	<u>100.0</u>

Source: *Oil and Gas Journal*, 27 December 1976, pp. 104-105.

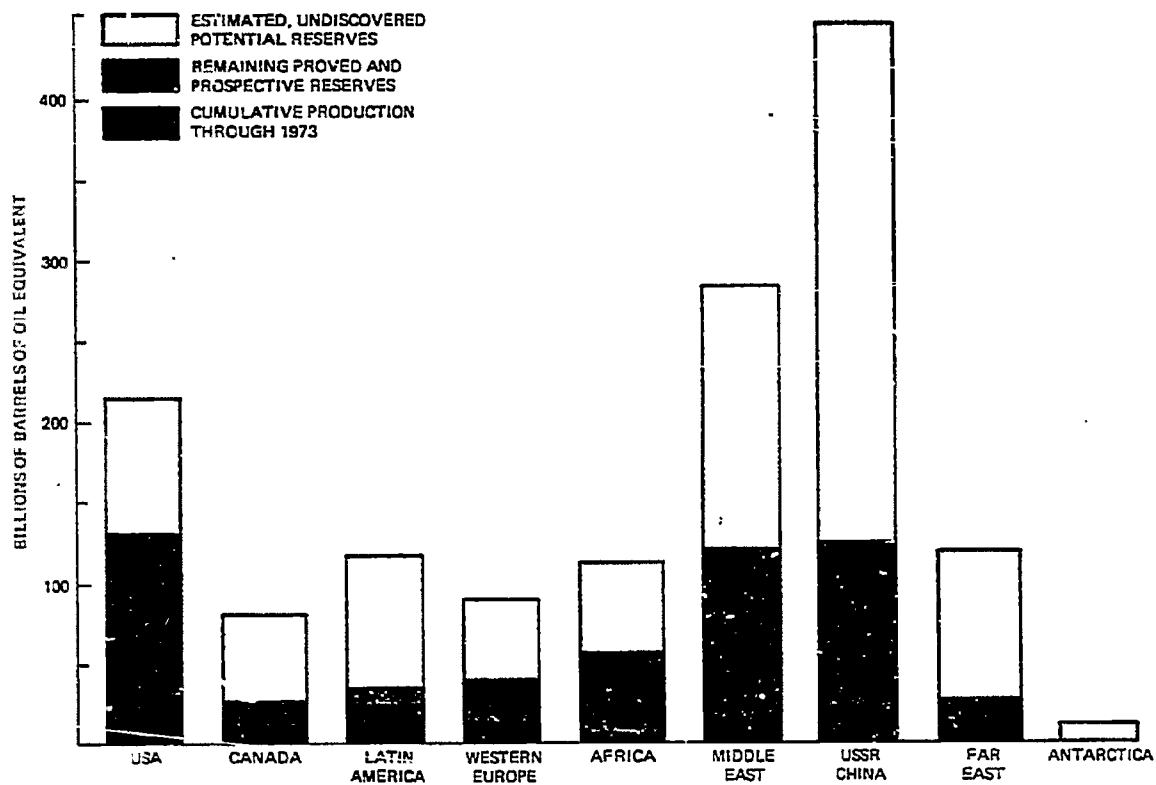
Table VIII-3

**DISTRIBUTION OF WORLD  
NATURAL GAS PRODUCTION, 1976<sup>a</sup>**

Area/ Country	Production (billions of cu. ft.)	Percent of World Total
North America	<u>23,951.4</u>	<u>47.4</u>
United States	20,021.7	39.6
Canada	3,140.3	6.2
Mexico	789.4	1.6
South America and Caribbean	<u>1,243.6</u>	<u>2.5</u>
Middle East	<u>2,091.3</u>	<u>4.1</u>
Iran	1,701.4	3.4
Other	389.9	0.7
Europe	<u>6,430.9</u>	<u>12.7</u>
Netherlands	3,639.0	7.2
United Kingdom	1,257.3	2.5
Other	1,514.6	3.0
Africa	<u>1,631.5</u>	<u>3.2</u>
Asia-Pacific	<u>966.7</u>	<u>1.9</u>
Communist Countries	<u>14,260.7</u>	<u>28.2</u>
USSR	11,244.7	22.2
Other	3,016.0	6.0
World Total	<u>50,576.1</u>	<u>100.0</u>

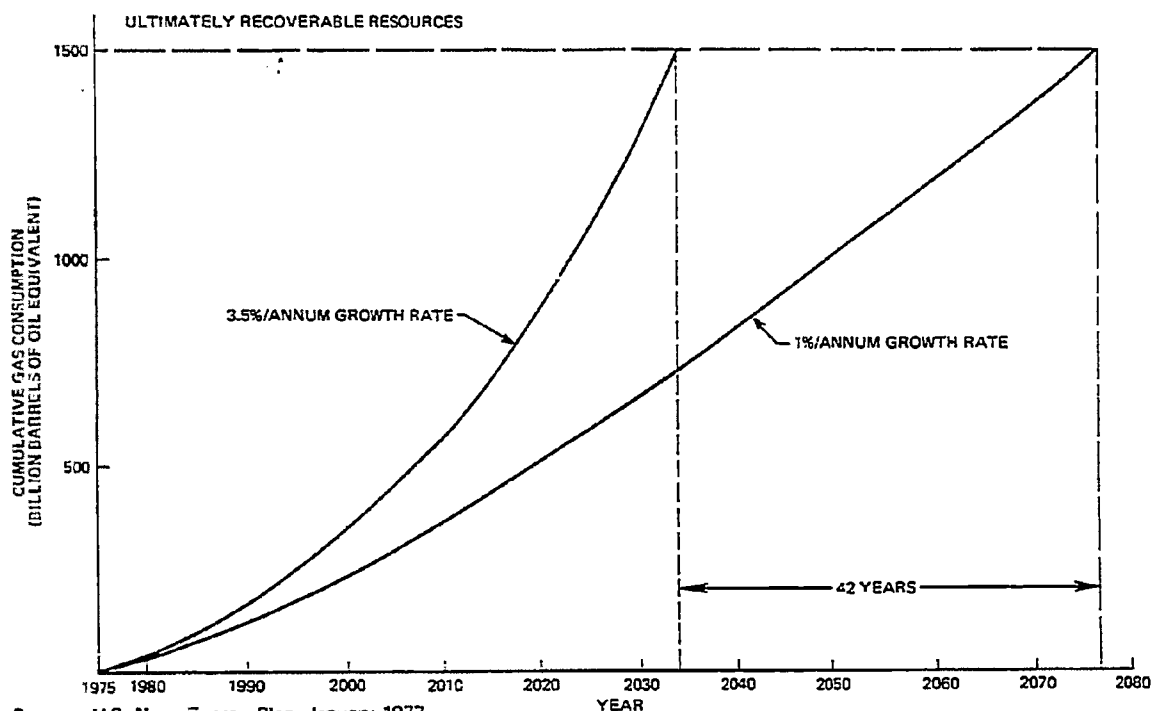
<sup>a</sup> Estimated.

Source: *Oil and Gas Journal*, 24 January 1977.



Source: U.S. Navy Energy Plan, January 1977

Figure VIII-2. ULTIMATELY RECOVERABLE NATURAL GAS



Source: U.S. Navy Energy Plan, January 1977

Figure VIII-3. WORLD NATURAL GAS EXHAUSTION

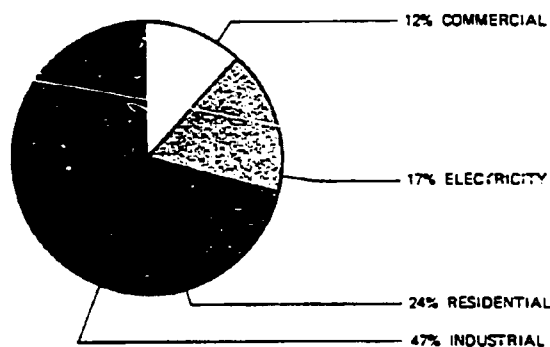
Table VIII-4

**TOTAL UNITED STATES NATURAL GAS SUPPLY AND PRODUCTION FOR 1945-1976**  
(TCF at 60° F and 14.73 psia)

Year	Annual Gross Additions to Proved Reserves	Cumulative Discoveries	Preliminary Annual Net Production	Cumulative Net Production	Proved Reserves	Gas in Underground Storage	Proved Reserves/Annual Production Ratio
1945	—	233.45	—	86.62	146.99	0.15	—
1946	17.63	251.09	4.92	91.54	159.70	0.15	32.46
1947	10.92	262.01	5.60	97.13	165.03	0.15	29.47
1948	13.82	275.83	5.98	103.11	172.93	0.20	28.92
1949	12.61	288.44	6.21	109.32	179.40	0.23	28.89
1950	11.99	300.42	6.86	116.18	184.58	0.34	26.91
1951	15.97	316.39	7.32	124.10	192.76	0.47	24.34
1952	14.27	330.65	8.59	132.69	198.63	0.67	23.12
1953	20.34	351.00	9.19	141.88	210.30	1.18	22.88
1954	9.55	360.54	9.38	151.26	210.56	1.27	22.45
1955	21.90	382.44	10.06	161.32	222.48	1.36	22.12
1956	24.72	407.16	10.85	172.17	236.48	1.49	21.80
1957	20.01	427.17	11.44	183.61	245.23	1.67	21.44
1958	18.90	446.06	11.42	195.03	252.76	1.73	22.13
1959	20.62	466.68	12.37	207.40	261.17	1.89	21.11
1960	13.89	480.56	13.02	220.42	262.33	2.17	20.15
1961	17.17	497.74	13.38	233.80	266.27	2.33	19.90
1962	19.48	517.23	13.64	247.44	272.28	2.49	19.96
1963	18.10	535.39	14.55	261.99	276.15	2.74	18.98
1964	20.25	555.64	15.35	277.33	281.25	2.94	18.32
1965	21.32	576.96	16.25	293.58	286.47	3.09	17.63
1966	20.22	597.18	17.49	311.08	289.33	3.22	16.54
1967	21.80	618.99	18.38	329.46	292.51	3.38	15.94
1968	13.70	632.69	19.37	348.83	287.35	3.49	14.83
1969	8.38	641.06	20.72	369.55	275.11	3.60	13.28
1970	37.20	678.26	21.96	391.51	290.75	4.00	13.24
1971	9.83	688.08	22.08	413.59	278.81	4.31	12.63
1972	9.63	697.72	22.51	436.10	266.08	4.47	11.82
1973	6.83	704.54	22.61	458.71	249.95	4.12	11.05
1974	8.68	713.22	21.32	480.03	237.13	3.94	11.12
1975	—	—	24.66	504.69	237.10	—	9.61
1976	—	—	23.95	528.64	220.00	—	9.19

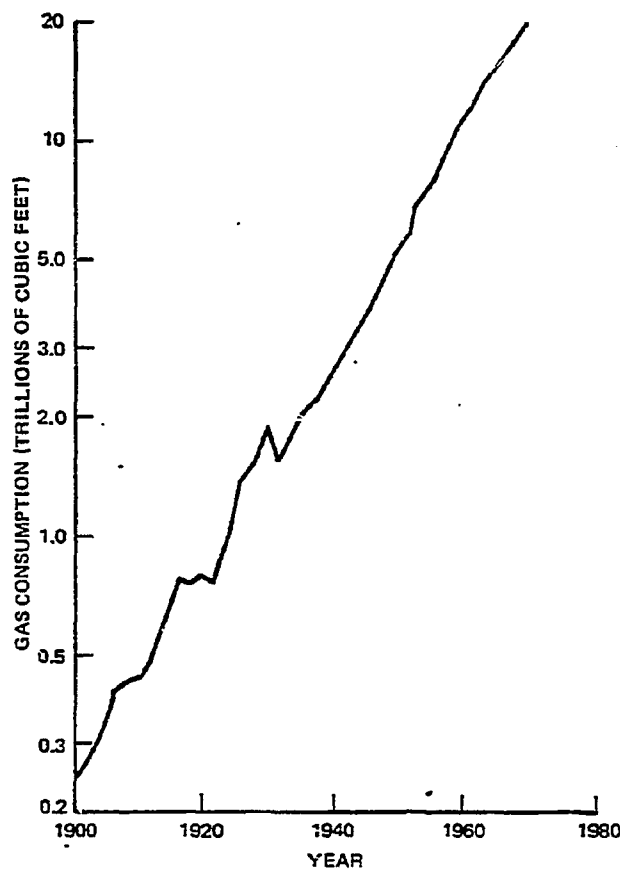
Note: The small inconsistencies between annual and cumulative discoveries and between annual and cumulative production are caused by rounding of values.

Sources: American Gas Association, July 15, 1975, and *Oil and Gas Journal*, 29 December 1975, 27 December 1976, and 24 January 1977.



Source: Federal Energy Administration, September 10, 1975.

Figure VIII-4. U.S. CONSUMPTION OF NATURAL GAS BY END USE



Source: Fuel and Energy Resources, 1972; Hearings Before the Committee on Interior and Insular Affairs, House of Representatives, April 12, 1972.

Figure VIII-5. ANNUAL CONSUMPTION OF NATURAL GAS

- Case II assumes a high finding rate, a medium growth in drilling rate, Alaskan North Slope production of gas by 1978, and an increase in average annual additions to reserves of 11 TCF/year to 21 TCF/year during the 1971-85 period.
- Case III assumes a low finding rate, a medium growth in drilling rate, Alaskan North Slope production of gas by 1978, and an increase in average annual additions to reserves of 11 TCF/year to 14 TCF/year during the 1971-1985 period.
- Case IV assumes a low finding rate, a continued current downtrend in drilling rate, Alaskan North Slope production of gas by 1983, and a decrease in average annual additions to reserves of 11 TCF/year to a 6 TCF/year during the 1971-1985 period.

Figures given for additions to reserves do not include Alaskan reserves of gas.

FPC also developed projections for four cases:

- Case I (see Table VIII-6) assumes that there will be little or no change from the current trends, with producers' prices held to \$0.25 to \$0.27/MCF through 1990, no development of Atlantic and Alaskan offshore areas, no gas from Alaska, only presently authorized imports, no gas from low-permeability reservoirs, and syngas only from coal and naphtha.
- Case II is conservative realistic, with prices rising from \$0.35/MCF in 1975 to \$0.58 in 1990, development of all offshore areas, available North Slope gas, additional pipeline imports, low production from

Table VIII-5

**DEPARTMENT OF INTERIOR AND NATIONAL  
PETROLEUM COUNCIL PROJECTIONS OF  
U.S. GAS SUPPLY, 1970-2000  
(Trillions of Cubic Feet)**

Source of Projection		Gas Supply Projections—Trillions of Cubic Feet				
		1970	1974	1980	1985	2000
Department of the Interior <sup>a</sup>			actual			
U.S. Production			20.84	18.68	18.21	16.53
Synthetic Gas			0	0.12	0.50	4.67
Pipeline Imports	(N/A)		0.94	0.80	0.70	1.00
LNG Imports			0	0.30	0.60	1.50
Total			21.78	20.10	20.01	23.70
National Petroleum Council <sup>b</sup>						
Case I:	U.S. Production	21.69		26.12	31.92	
	Synthetic Gas (Coal)	0	(N/A)	0.50	2.20	(N/A)
	Pipeline Import	0.92		1.55	2.62	
	LNG Imports	0		2.23	3.10	
	Total	22.61		30.40	39.84	
Case II:	U.S. Production	21.69		24.37	27.28	
	Synthetic Gas (Coal)	0		0.32	1.17	
	Pipeline Imports	0.92	(N/A)	1.55	2.62	(N/A)
	LNG Imports	0		2.23	3.29	
	Total	22.61		28.47	34.36	
Case III:	U.S. Production	21.69		20.49	21.20	
	Synthetic Gas (Coal)	0		0.32	1.17	
	Pipeline Imports	0.92	(N/A)	1.55	2.62	(N/A)
	LNG Imports	0		2.23	3.59	
	Total	22.61		24.59	28.58	
Case IV:	U.S. Production	21.69		17.35	14.99	
	Synthetic Gas (Coal)	0		0.16	0.48	
	Pipeline Imports	0.92	(N/A)	1.55	2.62	(N/A)
	LNG Imports	0		2.23	3.78	
	Total	22.61		21.29	21.87	

<sup>a</sup>U.S. Energy Through the Year 2000, U.S. Department of the Interior, p. 65, December 1975.

<sup>b</sup>U.S. Energy Outlook, National Petroleum Council, December 1972.

Table VIII-6

**FEDERAL POWER COMMISSION PROJECTIONS OF  
U.S. GAS SUPPLY, 1975-1990  
(Trillions of cubic feet)**

	Case I				Case II			
	1975	1980	1985	1990	1975	1980	1985	1990
Domestic Production	22.2	19.1	15.1	11.2	22.5	20.6	20.0	17.9
Syngas Production	0	0.2	0.7	1.2	0	0.3	1.1	2.2
Total U.S.	22.2	19.3	15.8	12.4	22.5	20.9	21.1	20.1
Imports	1.4	2.1	2.2	1.7	1.8	3.8	4.2	5.1
Total Supply	23.6	21.4	18.0	14.1	24.3	24.7	25.3	25.2
	Case III				Case IV			
	1975	1980	1985	1990	1975	1980	1985	1990
Domestic Productions	22.6	24.7	23.6	22.8	22.6	22.7	29.6	32.5
Syngas Production	0	0.4	1.3	3.0	0	0.6	1.9	5.1
Total U.S.	22.6	25.1	24.9	25.8	22.6	28.3	31.5	37.6
Imports	2.2	6.1	7.7	8.4	2.4	7.5	9.5	11.6
Total Supply	24.8	31.2	32.6	34.2	25.0	35.8	41.0	49.2

Source: *Future Domestic Natural Gas Supplies*, Federal Power Commission, June 1974.

low-permeability reservoirs after a five-year delay, and moderate development of a syngas industry with both foreign and domestic feedstocks.

- Case III is optimistic realistic, with prices rising from \$0.42 in 1975 to \$0.89 in 1990, availability of North Slope gas by 1979, substantial improvements in LNG and pipeline imports, low production from low-permeability reservoirs but with no production

delay, and development of syngas industry in line with industry forecasts.

- Case IV represents the maximum future supply that can reasonably be expected to be available from each source, including a price range assumption of \$0.50 in 1975 to \$1.21 in 1990. Under this case, supply will exceed FPC forecasts of future requirements.

## **DIRECTORY OF GAS INFORMATION SOURCES**

### **AMERICAN GAS ASSOCIATION LIBRARY**

1515 Wilson Boulevard  
Arlington, Virginia 22209

### **INSTITUTE OF GAS TECHNOLOGY**

Technical Information Services  
3424 South State Street  
Chicago, Illinois 60616  
Telephone: 312-225-9600 Ext 626

### **NATURAL GAS PROCESSORS ASSOCIATION**

808 Home Federal Building  
Tulsa, Oklahoma 74103  
Telephone: 918-582-5112

### **OFFICE OF OIL AND GAS**

U.S. Department of the Interior  
18th and C Streets, N.W.  
Washington, D.C. 20240  
Telephone: 202-343-3831

### **NATIONAL PETROLEUM COUNCIL**

1625 K Street, N.W.  
Washington, D.C. 20006  
Telephone: 202-393-6100

### **OFFICE OF MINERAL INFORMATION**

U.S. Bureau of Mines  
18th and C Streets, N.W.  
Washington, D.C. 20240  
Telephone: 202-343-4964

CHAPTER IX

COAL



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## INTRODUCTION

The most recent government estimates for U.S. coal resources remaining in the ground on January 1, 1974, are shown in Tables IX-1 and IX-2. The total, approximately 4 trillion tons, includes several categories according to degree of reliability of estimates.

In 1973, the United States contributed about 18 percent to total world coal production (3,288 million short tons); the USSR produced 22 percent, Europe, 14 per-

cent, and the Peoples' Republic of China, 14 percent.

According to data gathered at the 1974 World Energy Conference, the United States contains about 25 to 30 percent of the world's recoverable coal beds, although estimates could be greatly increased for Asia as more land areas in the Soviet Union and the Peoples' Republic of China are explored.

Table IX-1

### COAL FACTS SHEET

Classification <sup>a</sup>	Coals are classified as anthracite, bituminous, subbituminous, or lignite according to the amount of fixed carbon or calorific value	
Energy Content <sup>a</sup>	Lignite	12.6–15.6 million Btu per ton
	Subbituminous	16.6–23 million Btu per ton
	Bituminous	21–28 million Btu per ton
	Anthracite	> 25 million Btu per ton
Proven U.S. Reserves <sup>b</sup> (1974)	300 billion tons recoverable by underground mining methods 137 billion tons recoverable by surface mining methods 437 billion tons total	
Estimated U.S. Resources <sup>c</sup> (1974)	1734 billion tons mapped and explored 2238 billion tons unmapped and explored 3972 billion tons total	
U.S. Production <sup>d</sup> (1975)	640 million tons	
Exports <sup>d</sup> (1975)	65.7 million tons (including Canada)	
Imports <sup>d</sup> (1975)	0.9 million tons	
U.S. Consumption <sup>d</sup> (1975)	554.7 million tons	
Contribution to Demand <sup>e</sup>	Coal supplied 19.0 percent of the 1975 U.S. energy demand	

<sup>a</sup>"Standard Specification for Classification of Coals by Rank," ASTM Designation D388-66 (reapproved 1972), 1972 ASTM Standards—Part 19, pp. 54-58.

<sup>b</sup>"Demonstrated Coal Reserve Base of the United States, By Sulfur Category, on January 1, 1974," USDOl Bureau of Mines, May 1975.

<sup>c</sup>U.S. Geological Survey Bulletin No. 1412, 1975.

<sup>d</sup>Mineral Industry Surveys, USDOl Bureau of Mines, April 9, 1976.

<sup>e</sup>Status of the Mineral Industries, USDOl Bureau of Mines, 1976.

**TOTAL ESTIMATED REMAINING COAL RESOURCES OF THE UNITED STATES, JANUARY 1, 1974**

State	Overburden 0-3,000 feet					Overburden 3,000-8,000 feet		Overburden 8,000 feet	
	Remaining Identified Resources, Jan. 1, 1974					Estimated Hypothetical Resources in Unmapped and Unexplored Areas <sup>1</sup>	Estimated Total Identified and Hypothetical Resources Remaining in the Ground	Estimated Additional Hypothetical Resources in Deeper Structural Basins <sup>1</sup>	Estimated Total Identified and Hypothetical Resources Remaining in the Ground
	Bituminous Coal	Subbituminous Coal	Lignite	Anthracite and Semi-anthracite	Total				
Alabama	13,262	0	2,000	0	15,262	20,000	35,262	6,000	41,262
Alaska	19,413	110,666	2	3	130,079	130,000	260,079	5,000	265,079
Arizona	21,234 <sup>4</sup>	4	0	0	21,234	0	21,234	0	21,234
Arkansas	1,038	0	350	428	2,416	4,000 <sup>5</sup>	6,416	0	6,416
Colorado	109,117	19,733	20	78	128,948	161,272	290,220	143,981	434,201
Georgia	24	0	0	0	24	60	84	0	84
Illinois	146,001	0	0	0	146,001	100,000	246,001	0	246,001
Indiana	32,868	0	0	0	32,868	22,000	54,868	0	54,868
Iowa	6,606	0	0	0	6,606	14,000	20,606	0	20,606
Kansas	18,668	0	6	0	18,674	4,000	22,674	0	22,674
Kentucky									
Eastern	28,226	0	0	0	28,226	24,000	52,226	0	52,226
Western	36,120	0	0	0	36,120	28,000	64,120	0	64,120
Maryland	1,162	0	0	0	1,162	400	1,562	0	1,562
Michigan	296	0	0	0	296	600	896	0	896
Missouri	31,184	0	0	0	31,184	17,489	48,673	0	48,673
Montana	2,299	176,810	112,521	0	291,630	180,000	471,630	0	471,630
New Mexico	10,748	60,039	0	4	70,791	66,666 <sup>7</sup>	137,457	74,000	211,457
North Carolina	110	0	0	0	110	20	130	6	136
North Dakota	0	0	360,602	0	360,602	180,000	540,602	0	540,602
Ohio	41,166	0	0	0	41,166	6,162	47,328	0	47,328
Oklahoma	7,117	0	6	0	7,123	15,000	22,123	5,000 <sup>8</sup>	27,123
Oregon	60	284	0	0	344	100	444	0	444
Pennsylvania	63,940	0	0	18,812	82,752	4,000 <sup>9</sup>	86,752	3,600 <sup>10</sup>	90,352
South Dakota	0	0	2,186	0	2,186	1,000	3,186	0	3,186
Tennessee	2,630	0	0	0	2,630	2,000	4,630	0	4,630
Texas	6,048	0	10,293	0	16,341	112,100 <sup>11</sup>	128,441	11	128,452
Utah	23,186 <sup>12</sup>	173	0	0	23,359	22,000 <sup>13</sup>	45,359	35,000	80,359
Virginia	9,216	0	0	336	9,552	6,000	15,552	100	15,652
Washington	1,867	4,180	117	6	6,169	30,000	36,169	15,000	51,169
West Virginia	100,160	0	0	0	100,160	0	100,160	0	100,160
Wyoming	12,703	123,240	2	0	135,945	700,000	835,945	100,000	935,945
Other states <sup>14</sup>	610	32 <sup>16</sup>	46 <sup>16</sup>	0	688	1,000	1,688	0	1,688
<b>Total</b>	<b>747,367</b>	<b>486,766</b>	<b>478,134</b>	<b>10,862</b>	<b>1,735,000</b>	<b>1,849,049</b>	<b>3,584,088</b>	<b>387,086</b>	<b>3,971,135</b> <sup>17</sup>

Table IX-2

Table IX-2 (Cont'd)

Note: Estimates include beds of bituminous coal and anthracite generally 14 inches or more thick, and beds of subbituminous coal and lignite generally 2½ feet or more thick, to overburden depths of 3,000 and 8,000 feet. Figures are for resources in the ground.

<sup>1</sup>Source of estimates: Alabama, W. C. Culbertson; Arkansas, B. R. Haley; Colorado, Holt (1976); Illinois, M. E. Hopkins and J. A. Simon; Indiana, G. E. Wier; Iowa, E. R. Landis; Kentucky, K. J. Englund; Missouri, Robertson (1971, 1973); Montana, R. E. Matson; New Mexico, Fassett and Hinds (1971); North Dakota, R. A. Brant; Ohio, H. H. Collins and D. O. Johnson from data in Struble and others (1971); Oklahoma, S. A. Friedman; Oregon, R. S. Mason; Pennsylvania anthracite, Arndt and others (1968); Pennsylvania bituminous coal, W. E. Edmunds; Tennessee, E. T. Luther; Texas lignite, Kaiser (1974); Virginia, K. J. Englund; Utah, H. H. Doelling; Washington, H. M. Bulkman; Wyoming, N. M. Danson, G. B. Glass, W. R. Kaefer, and E. M. Schell; remaining States, by the author.

<sup>2</sup>Small resources of lignite included under subbituminous coal.

<sup>3</sup>Small resources of anthracite in the Bering River field believed to be too badly crushed and faulted to be economically recoverable (Barnes, 1961).

<sup>4</sup>All tonnage is in the Black Mesa field. Some coal in the Dakota Formation is near the rank boundary between bituminous and subbituminous coal. Does not include small resources of thin and impure coal in the Deer Creek and Pinodale fields.

<sup>5</sup>Lignite.

<sup>6</sup>Small resources of lignite in western Kansas and western Oklahoma in beds generally less than 30 inches thick.

<sup>7</sup>After Fassett and Hinds (1971), who reported 85,222 million tons "inferred by zone" to an overburden depth of 3,000 feet in the Fruitland Formation of the San Juan basin. Their figure has been reduced by 19,636 million tons as reported by Read and others (1960) for coal in all categories also to an overburden depth of 3,000 feet in the Fruitland Formation of the San Juan basin. The figure of Read and others was based on measured surface sections and is included in the identified tonnage recorded in Table IX-6.

<sup>8</sup>Includes 100 million tons inferred below 3,000 feet.

<sup>9</sup>Bituminous coal.

<sup>10</sup>Anthracite.

<sup>11</sup>Lignite, overburden 200–5,000 feet; identified and hypothetical resources undifferentiated. All beds assumed to be 2 feet thick, although many are thicker.

<sup>12</sup>Excludes coal in beds less than 4 feet thick.

<sup>13</sup>Includes coal in beds 14 inches or more thick, of which 16,000 million tons is in beds 4 feet or more thick.

<sup>14</sup>California, Idaho, Nebraska, and Nevada.

<sup>15</sup>California and Idaho.

<sup>16</sup>California, Idaho, Louisiana, and Mississippi.

<sup>17</sup>Four million short tons located not previously reported

Source: *Coal Sources of the United States, January 1, 1974*, U.S. Geological Survey Bulletin No. 1412.

## ASSESSING COAL RESOURCES

The estimates in the first five columns of Table IX-2, "remaining identified" resources, are based on factual information. All identified coal resources are further broken down into the "measured," "indicated" and "inferred" resource categories discussed below. The same information by coal basin appears in Table IX-3.

"Hypothetical resources" included in the last four columns of Table IX-2 are estimates of coal in the ground in unmapped and unexplored parts of known coal bases to an overburden of 6,000 feet. These estimates are determined by extrapolation from nearby areas of identified resources.

Approximately 44 percent of the total estimated remaining coal resources in the U.S. have been identified. At least 12.5 percent of these resources is considered economically recoverable, based on past recovery rates. Increased production by strip mining would increase this percentage since (1) strip-mined coal represents only 13 percent of past cumulative production and (2) average recoverability in strip mining is about 80 percent, while underground and auger mining average roughly 50 percent. Of the total identified resources, approximately 43 percent is bituminous coal, 91 percent is 1,000 feet or less below the surface, and 33 percent is in thick beds.

## DEMONSTRATED COAL RESERVE BASE

Figures IX-1 and IX-2 show the coal fields of the conterminous United States and Alaska.

The "demonstrated coal reserve base" shown in Tables IX-4 and IX-5 is a selected portion of the coal in the ground in the measured and indicated category as defined below. This demonstrated reserve base is restricted primarily to coal in thick and intermediate beds less than 1,000 feet below the surface that were deemed to be economically and legally available for mining at the time of the determination.

**Measured resources** — Tonnage of coal in the ground based on assured coal-bed correlations and on closely spaced observations about one-half mile apart. Computed tonnage judged to be accurate within 20 percent of the tonnage.

**Indicated resources** — Tonnage of coal in the ground based partly on specific observations (measured resources) and partly on reasonable geologic projection. The points of observation and measurement are about one mile apart for beds of known continuity.

**Demonstrated resources** — Combined tonnage in the measured and indicated resource categories.

**Inferred resources** — Tonnage of coal in the ground based on an assumed continuity of coal beds down-dip from and adjoining areas containing measured and indicated resources.

As shown in Table IX-4 and IX-5, about 46 percent of the reserve base coal contains less than 1 percent sulfur, and 84 percent of this low-sulfur coal is also of lower rank: it has been estimated that, on a calorific basis, only 10 to 15 percent (44 to 55 billion tons) of the nation's coal reserve base would be acceptable by present SO<sub>2</sub> pollution standards: 1.2 lb SO<sub>2</sub>/lb<sup>6</sup> Btu, without sulfur removal or gas scrubbing.

Details on the U.S. bituminous and lignite industry are provided in Tables IX-6 and IX-7; data on U.S. consumption of bituminous coal and lignite are given in Table IX-8, and coal consumption by sector, 1935-1972, is shown in Figure IX-3. Table IX-9 shows the U.S. coal production potential for 1985, assuming that imported oil costs \$13 per barrel. Table IX-10 shows reserves and resources of solid fossil fuels by nation.



Table IX-3

**IDENTIFIED COAL RESOURCES, JANUARY 1, 1974<sup>a</sup>**  
(Billions of Short Tons)

Basin or Region	Overburden 0-3,000 feet			
	Demonstrated Reserve Base, 0-1,000 ft Overburden <sup>b</sup> (from Table IX-1)		Resources in Thin Beds and Inferred Resources, 0-1,000 ft Overburden; and Identified Resources in All Beds 1,000-3,000 ft Overburden	Total Remaining Identified Resources (from Table IX-1 rounded)
	Tons	Percent		
Northern Appalachian basin (Pa., Ohio, W. Va., and Md.)	93	21	132	225
Southern Appalachian basin (eastern Ky., Va., Tenn., N.C., Ga., and Ala.)	20	5	36	56
Michigan basin	...	...	...	...
Illinois basin (Ill., Ind., and western Ky.)	89	20	126	215
Western interior basin (Iowa, Kansas, Mo., Okla., Ark., and Texas)	19	4	63	82
Northern Rocky Mountains (N. Dak., S. Dak., Mont., Wyo., and Idaho)	178	41	606	784
Southern Rocky Mountains (Colo., Utah, Ariz., and N. Mex.)	24	6	211	235
West Coast (Alaska, Wash., Oreg., and Calif.)	14	3	123	137
<b>Total</b>	<b>437</b>	<b>100</b>	<b>1,297</b>	<b>1,734</b>

Note: Leaders (...) indicate negligible amount of coal. Figures are for reserves and resources in the ground. At least half of the reserve base is recoverable.

<sup>a</sup>Includes coal reserve base and total remaining identified coal resources of the United States. The reserve base is a selected portion of the identified resources deemed to be suitable for mining by 1974 methods. The figures in the table are for coal in the ground. At least 50 percent of the coal in the ground is recoverable, and this portion is termed "reserves," as distinguished from the reserve base. To avoid any possible ambiguity, "reserves" may also be termed "recoverable reserves."

<sup>b</sup>Includes coal in the measured and indicated (demonstrated) category in beds 28 inches or more thick for bituminous coal and anthracite, and 5 feet or more thick for subbituminous coal and lignite. Maximum overburden is 1,000 feet for subbituminous coal, bituminous coal, and anthracite, and 120 feet for lignite. May include coal outside these parameters if such coal is being mined or is considered to be commercially minable (U.S. Bureau of Mines, 1974).

Source: *Coal Sources of the United States, January 1, 1974*, U.S. Geological Survey Bulletin No. 1412.

Table IX-4

**DEMONSTRATED SURFACE MINING COAL RESERVE BASE OF  
THE UNITED STATES, JANUARY 1, 1974<sup>a</sup>**  
(Millions of Tons)

State	Sulfur Content				
	≤ 1.0%	1.1-3.0%	> 3.0%	Unknown	Total <sup>b</sup>
Alabama	35.4	83.2	1.6	1,063.2	1,183.7
Alaska	7,377.6	21.0	0.0	0.0	7,399.0
Arizona	173.3	176.7	0.0	0.0	350.0
Arkansas	37.9	152.8	17.1	55.2	263.3
Colorado	724.2	146.2	0.0	0.0	870.0
Illinois	60.4	1,493.0	9,321.3	1,347.8	12,222.9
Indiana	105.3	559.2	907.3	101.6	1,674.1
Kansas	0.0	309.2	695.6	383.2	1,388.1
Kentucky, East	1,515.7	929.9	86.8	915.3	3,450.2
Kentucky, West	0.2	177.8	2,017.5	1,708.3	3,904.0
Maryland	28.6	66.6	16.2	34.6	146.3
Michigan	0.0	0.5	0.1	0.0	0.6
Missouri	0.0	47.8	1,635.8	1,730.0	3,413.7
Montana	38,182.4	2,175.2	46.4	2,166.7	42,561.9
New Mexico	1,681.0	579.3	0.0	0.0	2,258.3
North Carolina	0.0	0.0	0.0	0.4	0.4
North Dakota	5,389.0	10,325.4	263.7	15.0	16,003.0
Ohio	18.9	991.0	2,524.9	117.9	3,653.9
Oklahoma	120.5	88.1	38.8	186.2	434.1
Oregon	0.5	0.3	0.0	0.0	0.8
Pennsylvania	133.6	718.4	231.5	89.5	1,181.4
South Dakota	103.1	287.9	35.9	1.0	428.0
Tennessee	65.5	163.2	55.2	34.1	319.6
Texas	659.8	1,884.6	284.1	444.0	3,271.9
Utah	52.3	149.1	42.6	18.0	262.0
Virginia	411.6	218.1	2.1	46.7	579.2
Washington	172.5	307.7	25.8	2.2	508.1
West Virginia	3,005.5	1,422.8	270.4	509.6	5,212.0
Wyoming	13,192.8	10,122.3	425.5	105.3	23,845.3
Total <sup>b</sup>	73,252.3	33,597.4	18,950.9	11,076.1	136,885.7

<sup>a</sup>The reserve base is a selected portion of the identified resources deemed to be suitable for mining by 1974 methods. The figures in the table are for coal in the ground. At least 50 percent of the coal in the ground is recoverable, and this portion is termed "reserves," as distinguished from the reserve base. To avoid any possible ambiguity, "reserves" may also be termed "recoverable reserves."

<sup>b</sup>Data may not add to totals shown due to rounding.

Source: *Mineral Industry Surveys*, USDO, Bureau of Mines, May 1975.



Table IX-5

**DEMONSTRATED UNDERGROUND MINING COAL RESERVE  
BASE OF THE UNITED STATES, JANUARY 1, 1974<sup>a</sup>**  
(Millions of Tons)

State	Sulfur Content				
	≤ 1.0%	1.1-3.0%	> 3.0%	Unknown	Total <sup>b</sup>
Alabama	589.3	1,016.7	14.8	176.2	1,798.1
Alaska	4,080.8	163.2	0.0	0.0	4,246.4
Arkansas	43.3	310.3	29.2	19.1	402.4
Colorado	5,751.3	640.0	47.3	6,547.3	13,999.2
Georgia	0.3	0.0	0.0	0.2	0.5
Illinois	1,034.7	5,848.4	33,647.6	12,908.4	53,441.9
Indiana	443.5	2,746.6	4,355.1	1,402.5	8,948.5
Iowa	1.5	226.7	2,105.9	549.2	2,884.9
Kentucky, East	5,042.7	2,391.9	212.7	1,814.0	9,466.5
Kentucky, West	0.0	386.6	7,226.4	1,107.1	8,719.9
Maryland	106.5	623.9	171.2	0.0	901.9
Michigan	4.6	84.9	20.8	7.0	117.6
Missouri	0.0	134.2	3,590.2	2,350.5	6,073.6
Montana	63,464.2	1,939.8	456.2	0.0	65,834.3
New Mexico	1,894.3	214.1	0.9	27.5	2,126.5
North Carolina	0.0	0.0	0.8	31.3	31.3
Ohio	115.5	5,449.9	10,109.4	1,754.1	17,423.3
Oklahoma	154.5	238.5	202.6	264.3	860.1
Oregon	1.0	0.0	0.0	0	1.0
Pennsylvania	7,179.7	16,195.2	3,568.1	2,864.7	29,819.2
Tennessee	139.3	370.0	101.4	53.9	667.1
Utah	1,916.2	1,397.6	6.8	460.3	3,780.5
Virginia	1,728.5	945.4	12.0	283.3	2,970.7
Washington	431.0	957.8	13.2	42.9	1,445.9
West Virginia	11,086.6	12,583.4	6,552.9	4,142.9	34,377.8
Wyoming	20,719.5	4,535.1	1,275.6	2,955.0	29,490.8
Total <sup>b</sup>	126,928.8	59,400.2	73,720.2	39,761.6	299,839.7

<sup>a</sup>The reserve base is a selected portion of the identified resources deemed to be suitable for mining by 1974 methods. The figures in the table are for coal in the ground. At least 50 percent of the coal in the ground is recoverable, and this portion is termed "reserves," as distinguished from the reserve base. To avoid any possible ambiguity, "reserves" may also be termed "recoverable reserves."

<sup>b</sup>Data may not add to totals shown due to rounding.

Source: *Mineral Industry Surveys*, USDOl, Bureau of Mines, May 1975.

Table IX-6

**STATISTICS OF THE BITUMINOUS COAL AND  
LIGNITE INDUSTRY IN THE UNITED STATES**

	1971	1972	1973	1974	1975 Preliminary
Production (thousand short tons)	652,192	695,388	691,738	603,408	640,000
Value (thousands)	\$3,804,662	\$4,681,983	\$5,049,812	\$9,488,209	\$12,093,760
Consumption (thousand short tons)	494,862	518,778	558,022	652,709	664,749
Stocks at end of year:					
Industrial consumers and retail yards (thousand short tons)	89,985	118,500	103,022	95,520	127,159
Stocks on upper lake docks (thousand short tons)	1,205	939	822	1,051	1,185
Exports (thousand short tons)	66,033	65,697	62,803	69,928	65,889
Imports (thousand short tons)	111	47	127	2,080	840
Price indicators, average per net tons:					
Cost of coking coal at merchant coke ovens	\$15.28	\$17.67	\$10.77	\$34.20	\$40.00
Railroad freight charge <sup>a</sup>	\$3.70	\$3.67	\$3.71	4.71	\$5.25
Value F.O.B. mines (sold in open market)	\$8.68	\$7.35	\$8.07	\$15.13	\$18.20
Value F.O.B. mines	\$7.07	\$7.68	\$8.53	\$15.72	\$18.75
Method of Mining:					
Underground (total, in thousand short tons)	275,888	304,103	299,353	277,309	289,788
Cut by hand and shot from solid	4,700	4,188	4,288	4,947	4,800
Cut by cutting machine	111,693	113,768	107,024	91,480	98,000
Cut by continuous mining machines	162,943	178,375	178,600	171,287	178,588
Cut by longwall machines	8,552	7,763	8,442	9,574	10,400
Percentage mined by underground methods	60.0	51.1	50.6	48.0	45.3
Percentage mechanically loaded	98.2	99.0	99.3	99.7	99.7
Surface (total, in thousand short tons)	276,304	291,284	292,384	326,097	350,212
Percentage mined by surface methods	60.0	48.9	40.4	54.0	54.7
Mechanically cleaned (thousand short tons)	271,401	292,829	288,918	285,150	284,000
Percentage mechanically cleaned	49.1	49.2	48.8	43.9	41.3
Number of mines	5,149	4,879	4,744	5,247	5,100
Capacity at 235 days (thousand short tons)	618,000	622,000	613,000	653,458	692,000
Average number of men working daily: <sup>b</sup>					
Underground mines	109,311	112,252	111,083	119,418	140,000
Surface mines	38,353	37,013	37,038	47,285	54,550
<b>Total</b>	<b>145,664</b>	<b>149,265</b>	<b>148,121</b>	<b>166,701</b>	<b>194,550</b>
Average number of days worked:					
Underground mines	210	222	231	205	218
Surface mines	212	217	215	208	214
<b>Total</b>	<b>210</b>	<b>221</b>	<b>227</b>	<b>208</b>	<b>217</b>
Production per man per day: <sup>c</sup>					
Underground mines (short tons)	12.03	11.91	11.86	11.31	9.50
Surface mines (short tons)	35.88	36.33	38.67	33.18	30.00
<b>Total</b>	<b>18.02</b>	<b>17.74</b>	<b>17.58</b>	<b>17.58</b>	<b>15.15</b>

<sup>a</sup>Bureau of the Census, U.S. Department of Commerce.<sup>b</sup>Interstate Commerce Commission.<sup>c</sup>Estimates based on data supplied by Health and Safety Analysis Center, Mining Enforcement and Safety Administration.

Source: Mineral Industry Survey, USDOI, Bureau of Mines, Weekly Coal Report No. 3056, April 9, 1976

Table IX-7

**PRODUCTION AND AVERAGE MINE VALUE OF BITUMINOUS  
AND LIGNITE COAL, BY TYPE OF MINING, 1974**

State	Production by Type of Mining (thousand short tons)			Average F.O.B. Mine Value by Type of Mining (dollars)	
	Underground	Surface	All <sup>a</sup>	Underground	Surface
Alabama	7,053	12,771	19,824	30.30	17.09
Alaska	—	700	700	—	W
Arizona	—	6,448	6,448	—	W
Arkansas	—	455	455	—	21.28
Colorado	3,260	3,636	6,896	13.89	5.33
Illinois	31,256	26,960	58,216	11.12	8.70
Indiana	139	23,587	23,726	W	8.36
Iowa	379	211	590	W	9.15
Kansas	—	718	718	—	7.61
Kentucky	63,497	73,700	137,197	19.48	14.98
Maryland	90	2,247	2,337	W	20.79
Missouri	—	4,623	4,623	—	6.36
Montana	—	14,106	14,106	—	3.90
New Mexico	529	8,864	9,392	W	W
North Dakota	—	7,463	7,463	—	2.19
Ohio	14,365	31,044	45,409	13.70	11.68
Oklahoma	—	2,356	2,356	—	10.51
Pennsylvania	42,249	38,213	80,462	22.63	17.83
Tennessee	3,106	4,435	7,541	13.70	21.04
Texas	—	7,684	7,684	—	W
Utah	5,858	—	5,858	12.24	—
Virginia	22,767	11,559	34,326	25.87	23.11
Washington	15	3,698	3,913	28.70	W
West Virginia	82,220	20,242	102,462	21.76	21.21
Wyoming	526	20,177	20,703	10.19	4.88
Total	277,309	326,097	603,406	19.86	12.25

W = Withheld to avoid disclosing individual company confidential data.

<sup>a</sup> Data may not add to totals shown because of independent rounding.

Source: Mineral Industry Survey, USDOI, Bureau of Mines. Weekly Coal Report, November 21, 1975.

Table IX-8

**U.S. CONSUMPTION OF BITUMINOUS COAL AND  
LIGNITE, BY CONSUMER CLASS AND RETAIL DELIVERIES, 1976**  
(Thousands of Short Tons)

Month	Electric power utilities <sup>a</sup>	Bunker foreign and lake vessel <sup>b</sup>	Booth's coke plants	Oven coke plants	Steel and rolling mills <sup>c</sup>	Other manufacturing and mining industries <sup>d</sup>	Retail deliveries <sup>e</sup>	Total <sup>f</sup>
January	35,710	1	112	7,191	418	5,290	1,121	49,841
February	31,983	1	108	6,923	359	5,662	690	46,726
March	32,690	--	108	7,772	302	5,678	703	47,253
April	30,147	3	100	7,327	264	5,340	396	43,667
May	30,128	4	89	7,193	210	4,778	283	42,683
June	33,120	3	81	6,840	147	4,201	335	44,727
July	38,188	2	91	6,547	114	4,070	486	47,498
August	37,759	2	94	6,470	137	4,322	318	49,102
September	32,361	2	97	6,190	135	4,666	378	43,829
October	32,717	3	94	6,565	171	4,689	324	44,663
November	33,199	2	89	6,396	227	5,308	324	46,546
December	37,249	1	62	6,654	243	5,257	324	50,290
Total	403,249	24	1,125	82,068	2,715	59,759	5,682	554,622

<sup>a</sup> Federal Power Commission

<sup>b</sup> Bureau of the Census, U.S. Department of Commerce, Ore and Coal Exchange.

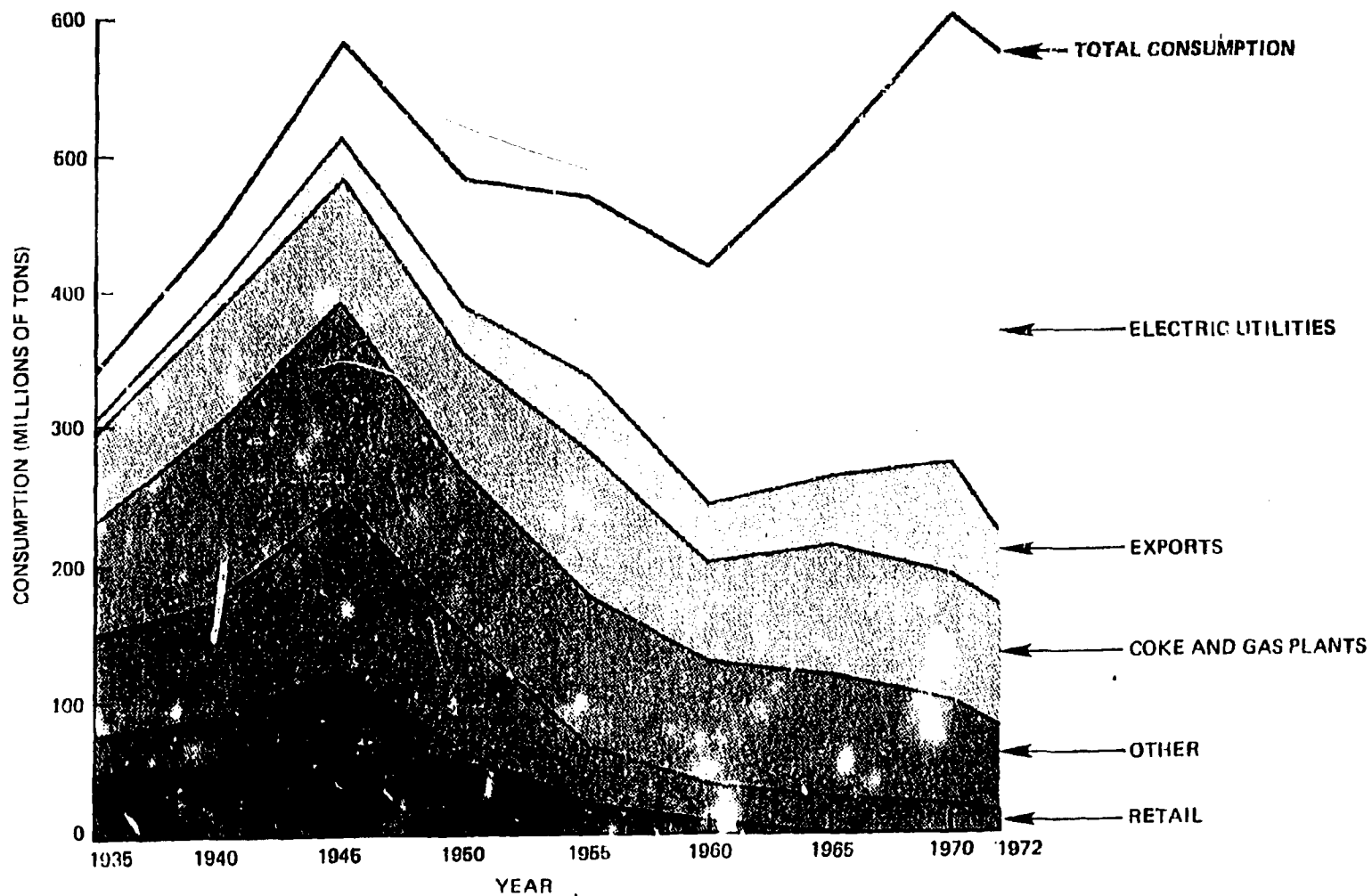
<sup>c</sup> Estimates based upon reports collected from a selected list of representative steel and rolling mills.

<sup>d</sup> Estimates based upon reports collected from a selected list of representative manufacturing plants.

<sup>e</sup> Estimates based upon reports collected from a selected list of representative retailers. Includes some coal shipped by truck from mine to final destination.

<sup>f</sup> The total of classes shown approximates total consumption. The calculation of consumption for production, imports, exports, and changes in stocks is not as accurate as the "Total of classes shown" because certain significant items of stocks are not included in monthly stocks. Those items are: Stocks on lake and tidewater docks, stocks at other intermediate storage piles between mine and consumer, and coal in transit.

Source: *Mineral Industry Survey*, USDO, Bureau of Mines, Weekly Coal Report No. 3080, May 7, 1976.



Source: *National Energy Outlook*, Federal Energy Administration, 1976.

Figure IX-3. COAL CONSUMPTION BY SECTOR, 1935-1972

Table IX-9

**U.S. COAL PRODUCTION POTENTIAL, 1985**  
(Millions of Tons)

Regions	Coal Type	1974	1985 BAU <sup>a</sup> Supply With Conservation	1985 Accelerated Supply With Conservation
Northern Appalachia	Metallurgical	12.9	20.3	20.3
	Low Sulfur	6.1	15.2	15.2
	High Sulfur	155.6	139.1	147.1
Central Appalachia	Metallurgical	87.8	100.7	100.7
	Low Sulfur	60.0	141.1	138.5
	High Sulfur	30.7	55.5	55.5
Southern Appalachia	Metallurgical	3.9	11.2	11.2
	Low Sulfur	5.8	8.5	8.1
	High Sulfur	9.8	5.6	5.6
Midwest	Low Sulfur	5.5	14.2	13.7
	High Sulfur	133.0	132.6	147.4
Central West	Metallurgical	9.9	—	—
	High Sulfur	7.9	9.3	10.9
Gulf	High Sulfur	7.7	20.6	25.3
Eastern Northern Great Plains	Low Sulfur	1.7	20.0	20.0
	High Sulfur	6.1	6.1	9.3
Western Northern Great Plains	Low Sulfur	2.1	213.8	220.4
	High Sulfur	32.2	21.9	25.1
Rockies	Metallurgical	6.1	6.1	6.1
	Low Sulfur	6.9	12.7	12.7
Southwest	Low Sulfur	1.2	7.7	7.7
	High Sulfur	14.8	8.3	10.8
Northwest	High Sulfur	4.9	1.0	2.6
Alaska	Low Sulfur	0.7	0.1	0.1
National	Metallurgical	111.6	138.3	138.3
	Low Sulfur	90.0	433.3	436.4
	High Sulfur	401.8	400.0	439.6
Total		603.4	971.6	1,014.3

<sup>a</sup>Business as usual.

Note: Production assumes imported oil will cost \$13/barrel.

Source: *National Energy Outlook*, Federal Energy Administration, February 1976, p. 207.

Table IX-10

**RESERVES AND RESOURCES OF SOLID FOSSIL  
FUELS, BY NATION**  
(Millions of Short Tons)

Nation	Reserves		Total Resources	Nation	Reserves		Total Resources
	Recoverable	Total			Recoverable	Total	
<b>Africa</b>				<b>Europe (Cont'd)</b>			
South Africa	11,642	26,646	48,773	East Germany	27,830	33,201	33,055
Rhodesia	1,529	1,936	7,274	Yugoslavia	18,577	19,774	23,926
Swaziland	2,002	2,224	5,524	Czechoslovakia	6,999	15,151	23,573
Zaire	792	792	792	Sweden	33	10,406	10,439
Botswana	557	557	557	Hungary	1,842	3,685	7,040
Mozambique	88	110	440	Bulgaria	4,826	4,826	5,753
Tanzania	198	340	407	Netherlands	2,024	4,076	4,076
Nigeria	248	494	494	Spain	1,807	2,422	3,911
Zambia	56	81	169	Iceland	—	2,200	2,200
Morocco	16	16	106	Romania	1,265	4,367	2,156
Malagasy	43	86	101	Greece	748	999	1,732
Malawi	—	—	42	France	504	1,548	1,548
Egypt	14	28	28	Denmark	22	617	639
Algeria	6	10	22	Ireland	460	464	493
Total Africa	17,191	33,320	64,728	Belgium	140	278	278
<b>Asia</b>				Austria	70	153	195
People's Rep. of China	88,000	330,000	1,100,000	Norway	2	2	167
India	12,738	25,476	91,275	Italy	36	121	121
Japan	1,129	9,491	9,491	Portugal	36	46	46
Turkey	2,228	3,182	8,010	Total Europe	144,612	401,663	718,176
Indonesia	3,394	2,335	2,786	<b>USSR</b>	150,260	300,520	6,284,960
Pakistan	189	884	2,135	<b>North America</b>			
Bangladesh	571	858	1,640	United States	199,959	399,918	3,216,953
North Korea	598	979	1,595	Canada	6,091	9,937	119,634
Taiwan	287	527	726	Mexico	692	5,848	13,200
Iran	212	424	424	Greenland	1	2	2
Burma	8	14	315	Total North America	206,743	415,705	3,349,789
Thailand	130	258	258	<b>Central and South America</b>			
Philippines	42	82	97	Peru	116	232	7,660
Afghanistan	—	—	94	Colombia	120	165	5,863
Vietnam	7	13	13	Chile	64	107	4,340
Total Asia	107,304	374,525	1,218,858	Brazil	1,969	3,582	3,582
<b>Oceania</b>	26,970	82,169	219,619	Venezuela	12	15	958
<b>Europe</b>				Argentina	110	171	611
West Germany	43,528	109,472	314,765	Honduras	—	—	6
United Kingdom	4,258	108,765	179,095	Total Central and South America	2,391	4,272	23,020
Poland	24,904	42,761	66,660				
Finland	4,719	36,300	36,300				

Source: Survey of World Energy Resources, World Energy Conference, 1974.

**CHAPTER X**

**COAL GASIFICATION**



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## INTRODUCTION

Gas manufactured from coal was first produced in the late 18th century by heating coal in the absence of air. The first coal-gas company, which distributed its product for lighting, was chartered in London in 1812; the first U.S. company was chartered in Baltimore in 1816.

"City gas" (carburetted water gas mixed with coal and coke-oven gas) had been the common source of fuel for cooking, domestic hot water, and street lighting in metropolitan centers for 150 years, until it began to be replaced by natural gas and electricity. City gas had a heating value of about 475 to 560 Btu per cubic foot (scf).<sup>1</sup> The substitution of natural gas, with a heating value of about 1,000 Btu per scf, permitted much more thermal energy to be supplied through the city-gas pipelines.

In the early days, synthetic gas was produced first by destructive distillation, that is, by heating the coal to a temperature at which it decomposed chemically. The gas produced had a heating value of about 550 Btu per scf. Subsequent to distillation, additional gas of lower heating value (300 Btu/scf) was produced by reacting the solid distillation residue (char) with air, steam, or mixtures of them. The heating value of the gas could be enriched further by spraying oil onto hot bricks, thus producing what is known as "carburetted blue gas" or "water gas."

Because the companies originally sold a coal gas with a heating value of about 550 Btu/scf, burners were designed to handle a gas of that quality. With burner designs fixed, manufactured gas, no matter how it was produced, was usually adjusted to that heating value.

The gas companies also manufactured a "producer gas" which was even cheaper than carburetted water gas. It had a heating value of 110 to 160 Btu/scf, which meant that it could not be widely distributed because the cost would be prohibitive. Producer gas served well, however, in industries that required a locally produced clean fuel for combustion or a source of heat for manufacturing.

Starting in about 1850 and continuing until World War II, the technology of making water gas and producer gas was improved steadily in the United States. After manufactured gas lost its markets in the United States, the technology was further improved in Europe, when coal was still the only indigenous fuel found in any significant quantity. New processes were investigated, taking advantage of technical advances in other fields such as the development of large-scale oxygen plants, new methods of handling solids in reactions with gas, and improved construction materials. At about the time the technology had reached a stage where plants could be installed, however, natural gas was discovered in the North Sea and in North Africa. In addition, most of the European nations decided to shift from an economy based on high-cost indigenous coal to one based on what was at the time low-cost imported petroleum. Few coal gasification plants embodying new technology were installed, and interest in further improving the technology lagged.<sup>2</sup>

<sup>1</sup>Standard cubic foot, that is a cubic foot of gas at standard temperature and pressure: 0° C and atmospheric pressure.

<sup>2</sup>Robert H. Perry and Cecil H. Chilton, *Chemical Engineers' Handbook*, pp 19-20, and *Evaluation of Coal Gasification Technology*, Office of Coal Research, p iv.

## CONVERTING COAL TO GAS

Because of recent energy shortages, the United States has renewed its interest in developing the technology that will permit rapid commercialization of processes for converting coal to low-, medium-, and high-Btu gas. Low-Btu gas, with a heating value of 100 to 250 Btu per scf, is the cheapest of the gaseous fuels produced from coal and can be used economically only on site, either as a fuel feedstock or for electric power generation in combined gas-steam turbines. On an equivalent-Btu basis, conversion of coal to low-Btu gas is less complex than conversion to high-Btu gas, and the capital costs are lower.

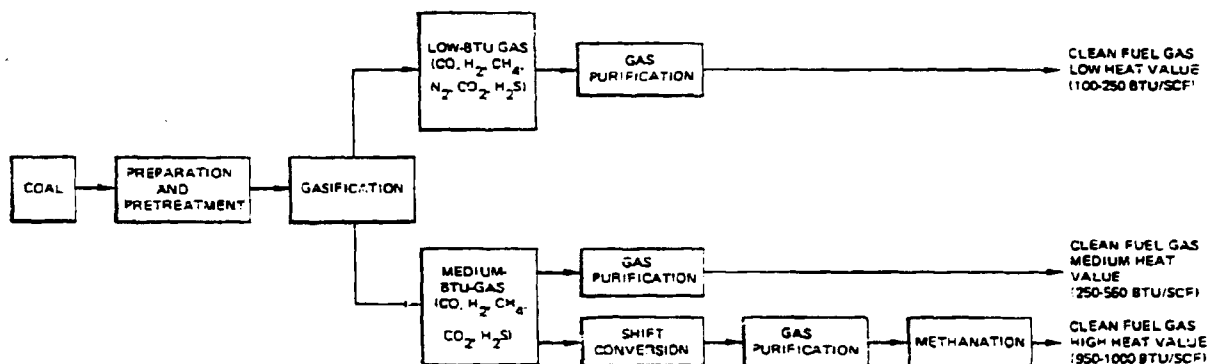
Medium-Btu gas (250 to 550 Btu per scf) is usually a feed gas for producing high-Btu gas.

High-Btu gas from coal, with a heating value of 950 to 1,000 Btu per scf, can be substituted for natural gas and can be distributed economically to consumers in the same pipelines now used to carry natural gas. Natural gas, a widely used heating fuel and industrial feedstock, is com-

posed essentially of methane and contains virtually no sulfur, carbon monoxide, or free hydrogen.

Converting coal to low-, medium-, or high-Btu gas requires a chemical and physical transformation of solid coal, a transformation made more difficult because coal's chemical and physical properties differ widely, depending on where the coal is mined. To find the most suitable techniques for gasifying coal, several conversion processes are being developed. A list of the major coal gasification processes and a brief description of each process and its development status are given in Table X-1. Although each process has unique characteristics, each requires five major steps to convert coal to gas: coal preparation and pretreatment, gasification, shift conversion, gas purification, and methanation. Figure X-1 is a generalized flow chart depicting these steps.<sup>1</sup>

<sup>1</sup>*Energy From Coal: A State-of-the-Art Review*, U.S. Energy Research and Development Administration, ERDA 76-67.



Source: Oil and Gas Journal, August 26, 1974.

Figure X-1. FUEL GAS FROM COAL

## COAL PREPARATION AND PRETREATMENT<sup>1</sup>

Two basic coal preparation methods are used: one for processes using batch reactors (such as Lurgi) and another for processes using fluidized-bed reactors. Batch reactors require a sized coal no larger than 2 inches and no smaller than 1/8 inch. This range is tightly controlled to achieve maximum gasifier output with minimum process difficulties from carry-over of fine coal particles into the gas stream. Fluidized-bed reactors require fine coal (less than 1/8 of an inch).

While standard coal preparation equipment is commercially available, crushing and screening techniques are being tested on the particular coal to be used for the gasification processes being developed. The test results will be used to improve engineering design and equipment selection.

If the rank or grade of the coal would cause caking or agglomeration in the gasifier, a pretreatment step is usually necessary. (Lignite, which does not agglomerate, requires no pretreatment before the gasification step. Certain gasifier reactor designs, such as the entrained-bed reactor and the free-fall reactor, also eliminate the need to pretreat bituminous coal.) Pretreatment of coal involves the partial volatilization and oxidation of the coal particle surface with steam and oxygen, a reaction that

results in a loss of a significant amount of potentially valuable volatile matter in the coal.

There are essentially three types of pretreaters: fixed bed, free fall, and fluidized bed. In fixed-bed pretreaters, the reaction temperature is about 800° F and the pressure, 325 psig. The units are pressurized by the steam-oxygen mixture.

In free-fall pretreaters, the reaction temperature is 1,100° F and the pressure is 300 psig. Coal is dropped through a countercurrent flow of steam containing 5 to 12 percent oxygen by volume; the residence time is approximately 2 seconds. The oxygen-to-coal ratio is about 2.4 scf per pound of coal. If the oxygen is insufficient or the reaction temperature is too low, the coal will agglomerate and plug the pretreater.

In fluidized-bed pretreaters, used to treat caking coal, oxygen mixes with steam or inert gases such as nitrogen and carbon dioxide. The reaction temperature is 700° F to 775° F.

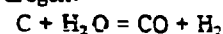
<sup>1</sup>Energy From Coal: A State-of-the-Art Review, U.S. Energy Research and Development Administration, ERDA 76-67, p VII-8, and Optimization of Coal Gasification Processes, Office of Coal Research, p 8.

## GASIFICATION

### Types of Process Reactions<sup>1</sup>

There are three major ways that coal can be converted to gas: gasification, hydrogasification, and pyrolysis.

Gasification is the reaction of coal or char with steam under pressure to produce a synthesis gas of carbon monoxide and hydrogen:



The oxidant may be oxygen, air, or oxygen-enriched air.

Thermodynamically, this reaction is highly endothermic. If the heat required is provided by direct coal oxidation, additional carbon monoxide and carbon dioxide are produced:

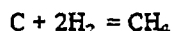


Indirect heating techniques typically use heat carriers, such as pebbles, molten salts, dolomite solids, or molten slag. Direct heating is more thermally efficient than is indirect heating, but the presence of carbon dioxide in the gasifier effluent when heating is direct requires more expensive purification systems.

Kinetically, the gasification reaction is favored at temperatures above 1,700° F, but is flexible with respect to operating pressure and product-gas composition. Control of the hydrocarbon, oxygen, and steam feed rates may yield a product that is as much as 96 percent H<sub>2</sub> by volume plus CO (heating value of about 300 Btu/scf) and small amounts of CO<sub>2</sub>, CH<sub>4</sub>, N<sub>2</sub>, and Ar (with some H<sub>2</sub> and COS if the feedstock contains sulfur). With air as the oxidant, there is a large concentration of nitrogen in the product gas.

The operating conditions and products of processes based on gasification reactions are shown in Table X-2.

Hydrogasification is the reaction of the carbon in coal with a stream of hydrogen-rich gas to form methane:



The reaction is exothermic, and is favored, kinetically, at high hydrogen partial pressures and at about 1,350° F. The coal particles go through a devolatilization stage when coming in contact with the hot gases in the reactor unit. Hydrogenation of coal is affected by the activity of the char produced by devolatilization. The reactivity of the particular coal or char used will also have a significant effect on the product gas quality and the reactor design. In hydrogasification reactors, the rate of conversion to methane (high heating value) is typically above 90 percent, compared to 70 percent or less in other reactors.

The operating conditions and products of processes based on hydrogasification reactions are shown in Table X-3.

Pyrolysis (also known as destructive distillation or devolatilization) is the vaporizing of volatile hydrocarbons from coal particles; volatile matter comprises more than 35 percent of the coal weight. In pyrolysis, coal is converted to gas, oil, char, and tar at high temperatures (above 1,000° F) and atmospheric pressure in a closed system with an oxygen-deficient environment. The amount of gas and oil produced by pyrolysis can be varied simply by changing the reaction temperature (high temperatures yield more gas and less oil) or the amount of moisture and the residence time. The product gas is

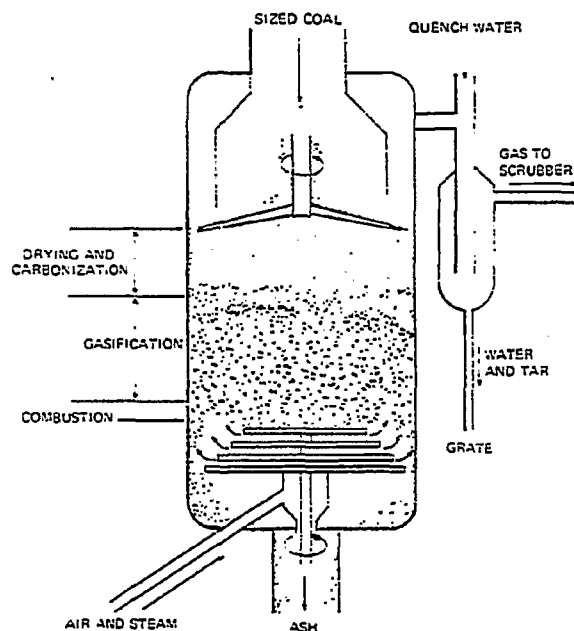
rich in methane and other higher hydrocarbons with a heating value of 475 to 560 Btu/scf.

The operating conditions and products of processes based on pyrolysis are shown in Table X-4.

## Types of Reactors<sup>2</sup>

Gasification, hydrogasification, and pyrolytic reactors for converting coal to gas are designed to control the mixing between chemical reactants, separate the product gases and by-products, and regulate temperatures. There are three major reactor types: fixed bed, fluidized bed, and entrained bed.

In a fixed-bed reactor (see Figure X-2), the gas velocity is relatively low and the solid particles remain stationary.



### MAJOR PROCESSES USING FIXED-BED REACTORS

LURGI GEGAS STIRRED, FIXED-BED (BUREAU OF MINES) WELLMAN-GALUSHA
---

Figure X-2. TYPICAL FIXED-BED REACTOR

<sup>1</sup> Optimization of Coal Gasification Processes, Office of Coal Research: Robert H. Perry and Cecil H. Chilton, *Chemical Engineers Handbook*, pp 19-20; and Considine, *Chemical Process Technology Encyclopedia*, p 549.

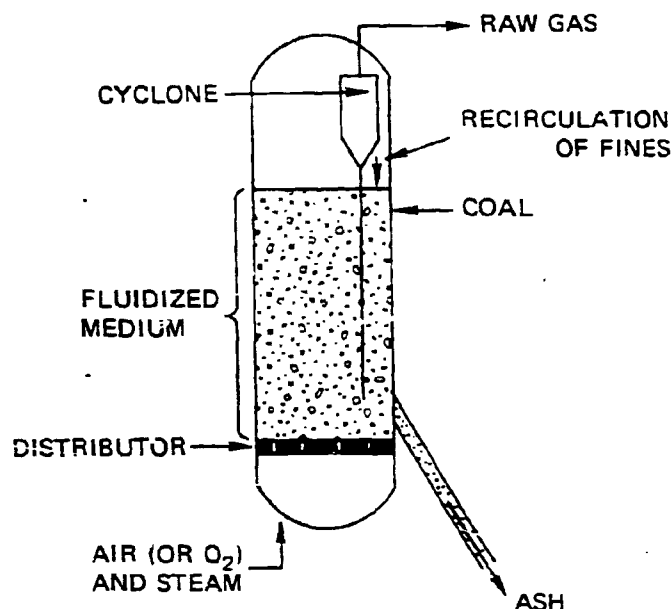
<sup>2</sup> Energy From Coal: A State-of-the-Art Review, U.S. Energy Research and Development Administration, ERDA 76-67, pp VII-12-17.

A metallic grid or grate, generally mounted a short distance above the bottom of the reactor, supports the coal. A rotating grate promotes an even distribution of the reacting gases and provides a means of drawing off the bottom of the bed. Continuous, fixed-bed reactors have been developed to permit continuous input of coal and reacting gases, and removal of ash. In dry ash gasifiers, which generally operate at 1,800° F, the ash is removed in solid form. Slagging gasifiers, in which ash is removed in liquid form, operate with an ash zone temperature of approximately 3,000° F to melt the slag. Slagging permits the gasification of lump coal at higher temperatures and offers better steam decomposition and higher throughput than nonslagging. However, high reaction temperatures tend to aggravate refractory erosion caused by the molten slag.

In the fluidized-bed reactor (Figure X-3), air or oxygen and steam enter at the base of the reactor and are forced up under pressure through the fine grid distributor plate that supports the pulverized or pretreated coal. Above the distributor plate, the gaseous medium passes between bed particles forcing them apart and opening larger pathways

through which to flow. The downward gravitational force on the particles becomes balanced by the upward drag force on the particles by the gaseous stream. Small particle sizes (8 to 100 mesh) are necessary to achieve this balance. At these sizes, the weight of the individual particles is reduced and gas stream pathways are reduced, which increases the drag force. Above the fluidized bed, there is a raw-gas zone, which is relatively free of particles. Here, fine particles ejected from the bed decelerate and return. An internal cyclone is usually used in the raw-gas zone to remove any entrained particles and return them to the bed. The temperature and composition of the bed are fairly uniform throughout because of the random motion of uniform particles in fluidized-bed reactors. Reaction zones operating at different temperatures, analogous to those in fixed-bed reactors, may be established by using a series of fluidized reactors.

Another type of fluidized-bed reactor is the molten bath reactor shown in Figure X-4. The molten bath provides a well-mixed medium in which combustion and gasification occur simultaneously. The molten medium which can be a salt such as sodium carbonate, provides



MAJOR PROCESSES USING FLUIDIZED-BED REACTORS	
SINGLE STAGE	TWO STAGE
SYNTHANE } WINKLER } DRY ASH U-GAS (ASH AGGLOMERATING)	SELF-AGGLOMERATING (BATTELLE) CO <sub>2</sub> ACCEPTOR ADVANCED SYSTEM (WESTINGHOUSE) COMBINED CYCLE (FOSTER WHEELER) HYGAS HYDRANE (LOWER STAGE)

Figure X-3. TYPICAL FLUIDIZED-BED REACTOR

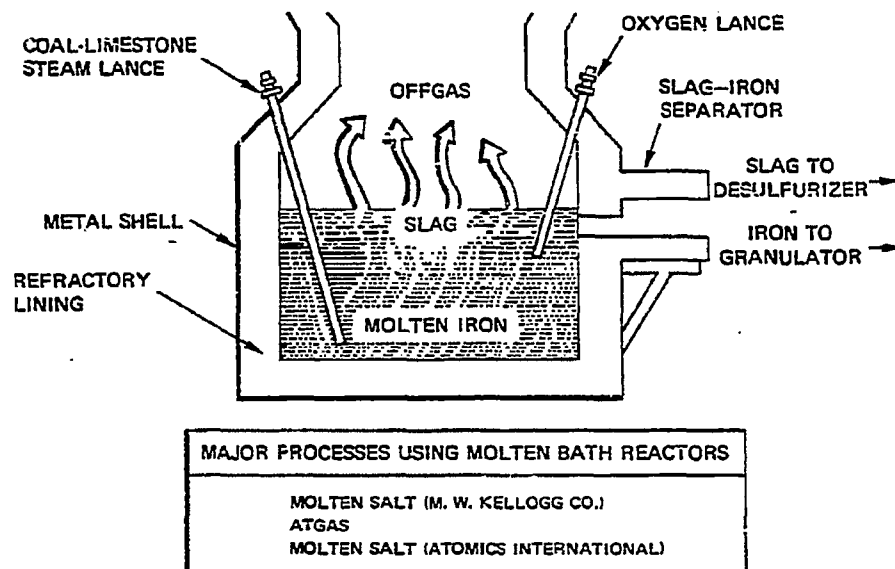
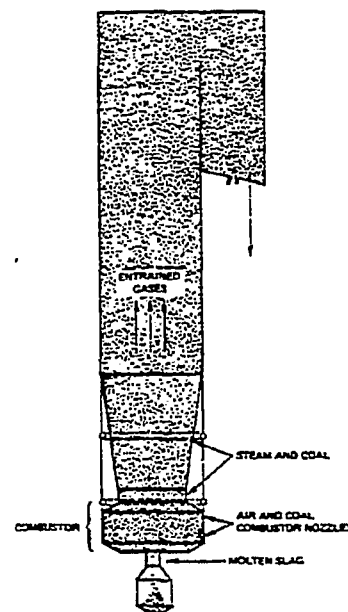


Figure X-4. TYPICAL MOLTEN BATH REACTOR

way to transfer and store heat as well as to disperse the reactants. The medium may be reactive, catalytic, or passive. The reaction takes place above the melting temperature of the medium and above the slagging temperature of the ash. As a result, an ash-free product stream is generated. Limestone added to the melt will tend to absorb the sulfur in the coal. Sulfur can then be removed with the slag, resulting in a low-sulfur raw gas.

The entrained-bed reactor shown in Figure X-5 is characterized by very high gas phase velocities and very small particle sizes (about 200 mesh). The drag force on the particles exceeds the gravity force, carrying the particles along with the gases. The reactants pass through the reaction zone for only a short time, but the very small size of the coal particles and high temperatures ensure a rapid reaction. Since all the reactants travel through the reaction zone at essentially the same velocity, the entrained flow gases are not mixed (as in the fluidized bed), but react sequentially as in a fixed-bed reactor.

The differentiation between single- and two-stage processes is simply one of physical location of the oxidant and steam injection point. When injected together, a single-stage process results. When the oxidant is injected upstream of the steam, two reaction stages result: combustion and gasification. The most common mode of operation is at temperatures above the slagging temperature in the combustion zone. This condition may be achieved by adjusting the fuel-oxidant ratio. The short contact time in the reaction zone requires high temperatures to increase reaction rates. The excess heat in the product gas at these high temperatures is used to generate process steam.



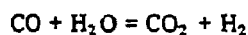
MAJOR GASIFICATION USING ENTRAINED-BED REACTORS
KOPPERS-TOTZEK
TEXACO
BI-GAS (TWO-STAGE)
HYDRANE (UPPER STAGE)
GARRETT

Figure X-5. TYPICAL ENTRAINED-BED REACTOR

## SHIFT CONVERSION<sup>1</sup>

The raw gas from the reactor often has to be processed further to produce a substitute natural gas with a high heating value. One step is shift conversion, which adjusts the H<sub>2</sub>-to-CO ratio to about 3 to 1 to increase methane production, (3H<sub>2</sub> + CO = CH<sub>4</sub> + H<sub>2</sub>O). The hydrogen-rich gas can also be used in hydrogasification processes.

The main reaction taking place in the shift converter is:



This reaction is mildly exothermic. The cooled gas (about 800° F) from the gasifier is cleaned of dust and tar and then mixed with a specific amount of steam before entering the shift converter. The added steam not only supplies the water required for shift conversion but also plays a role as a diluent to depress the decomposition of the carbon. Catalysts used for shift conversion are iron-chromium oxide compounds.

<sup>1</sup> *Optimization of Coal Gasification Processes*, Office of Coal Research.

## GAS PURIFICATION<sup>1</sup>

Gas must be purified to help raise its caloric value and to reduce pollution. Carbon dioxide adds nothing to the heating value of the gas, for example, and dilutes the concentration of the H<sub>2</sub> and CO in the stream entering the catalytic methanator. Furthermore, the methanation catalysts, usually containing nickel compounds, are sensitive to any contaminating sulfur species.

Gas purification is the removal of vapor-phase impur-

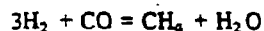
ities (H<sub>2</sub>S and CO<sub>2</sub> mainly) from the effluent gas streams. The processes which have been developed to accomplish gas purification vary from simple once-through wash operations to complex multiple-step recycle systems. The processes generally fall into one of three categories: absorption into liquid, absorption on a solid, and chemical conversion to another compound.

<sup>1</sup> A. L. Kohl and F. C. Reisenfeld, *Gas Purification*

## METHANATION<sup>1</sup>

The last step in converting coal to high-Btu gas is methanation—the conversion of excess carbon monoxide and hydrogen into methane.

The reaction taking place in the methanation unit is:



This is a highly exothermic reaction, and the method of removing heat from the reacting gas is the major problem

in economic operation of methanators.

The nickel or ruthenium catalysts used for methanation are easily poisoned by sulfur compounds; consequently, gases entering the methanator must be as pure as possible.

<sup>1</sup> *Optimization of Coal Gasification Processes*, Office of Coal Research.

Table X-1

## GASIFICATION PROCESSES AND STATUS

Process	Owner or Contractor and Site	Process Description	Coal Type	Input (Tons/day)	Output (10 <sup>6</sup> scf/day)	Status
High-Btu Processes						
ATGAS-PA'GAS	Applied Technology Corp., Pittsburgh, Pa.	Coal, crushed and dried, is injected into a molten iron bath through steam lances. Oxygen is introduced through lances located at the iron-bath surface. Coal dissolves in the molten iron where the volatiles crack and are converted into carbon monoxide and hydrogen. Sulfur in the coal migrates to a lime slag floating on the molten iron, and forms calcium sulfide. The slag, containing ash and sulfur, is continuously withdrawn from the gasifier and desulfurized with steam to yield sulfur and desulfurized slag. The raw gas from the gasifier can be used as medium-Btu fuel or upgraded to high-Btu fuel.	All U.S. coals			The process has been under investigation in laboratories since 1967, and has been demonstrated in short-duration runs in a 2-foot internal diameter gasifier. Plans for further development involve a larger gasifier to demonstrate long-duration operation.
BI-GAS	Bituminous Coal Research, Inc., Pittsburgh, Pa.	Coal is introduced into the upper section of a two-stage reactor where it is contacted with hydrogen-rich gas and partially gasified. The hydrogen-rich gas is produced in the lower section of the reactor by the slagging gasification of recycle char with oxygen and steam. The product gas must be methanated to produce high-Btu gas.	All U.S. coals	120	2-3	Construction of the pilot plant was completed in mid-1976, and shakedown and operation started.
Chevron	Chevron Research Co.	High-Btu gas is produced from a wide range of organic feeds such as lignite and organic waste materials. The organic feed is reacted with steam at 300-800 psi and 1,700°-1,400° F in the presence of an alkali metal catalyst (e.g., K <sub>2</sub> CO <sub>3</sub> ). High-Btu gas is produced by the catalytic steam-reforming of the products of degradation of the feed.				Details of the development of the process are not available.



Table X-1

## GASIFICATION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor and Site	Process Description	Coal Type	Input (Tons/day)	Output (10 <sup>6</sup> scf/day)	Status
CO <sub>2</sub> Acceptor	Consolidation Coal Co., Pittsburgh, Pa.	Coal is charged to a devolatilizer and is contacted at 300 psi with hydrogen-rich gas from a gasifier vessel. Calcined dolomite (the acceptor) is added to both vessels, where it reacts with carbon dioxide. Acceptor regeneration and ash removal is done in an air-blown regeneration vessel where spent char is combusted. The product gas must be purified and methanated to produce high-Btu gas.	Lignite Subbituminous	40 (pilot plant)	2	The objective of CO <sub>2</sub> acceptor process development is to keep the pilot plant operating to identify and resolve process and equipment problems relevant to commercialization. Process efficiency of 77 percent has been demonstrated. The pilot plant is being operated on an integrated basis with the liquid phase methanation process.
Electrofluidic Gasification	Iowa State Univ. Ames, Iowa	A fluidized bed of conducting particles is heated by passing an electrical current through the bed. The bed itself acts as a resistor between electrodes placed in contact with the bed. Reacting steam and coal char in the reactor provide a wide range of hydrogen-carbon monoxide mixtures, as well as mixtures containing methane suitable for upgrading to high-Btu gas.				Four- and 12-inch-diameter reactors have been successfully operated. The process is being integrated with pilot plant tests of the HYGAS process electro-gasifier.
Exxon	Esso Research and Engineering Co., Baytown, Texas	Coal is reacted with steam in a fluidized-bed gasifier at 1,600° F.-1,700° F. A stream of circulating char is withdrawn from the gasifier and partially burned with air in a char heater. The heated char is returned to the gasifier after separation from the flue gas. The medium-Btu gas produced can be upgraded to high-Btu gas.	All U.S. coals			A 0.5 ton/day pilot plant has been in operation for several years.
Garrett's Coal Gasification	Garrett Research & Development Co., La Verne, Calif.	Coal is introduced into a simple reactor at atmospheric pressure where gas is produced by rapid devolatilization of coal. Large amounts of excess char are produced.	All U.S. coals			Garrett, in conjunction with Colorado Interstate Gas, initiated development of the coal-gasification process in 1971. The process has been successfully evaluated in a pilot plant. The results of the pilot plant testing provided data that were evaluated by Combustion Engineering subsidiary, Lummus Co., to provide a detailed design for a 40,000 ton/day commercial plant. The plant would yield

Table X-1

## GASIFICATION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor and Site	Process Description	Coal Type	Input (Tons/day)	Output (10 <sup>6</sup> scf/day)	Status
Garrett's Coal Gasification (Cont'd.)						<p>260 million scf/day of pipeline quality gas and sufficient char to feed a 1,200 MW power plant.</p> <p>Garrett plans a 260 ton/day demonstration plant to be located near a power utility. Design and construction of the commercial plant could be started during operation of the demonstration plant.</p> <p>Operation of the commercial-scale pyrolysis reactor has been simulated with the operation of a continuous 3-16 lb/hour laboratory-scale reactor, which had the same configuration as the projected commercial unit except that its heat source was electrical. Results have indicated yields of pipeline-gas equivalents ranging from 4,600 scf/ton of MAF coal at 1,600° F to 7,600 scf/ton at 1,700° F, depending on coal type. Commercial-scale operation should yield an additional 1,000 scf/ton at 1,700° F of pipeline-gas equivalent by recycling the tar produced in the pyrolysis step to the reactor for further cracking.</p> <p>The commercial plant could be on-stream in 1980.</p>
Hydrano	U.S. Bureau of Mines, Pittsburgh Energy Research Center, Pittsburgh Pa.	Crushed raw coal is fed to a two-zone hydrogenation reactor operated at 1,000 psi and 1,650° F. In the top zone, the coal falls freely through a hydrogen-rich gas containing some methane from the lower zone. About 20% of the carbon is converted to methane. The char from the top stage falls into the lower zone where hydrogen feed gas maintains the particles in a fluidized state and reacts with about 34% more of the carbon to make methane. Char from the lower zone is reacted with steam and oxygen to generate the needed hydrogen.				<p>A second-generation hydrano process is in the engineering evaluation and design phase of development. This phase is scheduled to continue through the third quarter of FY 1978. Construction of a process development unit is scheduled to begin early in FY 1977 and continue through FY 1979, at which time the operation phase will begin.</p> <p>Laboratory studies are being conducted to acquire yield data, test operability using various coals, and obtain hydrogasification kinetic scale-up data.</p>

Table X-1

## GASIFICATION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor and Site	Process Description	Coal Type	Input (Tons/day)	Output (10 <sup>6</sup> scf/day)	Status
HYGAS	Institute of Gas Technology, Chicago, Ill.	Ground, dried coal is pretreated with air, stirred with by-product oil, and fed to a two-stage fluidized-bed hydrogasifier operating at 1,000-1,600 psia. Hydrogen-rich gas for the reaction can be furnished by processes using electric energy or oxygen, or by the steam-iron process. Gas from the reactor must be purified and methanated to produce high-Btu gas.	All U.S. coals	76 (pilot plant)	1.5	The pilot plant is being operated to obtain data. Improvements in oil/gas separation and oil recovery are being developed. An ash-agglomerating gasifier that could improve overall char utilization of the process is in operation. A decision to connect the steam-iron unit for hydrogen production from char will be made in FY 1977.
Koppers-Totzek	Heinrich Koppers GmbH Essen, W. Germany	Raw coal is dried, ground, and charged to a gasifier by a screw conveyor with a mixing head in which oxygen and steam are added. The reactor operates at atmospheric pressure and at 2,700° F. The product gas, mostly hydrogen and carbon monoxide, can be methanated to produce high-Btu gas.	All U.S. coals			<p>There are 16 Koppers-Totzek plants around the world, none of which is in the United States; five new plants are being built.</p> <p>An interesting new development of Heinrich Koppers and Imperial Chemical Industries (I.C.I.), Billingham, U.K., is a combined carbon monoxide-shift conversion and methanation unit. This unit's reactor uses a nickel catalyst that simultaneously promotes both shift and methanation reactions. Testing of this reactor by I.C.I. on a pilot scale has indicated that commercially acceptable lifetimes for the catalysts can be expected.</p> <p>A demonstration plant will be built in Germany to produce 2.8 scf/day from a coal feed of 146 tons/day. The Koppers-I.C.I. combined shift conversion and methanation reactor will be installed in the demonstration plant to upgrade the Koppers-Totzek gasifier raw gas to pipeline gas.</p> <p>Estimates for a Koppers-Totzek plant producing 250 million scf/day of high-Btu gas indicate a coal feed rate of 25,000 short tons/day to a battery of 24 Koppers-Totzek gasifiers.</p>

Table X-1

## GASIFICATION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor and Site	Process Description	Coal Type	Inputs (Tons/day)	Output (10 <sup>6</sup> scf/day)	Status
Koppers-Totzek (Cont'd.)						In the United States, Northern Illinois Gas Co. and the State of Illinois are studying the process, among others, for application at their proposed 80-90 million scf per day synthetic natural gas demonstration plant to be completed in Illinois in the early 1980's.
Lurgi Pressure Gasification	Lurgi Gesellschaft für Wärme-und Chemietechnik mbH Frankfurt, West Germany	Crushed coal is fed to the gasifier vessel through lock hoppers, and travels downward as a moving bed. The process operates at 350 to 450 psi. Steam and oxygen are introduced through a revolving steam-cooled grate, which also removes ash at the bottom of the gasifier. The hydrogen-rich gas passes up through the coal bed, producing some methane by hydrogenation of coal. The product gas is purified and methanated to produce high-Btu gas.	Noncaking coals			The first commercial plant was constructed in 1936 and, to date, 14 plants (comprising 68 units) have been built and additional plants, either with or without a methanation step, are under construction or in the planning stages.
Molten Salt	M. W. Kellogg Co. Piscataway, N.J.	Crushed and dried coal, oxygen, and steam are injected into a high-purity alumina reaction vessel with molten sodium carbonate. Coal-steam reaction is catalyzed by the molten salt contained in the reactor. The product gas can be purified and methanated to produce high-Btu gas.	All U.S. coals			In early tests of the process, under Office of Coal Research sponsorship from 1964 to 1967, two vessels were used. In the first, steam and coal were reacted in a molten-salt bath to yield synthesis gas. In the second vessel, the residual carbon in the circulating molten carbonate was burned with air to reheat the sodium carbonate for recirculation. Because of problems arising from the corrosive nature of the salt, the small-scale tests of this process were discontinued. W.M. Kellogg Co., continued their research and developed a noncorrosive alumina reactor lining to overcome the corrosion problem, and incorporated the use of a single reactor vessel, which not only eliminates circulation of the molten salt, but also simplifies gas handling and reduces further processing requirements.

Table X-1

## GASIFICATION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor and Site	Process Description	Coal Type	Input (Tons/day)	Output (10 <sup>6</sup> scf/day)	Status
Molten Salt (Cont'd.)						Because of these new developments, the Office of Coal Research sponsored additional work, with special emphasis on the suitability of the process as a method for generating a fuel gas suitable for magneto-hydrodynamic generating systems. The process is now being tested in a process development unit 10 times larger than earlier vessels.
Multiple Catalyst	Univ. of Wyoming Laramie, Wyo.	Methane is produced directly from coal and steam with the methanating catalyst bed placed in the middle of the reactor and heated to the desired temperature by a Lindberg furnace. The temperature is monitored by thermocouples located in the thermo-well inside the reactor. The methane-rich product gas passes through a motor valve which allows the pressure to be controlled.				The concept was developed at the Univ. of Wyoming and supported for 5 years by OCR. Babcock and Wilcox have undertaken further development of a better catalyst system, which could assure long catalyst life. The U.S. Bureau of Mines has conducted bench-scale experiments on the catalytic reaction of coal and steam at 1,800° F using tungsten-sulfide as a catalyst.
Self-Agglomerating Ash	Battelle Memorial Institute, Columbus Laboratories, Columbus, Ohio	Coal is reacted with steam in a two-stage fluidized-bed system. Air is used for combustion of part of the coal to provide heat for the gasification process. The process operates at up to 100 psi to produce a synthesis gas suitable for conversion to high-Btu pipeline gas by methanation.	Bituminous	26	0.8	Construction of the process development unit was completed in mid-1976, and shutdown started. The unit will be operated through mid-1977. The process engineering and economics data generated will be used to design a larger unit.
Synthane	U.S. Bureau of Mines, Pittsburgh Energy Research Center, Bruceton Pa.	Coal is fed into a reactor incorporating three processing steps: a free-fall oxygen-steam pretreatment zone, a dense fluid-bed carbonizer, and a dilute fluid-bed gasifier. Hydrogen-rich gas for the reaction is produced by the use of oxygen in the reactor. The process operates at 500 to 1,000 psia. The product gas can be purified and methanated to produce high-Btu gas.	All U.S. coals	70 (pilot plant)	1.4	Pilot plant design and construction were completed in 1976 and are currently in the shutdown phase. The plant is being operated to obtain enough data for designing a commercial plant.

Table X-1

## GASIFICATION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor and Site	Process Description	Coal Type	Input (Tons/day)	Output (10 <sup>6</sup> scf/day)	Status
Two-stage Fluidized Gasification	Midlands Research Station, United Kingdom	Coal is subjected to hydrogenation in two stages: a rapid reaction at 1,470°F-1,660°F and a slower reaction at 1,650°F-1,740°F at 750 psi. The char produced then passes to a fluidized-bed gasifier operating at 1,900°F, which produces a gas which is upgraded by catalytic methanation to pipeline quality.				Work has been done using fluidized-bed models under different operating conditions. From the results, a pilot plant to produce 4 million scf/day of synthesis gas was designed.
Wellman-Galusha	McDowell-Wellman Co. and Wellman-Galusha Co.	Crushed coal, dried and fed by an oxygen-steam mixture, is introduced through a revolving grate at the bottom of the reactor. Gasifiers are available with or without an agitator, which reduces channelling and maintains a uniform bed. The ash is removed continuously through a slowly revolving grate at the bottom of the reactor. The gas produced can be upgraded to high-Btu gas.				The process has been commercial for over 30 years. Two units are operating in the U.S. serving large industrial plants. McDowell-Wellman Co. is under contract to determine the feasibility of constructing a fixed-bed gasifier for operation on caking coals.
Winkler	Davy Powergas, Inc. Lakeland, Florida	Crushed coal is dried and fed to a fluidized-bed gasifier through a variable-speed screw feeder. Coal reacts with oxygen and steam to produce offgas rich in carbon monoxide and hydrogen. Because of the high temperatures, all tars and heavy hydrocarbons are reacted. Unreacted carbon carried over by gas is converted by secondary steam and oxygen in the space above the fluidized-bed. Raw gas leaving the gasifier is passed through a further waste-heat recovery section. Fly-ash is removed by cyclones, wet scrubbers, and an electrostatic precipitator. Gas is then compressed, shifted, purified, and methanated.				The process has been in use commercially at 16 plants in a number of countries since its development in Europe 60 years ago. The plants produce low-Btu fuel gas and synthesis gas. Davy Powergas, Inc., is currently developing a high-pressure modification of the Winkler process which should increase the thermal efficiency.

Table X-1

## GASIFICATION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor and Site	Process Description	Coal Type	Input (Tons/day)	Output (10 <sup>6</sup> scf/day)	Status
Medium- and Low-Btu Processes						
Advanced System	Westinghouse Electric Corp. Pittsburgh, Pa.	Crushed, dried coal is fed into a central draft tube of a devolatilizer desulfurizer. Coal and recycled solids are carried upward from a combustor by hot gases flowing at a velocity greater than 15 feet per second. Recycle solids flow downward in a fluidized bed surrounding the draft tube at rates up to 100 times the coal feed rate. Heat is provided by hot combustor gases. A lime sorbent is added to the gasifier to remove sulfur. Spent sorbent is removed, stripped of char, regenerated, and recycled to the gasifier. Char is removed from the top section of the gasifier and fed to the combustor. Raw product gas passes through a cyclone to remove fines and then through a heat-recovery unit.				This process is being tested in a 1,200 lb/hour pilot plant at Waltz Mill, Pa. Westinghouse, in late 1972, began a 9-year research and development program expected to cost \$80 million, cosponsored by Bechtel Corp., AMAX Coal, Peabody Coal Co., and the Public Service Co. of Indiana. Eleven electric power utilities are also sponsoring the program as associate members. A 60-ton/hour commercial, low-Btu gasification and electric power plant is under construction at the Dresser Station of the Public Service Co. of Indiana at Terre Haute, Indiana. This project, sponsored by ERDA, will utilize a combined-cycle coal gasification-power system fueled by the Westinghouse gasifier. The plant is expected to be operational during 1978.
BCR						
BCK Fluid-bed Three-stage Pressurized	Bituminous Coal Research Monroeville, Pa.	This process consists of three fluidized beds. Raw coal is fed into Stage 1. This stage acts as a pretreatment stage, devolatilizing the coal with the offgas from Stage 3. From Stage 1 the coal flows by gravity to Stage 2 where it is gasified with air and steam. Stage 3 functions as a char combustion step, operates at the highest temperature, and maximizes char utilization.	All U.S. coals	1		Construction of a one-ton per day process development unit was completed late in 1976. The unit will be operated for two years, and will be used to study and optimize the multistage system. Data generated from operation will be used for scale-up design. Laboratory research has been done to further refine the process.
Combined Cycle	Babcock & Wilcox Co. Alliance, Ohio	Coal and air are fed to a pressurized, water-cooled gasifier where they react to form a combustible gas. After cleaning, the gas is fired in a combustor that discharges to a high-temperature gas turbine, which, in turn, exhausts to the steam generating portion of the cycle to power a steam-turbine generator.				A 480 ton/day pilot plant is planned to be installed at a power generation utility site yet to be selected. Testing in a 60 ton/day plant has been under evaluation since 1961.

Table X-1

## GASIFICATION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor and Site	Process Description	Coal Type	Input (Tons/day)	Output (10 <sup>6</sup> scf/day)	Status
Combined Cycle	Foster-Wheeler Corp., Livingston N.J.	The process utilizes an entrained-bed, two-stage slagging pressure gasifier. The low-Btu fuel gas produced by the reaction of coal, steam, and air is cleaned and fired in a combustor that discharges to a gas turbine. The hot gas expanding through the turbine is sent to the steam-generating portion of the cycle to power a steam-turbine generator.				A research and development program initiated in 1972 will culminate in the operation of a 1,200 ton/day demonstration plant at Northern States Power Co.'s Lawrence Plant near Sioux Falls, S.D. Foster-Wheeler is developing a detailed conceptual design of the demonstration plant.
Entrained Fuel	Combustion Engineering, Inc. Windsor, Conn.	The gasifier consists of two sections: a combustion chamber that burns coal and recycle char to provide heat to the gasifier, and a reducing chamber where coal is reacted with steam to produce low-Btu gas. The gasifier is an entrained-bed reactor operating at atmospheric pressure. The product gas with a heating value of 125 Btu/scf leaves the gasifier at 1,800°F and enters the heat-recovery train. The gas is cooled further to 300°F.		120		A 120 ton/day plant is being built and is scheduled for completion in 1977. The plant will be operated to determine the technical and economic feasibility of the process. Continuous operation will be attempted to demonstrate equipment reliability. Cost and performance estimates for a commercial-size plant will be determined.
Fixed Bed	M. W. Kellogg Co., Piscataway	This process uses a low-pressure fixed-bed, revolving-grate gasifier to produce a low-Btu fuel gas with air, and a medium-Btu fuel gas with oxygen. By-product tar and oil are used as plant fuel or chemical feedstock.				The company is presently studying the formation of a consortium to erect a demonstration plant at an, as yet, unselected utility site.
GEGAS	General Electric Research and Development Center, Schenectady, N.Y.	This process utilizes a moving fixed-bed air-blown gasifier operating at 120 psi and 1,000°F. An extrusion process is used for coal feeding and off-gases are cleaned of hydrogen sulfide.				The process has been tested at a 50 lb/hour facility. A pilot plant will be built at a utility site. G.E. will initiate construction and operation of a pilot-plant heat exchanger to determine the effects of high-temperature coal gasification products discharging through an MHD generator.



Table X-1  
GASIFICATION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor and Site	Process Description	Coal Type	Input (Tons/day)	Output (10 <sup>6</sup> scf/day)	Status
HRI Fluidized Bed	Hydrocarbon Research, Inc. Princeton, N.J.	Steam and oxygen fluidize a bed with a fuel depth of 26 feet operating at pressures up to 400 psia, and at 1,450°F to 1,850°F to produce a synthesis gas of 320 Btu/scf.				Work was done in the 1950s using a 28-inch diameter fluidized-bed gasifier.
Kerpely Producer	U.S. Bureau of Mines, Louisiana, Missouri	Coal passes through a lock hopper down into a fixed-bed cylindrical unit, and is gasified by a steam-oxygen (or air) blast through a revolving grate, which removes the ash continuously. The unit operates at atmospheric pressure to produce a 280 Btu/scf gas with oxygen or a 130 Btu/scf gas with air.				A 7-foot internal diameter unit was operated by the U.S. Bureau of Mines. About 2 million scf/day of 280 Btu/scf synthesis gas with oxygen blasts were produced.
Molten Salt	Atomics International Norwalk, Conn.	Coal is gasified in a molten pool of sodium carbonate sulfide and sulfate through which air is blown. The product gas has a heating value of 160 Btu/scf. Conducting gasification reactions in the molten salt medium permits the attainment of very high oxidation rates and traps ash and sulfur in the melt.	All U.S. coals			Development tests, including hydraulic, quench tests, ash settling, solubility characteristics and regeneration of the molten salt, were conducted in FY 1976. A 24 ton/day process development unit has been designed.
Ruhrgas Vortex	Ruhrgas A.G. West Germany	High-ash coal or lignite, crushed to a 1/16-inch top size, is fed with air, preheated to 1,300°F, into a vortex chamber where it is gasified without steam and under slopping conditions. The slag passes out the bottom and the reactants pass upward into a tall shaft of larger diameter where the greater part of the gasification occurs at 3,100°F. The 100-120 Btu/scf off-gas is passed through cyclones and bag filters for dust removal and recycling of entrained gas.				The process has been in commercial use for many years to produce low-Btu fuel gas.

Table X-1

## GASIFICATION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor and Site	Process Description	Coal Type	Input (Tons/day)	Output (10 <sup>6</sup> scf/day)	Status
Stirred Fixed Bed	U.S. Bureau of Mines, Pittsburgh, Pa.	Unsize coal is fed to the top of the gasifier, which operates at 300 psi. Steam and air are introduced below the grate at the bottom. The nominal steam: coal feed ratio is 1:2 and the air: coal ratio is 3:1. Gasifier temperatures range from 2,400°F just above the grate to 880-1200°F at the gas exit. A water cooled stirrer is used to control caking and eliminate voids. The product is low-Btu gas.	Bituminous Subbituminous Lignite	12		A low-Btu gasification process development unit is operating at Morgantown Energy Research Center. Continued operation of the gasifier at different pressures with different types and sizes of coal to determine maximum capacity will provide the necessary data for design scale-up and economic evaluation. Construction of gas scrubber, hydrogen sulfide removal, and full blown combustion/turbine subsystems will begin in FY 1977. Operation of the fully integrated process, consisting of gasifier, cleanup, combustion, and turbine, will begin in FY 1978.
Toxaco Gasification	Toxaco Development Co.	Pulverized coal, suspended in steam at 950°F, is fed into the top of a downflow cylindrical reactor, where it is gasified with oxygen to produce 280 Btu/scf gas. The unit operates at 260 psi and temperatures above the ash fusion point. The product gas and slag are removed at the base of the vessel.				This process has been tested in a down-flow plant and has also been utilized in the HYGAS pilot plant for producing hydrogen.
Two Stage (Submerged Coal Combustion)	Applied Technology Corp.	The process is based on the molten-iron gasification process with air/coal feed to yield a 186 Btu/scf offgas and is similar to the ATGAS/PATGAS process.				Testing has been carried out in short runs using a 2-foot internal diameter vessel. The U.S. Environmental Protection Agency is sponsoring a design study for a 60 to 100 MW power generating plant using the process low-Btu offgas.
Two-step Coal Pyrolysis	West Virginia University Morgantown, West Virginia	Coal is fed to a sand fluidized-bed for pyrolysis at 1,400°F. Char produced is separated from effluent gas and reacted with air and steam in a gasifier to produce fluidizing gases for the pyrolyzer. A small quantity of raw coal is added to the gasifier char feed where the temperature is maintained at 1,900°F.	All U.S. coals			Feasibility has been demonstrated in bench-scale experiments using a 16-inch diameter fluidized-bed reactor. A conceptual study has been made of the process for application in power generation by coupling this process with an advanced-design combined gas and steam turbine power cycle.

Table X-1

## GASIFICATION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor and Site	Process Description	Coal Type	Input (Tons/day)	Output (10 <sup>6</sup> scf/day)	Status
U-GAS	Institute of Gas Technology	Crushed coal is pressurized in a lock hopper operating at 350 psi and 800°F, reacted with air, and fed to a fluidized-bed gasifier operating at 350 psi and 1,900°F. Air and steam are introduced through the base of the gasifier and ash removed through lock hoppers. Gases from the preheater and gasifier pass through heat-recovery and sulfur removal systems and power-recovery turbines. Gas produced has a heating value of 165 Btu/scf. Substituting oxygen for air produces a medium-Btu fuel gas.				<p>The process has been tested in an air-blown 486 lb/hour unit, which showed the suitability of the process for both combined-cycle power generation and as a "grass-roots" source of industrial and power generation energy.</p> <p>A 10 to 35 ton/hour pilot plant, sufficient to fuel a 100 MW power utility, is being designed.</p>

Sources: *Coal Conversion Technology: A review*, I. Howard-Smith and G. J. Werner, 1976, and *Fossil Energy Research Program of the Energy Research and Development Administration, FY 1977*, ERDA 78-83.

Table X-2.

## PROCESSES USING GASIFICATION REACTORS

Process	Reactor bed type	Temperature (° F)	Pressure (psig)	Reactants	Heating value of raw gas produced (Btu/scf) <sup>a</sup>
High-Btu Gasification					
ATGAS-PATGAS (Applied Technology Corp.)	Molten bath	2,600	50	Coal Oxygen Limestone Steam	316
BI-GAS (Bituminous Coal Research, Inc.)	Entrained (Upper Stage)	1,400-1,700	1,000-1,500	Coal Steam	378
	Vortex (Lower Stage)	2,800	1,000-1,500		
Chovron (Chevron Research Co.)	Catalytic	1,200-1,400	300-800	Organic feed Steam	Unknown
CO <sub>2</sub> Acceptor (Consolidation Coal Co.)	Fluidized	1,600	150-300	Coal Steam	400
	Regenerator	1,900	150-300	CaO Char Air Dolomite	
Electrofluidic Gasification (Iowa State Univ.)	Fluidized	1,600	1,600	Char Steam	300
Wollman-Galusha (McDowell-Wollman Co. and Wollman-Galusha Co.)	Fluidized (Revolving grate)	1,200	14.7	Coal Steam Oxygen	270
Winkler (Davy Powargas, Inc.)	Fluidized	1,600-1,800	14.7	Coal Steam Oxygen	276
Exxon (Esso Research & Engineering Co.)	Fluidized	1,500-1,700	—	Coal Steam	260-560
Koppers-Totzek (Heinrich Koppers GmbH)	Entrained	3,300	14.7	Coal Steam Oxygen	300

<sup>a</sup>In high-Btu processes, the raw gas must be upgraded to pipeline-quality gas by methanation.

Table X-2.  
PROCESSES USING GASIFICATION REACTORS (Cont'd.)

Process	Reactor Bed Type	Temperature (° F)	Pressure (psig)	Reactants	Heating value of raw gas produced (Btu/scf)
Lurgi Pressure Gasification (Lurgi Gesellschaft für Wärme-und Chemotechnik mbH)	Fixed	1,140-1,400	450	Coal Steam Oxygen	450
Molten-Salt (M. W. Kellogg Co.)	Catalytic Molten Sodium Carbonate	1,830	450	Coal Steam Oxygen	330
Multiple Catalyst (Univ. of Wyoming)	Heated Nickel Catalyst	1,200-1,300	100	Coal Steam	850
Self-agglomerating Ash (Battelle Memorial Institute, Columbus Laboratories)	Fluidized	1,700	100	Coal Steam	300
Synthane (U.S. Bureau of Mines)	Fluidized	1,800	1,000	Coal Steam Oxygen	405
Medium- and Low-Btu Gasification					
Advanced System (Westinghouse Electric Corp.)	Fluidized	2,100	180	Coal Air Steam	135
BCR Fluid-bed Three-Stage Pressurized (Bituminous Coal Research)	Fluidized	—	—	—	—
Combined Cycle (Babcock & Wilcox Co.)	Entrained (Two Stage)	900 1,600 (combustor)	95	Coal Air	100-250
Combined Cycle (Foster-Wheeler Corp.)	Entrained	2,100	510	Coal Steam Air	100-250
Entrained Fuel (Combustion Engineering, Inc.)	Entrained (slugging conditions)	3,300-3,400	14.7	Coal Steam Air	125

**Table X-2.**  
**PROCESSES USING GASIFICATION REACTORS (Cont'd.)**

Process	Reactor Bed Type	Temperature (° F)	Pressure (psig)	Reactants	Heating value of raw gas produced (Btu/scf)
Fixed Bed (M. W. Kellogg Co.)	Fixed (Revolving grate)	—	30-60	Coal Air Coal Oxygen	160 300
GEGAS (General Electric Research and Development Center)	Moving Fixed	1,000	120	Steam Air Coal	100-250
HRI Fluidized Bed (Hydrocarbon Research, Inc.)	Fluidized	1,450-1,650	400	Coal Steam Oxygen	320
Kerpely Producer (U.S. Bureau of Mines)	Fixed	—	14.7	Coal Steam Oxygen Coal Steam Air	280 130
Ruhrgas Vortex (Ruhrgas A.G.)	Vortex	1,300 (1st Chamber) 3,110 (2nd Chamber)	—	Coal Air	100-120
Stirred Fixed Bed (U.S. Bureau of Mines)	Fixed	1,000	300	Coal Steam Air	130-170
Texaco Gasification (Texaco Development Co.)	Fluidized	950	260	Coal Steam Oxygen	280
Two stage (Submerged Coal Combustion) (Applied Technology Corp.)	Molten Bath	2,500	60	Coal Air Limestone Steam	185
U-Gas (Institute of Gas Technology)	Fluidized	800	350	Coal Air Steam	165

Table X-2.

## PROCESSES USING GASIFICATION REACTORS (Cont'd.)

Process	Reactor Bed Type	Temperature (° F)	Pressure (psig)	Reactants	Heating value of raw gas produced (Btu/scf)
Wellman-Galusha (McDowell-Wellman Co. and Wellman-Galusha Co.)	Fluidized (Revolving Grate)	1,200	14.7	Coal Steam	120-160
Winkler (Davy Powergas, Inc.)	Fluidized	1,600-1,800	14.7	Coal Steam Air	120

Source: I. Howard Smith and G. J. Warner, *Coal Conversion Technology: A Review*, 1975.

Table X-3

## PROCESSES USING HYDROGASIFICATION REACTORS

Process	Reactor Bed Type	Temperature (° F)	Pressure (psig)	Reactants	Heating value of gas produced (Btu/scf)
Hydrane (U.S. Bureau of Mines)	Fluidized	1,650	1,000	Char Hydrogen	826
HYGAS (Institute of Gas Technology)	Fluidized	1,300-1,500 (Stage 1) 1,700-1,800 (Stage 2)	1,000-1,500	Coal Char Hydrogen-rich gas	950-1,000
Two-stage fluidized gasification (Midlands Research Station—United Kingdom)	Fluidized	1,470-1,560 (Stage 1) 1,650-1,740 (Stage 2)	750	Coal Char Hydrogen	950-1,000

Source: I. Howard-Smith and G. J. Werner, *Coal Conversion Technology: A Review*, 1975.

Table X-4

## PROCESSES USING PYROLYTIC REACTORS

Process	Reactor Bed Type	Temperature (° F)	Pressure (psig)	Reactants	Heating value of raw gas produced (Btu/scf) <sup>a</sup>
High-Btu Pyrolysis					
Garrett's Coal Gasification (Garrett Research & Development Company)	Entrained	1,500-1,700	14.7	Coal Hot char	600-650
Medium- and Low-Btu Pyrolysis					
Two-step Coal Pyrolysis (West Virginia Univ.)	Fluidized	1,400 (Pyrolyzer) 1,900 (Gasifier)	10 10	Coal Heat Char Air Steam	Pyrolysis Gas 100-250

<sup>a</sup>In high-Btu processes, the raw gas must be upgraded to pipeline-quality gas by methanation.

Source: I. Howard-Smith and G. J. Werner, *Coal Conversion Technology: A Review*, 1975.



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## INTRODUCTION

Coal has been burned directly for centuries and a fuel gas was made from coal almost 200 years ago; coal liquids derived from pyrolysis, synthesis, or hydroliquefaction were first produced about 50 years ago.

The most notable example of production of coal liquids is the German experience during World War II. Germany had built several synthetic fuel plants with a combined output of 5 million tonnes<sup>1</sup> per year (approximately 100,000 bbl/day). About 20 percent of the production came from the distillation (pyrolysis) of brown and bituminous coal, 12 percent came from the Fischer-Tropsch synthesis process, and 68 percent came from the direct hydrogenation of coal.

Germany's supply of petroleum was limited before World War II. Consequently, building synthetic fuel plants was a part of Germany's rearmament program. Germany, in an effort to be self-sufficient, demonstrated the ability to derive adequate synthetic fuels from coal, although these fuels were uneconomical compared with natural crude oil.

After World War II, the synthetic fuel industry dwindled. In 1956, however, a new plant started production in South Africa based on the Fischer-Tropsch synthesis technology (5,000 to 6,000 bbl/day). Also, it was reported that

three of the World War II German synthetic fuel plants located in East Germany had a combined annual output in 1956 of approximately 11 million barrels of products per year (30,000 bbl/day).

The basic conversion technology required to use coal as a source of liquid fuels has existed for many years. Most of this conversion technology has not been economical when faced with competition from low-priced natural crude. However, over the last two decades, considerable research and development efforts have been expended by the United States Office of Coal Research, Bureau of Mines (now part of the Energy Research and Development Administration) and various energy companies to improve the efficiency of conversion processes, lower the cost of the facilities required, and in general make these alternate fuel sources more competitive. These research efforts have had considerable success; many new and refined process technologies now exist. The most recent development has been directed toward building pilot plants based on these improved technologies as a first step toward a full-scale commercial plant.

<sup>1</sup> Tonne = 1000 kg = 2204.6 lb.

## CHEMISTRY OF COAL LIQUEFACTION

A simplified treatment of the chemistry of coal conversion is helpful in understanding the different coal processes. Basically, coal is a solid hydrocarbon with a hydrogen-to-carbon mole ratio of approximately 0.9 (coal can be represented as CH<sub>0.9</sub>). In addition, coal has varying amounts of oxygen, nitrogen, sulfur, ash, and moisture. Typical equivalent chemical formulas for moisture- and ash-free (MAF) bituminous and subbituminous coals are compared in Table XI-1 to the equivalent chemical formulas for gasoline, jet fuel, light fuel oil, heavy fuel oil, coal-derived synthetic crude oil, paraffin-based natural crude (Pennsylvania pipeline), and naphthene-based natural crude (Coalinga, Calif.). Examination of the table shows that it is necessary to increase the relative amounts of hydrogen in coal to convert it to a useful liquid fuel. In reality, however, conversion is much more complicated because coal tends to be highly aromatic and requires sophisticated treatment to convert it to paraffin or olefin products. Coal, for example, makes better gasoline than it does jet or diesel fuel.

Table XI-1

EQUIVALENT CHEMICAL FORMULAS FOR  
VARIOUS FEEDSTOCKS AND  
HYDROCARBON PRODUCTS

Feed Stocks		
Bituminous Coal		CH <sub>0.9</sub> O <sub>0.1</sub> S <sub>0.02</sub> N <sub>0.01</sub> + Ash + Moisture
Sub-bituminous Coal		CH <sub>0.9</sub> O <sub>0.2</sub> S <sub>0.004</sub> N <sub>0.01</sub> + Ash + Moisture
Coal Derived Syn crude (H-Coal)		CH <sub>1.5</sub> O <sub>0.02</sub> S <sub>0.001</sub> N <sub>0.002</sub>
Paraffin Crude Oil		CH <sub>2.0</sub>
Naphthene Crude Oil		CH <sub>1.6</sub> N <sub>0.01</sub> S <sub>0.003</sub>
Products		
Gasoline	CH <sub>2.1</sub>	Jet Fuel CH <sub>2</sub>
Light Fuel Oil	CH <sub>1.8</sub>	Heavy Fuel Oil CH <sub>1.3</sub> S <sub>0.002</sub>

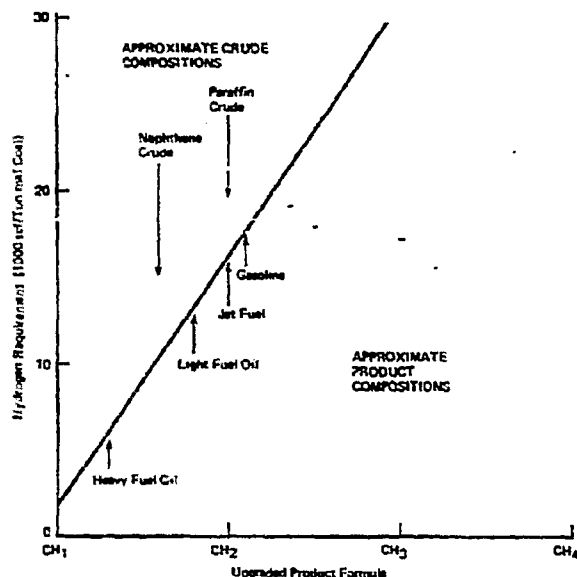


Figure XI-1. MINIMUM HYDROGEN REQUIREMENTS FOR COAL LIQUEFACTION

Increasing the hydrogen-to-carbon ratio of coal can be accomplished by reducing the amount of carbon by coking or pyrolysis or by adding hydrogen from a second source to the coal molecule, as is done in solvent refining or catalytic hydrogenation. If the coal is totally gasified by partial oxidation, the resulting hydrogen and carbon monoxide can be reformed using the Fischer-Tropsch synthesis over the proper catalysts to yield almost any desired hydrocarbon product.

Estimates of hydrogen required to convert coal ( $\text{CH}_{0.9}$ ) to the various hydrocarbon products, based on perfect conversion, are shown in Figure XI-1. The hydrogen requirements of a real plant would exceed this minimum amount because of normal process inefficiencies and the need to provide hydrogen for sulfur removal.

## COAL LIQUEFACTION TECHNOLOGY

Three methods exist for converting coal into liquid hydrocarbon fuels: synthesis gas, pyrolysis (coking), and hydrogenation. Hydrogenation is frequently subdivided into noncatalytic processes such as solvent-refined coal (SRC) and catalytic processes such as H-Coal. This fact book considers the three major methods. Figure XI-2 shows a general schematic of the methods for converting coal to liquid fuels. A list of specific liquefaction processes being developed and a brief description of each process and its development status are given in Table XI-2.

### Synthesis Gas

The production of synthetic fuels using the synthetic gas process is a well known, relatively simple, but generally more expensive than competing processes. The advantage of this process is that there is more control over the type of products manufactured. Consequently, this process would be preferred where part of the product mix would be used to supply a petrochemical industry.

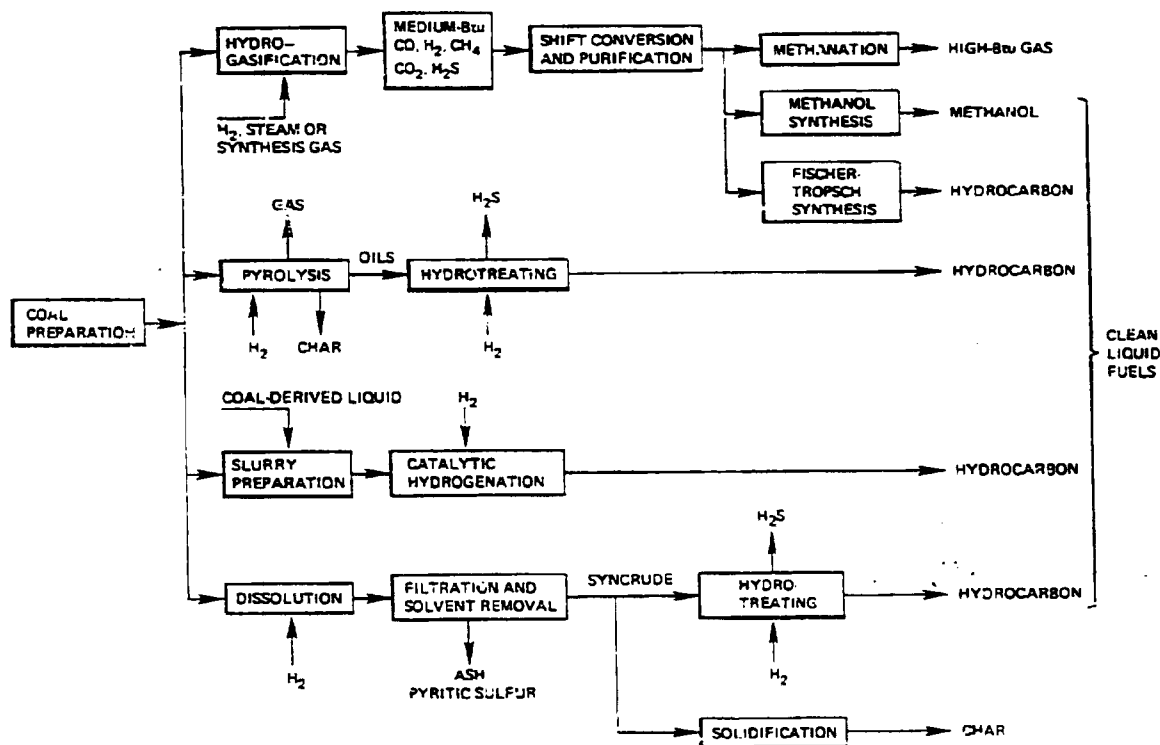
The synthesis gas technology could also be applied to any hydrocarbon starting material. Basically, the processes partially oxidize the coal (or any other organic materials) to

produce carbon monoxide and hydrogen. This synthesis gas, passed over an appropriate catalyst at a particular pressure and temperature, will form a synthetic liquid product, which is then refined into the useful fuel fractions. The ratio of carbon monoxide to hydrogen, the particular catalyst used, and the pressure and temperature all influence product distribution obtained in the processes. Modifications of the synthesis gas process have been used to manufacture methyl and higher alcohols from combustible waste.

The operating conditions and products of synthesis gas processes are shown in Table XI-3.

### Pyrolysis

The thermal distillation of coal into coke, fuel gases, and liquid fuels has been done commercially for many years. Adaptation of these pyrolysis techniques to produce primarily liquid and gaseous products with a wide range of coal types has been pursued by several organizations. Some of the more noteworthy U.S. research efforts have been Project Seacoke, sponsored by ERDA and conducted by



Source: *Energy From Coal, A State-of-the Art Review*, U.S. Energy Research and Development Administration, ERDA 76-67.

Figure XI-2. LIQUID FUELS FROM COAL

the Atlantic Richfield Company; Project COED, sponsored by ERDA and conducted by FMC; TOSCOAL, conducted by The Oil Shale Corporation; and the independent work conducted by Garrett, a subsidiary of Occidental Petroleum Company.

The operating conditions and products of pyrolysis processes are shown in Table XI-4.

### Hydrogenation

The direct hydrogenation of coal, either with or without catalysts, appears to be one of the most promising of the evolving synthetic fuel technologies. It seems to offer higher overall thermal efficiencies and, in all probability, lower costs. The Germans used direct hydrogenation much more extensively than either pyrolysis or synthesis gas during World War II. The early German work of Bergius used a process in which pulverized coal and hydrogen were allowed to react in the presence of a catalyst at a particular pressure and temperature. By varying the choice of catalyst, the coal-to-hydrogen ratio, and the operating pressures and temperatures, a liquid product could be obtained approxi-

imating a very heavy fuel oil or a product containing mostly volatile aviation fuel and hydrocarbon gases.

The recent research efforts have all been aimed at improving the conversion yield of the hydrogenation process, in tailoring the catalyst and operating conditions for particular products, and in improving the process economics. Different approaches to the chemical reactor have also been tried. Hydrocarbon Research, Inc. (H-Coal), has used improved catalysts in a fluidized-bed reactor, whereas the U.S. Bureau of Mines (Synthoil) has been using improved catalysts in a fixed-bed reactor. In general, a direct hydrogenation process will yield 3 to 4 barrels of liquid products per ton of coal and should be operational at 70 to 80 percent thermodynamic efficiency.

Both private industry and the U.S. government are sponsoring major direct hydrogenation projects, but most projects are just moving into the pilot plant stages. Based on the present rate of progress, it will be several years before commercialization is achieved.

The operating conditions and products of hydrogenation processes are shown in Table XI-5.

Table XI-2

## LIQUEFACTION PROCESSES AND STATUS

Process	Owner or Contractor, Site, and Capacity	Process Description	Status
Borgius	None	Finely ground coal is mixed with process-derived hydrocarbon liquid and a catalyst. The mixture is reacted with hydrogen at 3,000 psi to 10,000 psi. The products from the first reactor are separated into light, middle, and bottom fractions. The middle fraction is further treated over a catalyst in a vapor phase to produce petroleum-like products.	In the 1960s, a large government ammonia plant in Louisiana, Mo., was converted into two liquefaction demonstration plants, one of which used the Borgius process to produce about 200 barrels per day of gasoline. No Borgius plants are currently operating.
Catalytic Coal Liquefaction	Gulf Research and Development Co. 1 ton/day pilot plant	Dried and pulverized coal is mixed with a process-derived oil. The resultant slurry is forced through an arrangement of fixed catalysts by a stream of hydrogen at about 2,000 psi. The liquid product can be used for producing gasoline, diesel fuels, or petrochemical feedstocks.	Gulf Research and Development Co. has been testing this process for 8 years on a bench-scale level. In January 1976, the 1 ton/day pilot plant began operation. It is designed to yield 3 barrels of oil from each ton of MAF coal. A conceptual design of a larger demonstration plant is being prepared based on data from pilot plant operations.
Char-Oil Energy Development (COED)	FMC Corp. Princeton, N.J. 36 ton/day pilot plant	Coal is crushed and dried, then heated to successively higher temperatures in a series of fluidized-bed reactors. The temperature of each bed is just short of the maximum temperature to which coal can be heated without agglomerating and defluidizing the bed. The number of stages and temperatures vary with the agglomerating properties of the coal. The volatile matter released from the coal in the pyrolysis reactor is condensed in a product-recovery system.	The pilot plant has been operational since 1970. Only large-scale gasification of the pyrolysis char product remains to be demonstrated. A preliminary estimate has been made for a 24,000 ton/day COED plant to produce 26,400 barrels of oil per day, 12,000 tons of char per day, and 390 million scf of synthesis gas (400 to 600 Btu/scf) per day.
Clean Coku Process	U.S. Steel Corp. Monroeville, Pa. Five 600 lb/day process development units 100 ton/day pilot plant being designed 17,000 ton/day commercial plant planned	Coal, after beneficiation and sizing in a coal-preparation plant, is split into two fractions: part is processed through a carbonization unit where it is devolatilized, and the remainder is slurried with a process-derived carrier oil and is hydrogenated to convert a large portion of the coal to liquid. The liquid products from both units are converted into low-sulfur liquid fuels, chemical feedstocks, and three oil fractions that are recycled into other areas of the process.	Design and operation of the five 600 lb/day process development units is planned by 1977. Bench-scale studies to aid design and operation of these units are being conducted, and a 100-ton/day pilot plant is being designed. The planned commercial plant will produce, annually, 2.2 million tons of coku, 669,000 tons of oil residue, 750,000 tons of chemical products, 34,000 tons of ammonia, 49,000 tons of sulfur, 80 million gallons benzene, and 8 million gallons of tar products.
Coal-Oil-Gas (COG) (Liquefaction section)	Pittsburg & Midway Coal Mining Co. Marshall, Kansas	Crushed coal is combined with unfiltered solvent to produce a 60 weight percent slurry, which is sent to the preheat furnace. The slurry is combined with	The Ralph M. Parsons Co. was awarded a contract for designing a COG demonstration plant, based on design data supplied by the individual process

Table XI-2

## LIQUEFACTION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor, Site, and Capacity	Process Description	Status
COG (cont'd)	0 ton/day pilot plant 50 ton/day pilot plant	synthesis gas and water, then fed to the reactor. The solid phase is separated by filtration from a portion of the liquid phase, and is transferred to the gasification plant. The filtrate is fractionated to produce naphtha, distillate that is desulfurized to a higher boiler fuel, and residual fuel oil. Solid solvent-refined coal can be produced by distillation if required.	developers. This demonstration plant is designed to process 10,000 tons of coal feed per day to produce 2,011 barrels of naphtha, 8,472 barrels of fuel oil, 11,346 barrels of heavy liquid product, 121 tons of heavy liquid plant fuel, 2,142 tons of fuel gas, and 317 tons of sulfur per day.
COGAS	COGAS Development Co. Princeton, N.J.  36 ton/day pyrolysis pilot plant 50 ton/day char heat-carrier pilot plant	Gasification-combustion of coal is integrated with multistage fluidized-bed coal pyrolysis. The products of pyrolysis are a reactive char and pyrolysis oil and gas. The char is sent to the gasifier; the oil can be upgraded by hydrogenation to a high-grade synthetic crude oil or, by using less hydrogen, to a low-sulfur fuel oil.	The pyrolysis section of the process is based on the COED process. The pilot plants at Leatherhead, England, and Princeton have successfully demonstrated most of the key features of the COGAS process, and are providing design data for an 800 to 1,000 ton/day demonstration pilot plant.
Consol Synthetic Fuel (CSF)	Consolidation Coal Co. Cresap, W.V.  20 ton/day pilot plant 900 ton/day demonstration plant planned	Crushed coal is preheated in a fluidized bed to 450° F, then slurried in process-derived solvent. The slurry is pumped to a stirred solvent-extraction vessel where extraction occurs at 785° F and 160 to 400 psi. Recycle solvent, distillate, and liquid product for hydro-treatment to naphtha are produced. Solid residue in a concentrated slurry is sent to a low-temperature carbonization reactor where the slurry is pyrolyzed at 800° F to 900° F and low pressure to recover the solvent and also to produce additional distillate by coking the residue and the extract. In the hydrotreatment section, liquid product from the fractionation step and tar from the carbonization step are hydrogenated in a catalytic reactor operating at 800° F and 3,000 psi to produce naphtha, light oil, gas, and makeup solvent.	This process was tested in the pilot plant from 1967 to 1970. The results were less favorable than predicted, based on bench-scale tests. A detailed assessment of the process indicated that it was technically sound but that major mechanical modifications were necessary to improve operating reliability. In 1974, Fluor Corp. was awarded a 3-year contract to re-visit the Cresap pilot plant and supplement existing equipment with new equipment designed to produce fuel oil for power generation and industrial uses. The plant may also be modified to evaluate several coal liquefaction processes for various types of coals.
Exxon Liquefaction	Exxon Research and Engineering Co. Baytown, Texas  0.6 ton/day laboratory unit	Crushed coal is slurried with a recycle solvent, preheated to about 800° F, and pumped into the liquefaction reactor operating at about 2,000 psi. Pre-treated hydrogen is also added to the reactor. The product is separated into gas, naphtha, recycle solvent, distillate, and heavy bottoms. The recycle solvent is catalytically hydrogenated and slurried with fresh coal to repeat the cycle.	Laboratory work on this process has been done since 1968. Exxon recently proposed government funding of a planned 200 ton/day plant for demonstrating critical process features.

Table XI-2

LIQUEFACTION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor, Site, and Capacity	Process Description	Status
Fischer-Tropsch Synthesis	South African Coal, Oil, and Gas Corp., Ltd. (SASOL)  6,600 ton/day commercial plant  30,000 ton/day commercial plant	In the SASOL Fischer-Tropsch plant, coal is gasified in 13 Lurgi high-pressure, steam-oxygen gasifiers. The gas produced consists primarily of carbon monoxide and hydrogen. The gas is quenched to remove tar and oil and purified by the Rectisol (Lurgi) process. Part of the gas is passed through a fixed-bed catalytic reactor (Argo synthesis). The products are straight-chain high-boiling hydrocarbons with some medium-boiling oils, diesel oil, L.P.G., and oxygenated compounds such as alcohols. The other portion of the gas goes to the Synthol plant (Kellogg synthesis), which is a fluidized-bed catalytic iron reactor. Products are gasoline, alcohol, oil, and gas.	The SASOL plant is the only one producing liquid hydrocarbons from coal-derived synthesis gas using the Fischer-Tropsch process. The plant has been operating since 1956, and produces about 2.6 million tons of petrochemicals per year. A second SASOL plant is planned, and should come on-stream in 1979-1981. This plant should produce about 10 million tons of gasoline per year.  In the United States, the Ralph M. Parsons Co. was awarded a 3-year contract in 1974 that includes preliminary design work on a Fischer-Tropsch synthesis plant to produce substitute natural gas and motor fuels. ERDA's R&D program includes the preliminary design of a process development unit to evaluate modifications to the process.
Garrett's Coal Pyrolysis	Garrett Research and Development Co. La Verne, Calif.  3.6 ton/day pilot plant	Crushed coal, in a stream of recycled gas, is pyrolyzed at 1,100° F through contact with hot char from a char heater vessel. Effluent from the pyrolysis reactor is sent to a series of cyclones for separation of gas and entrained char. A portion of the char is cooled as product char. The remaining char is sent to the char heater where a portion is burned with air to heat the contents to 1,400° F. Hot char is cycled to the pyrolysis reactor. Part of the gas from the cyclones is cooled, scrubbed, and sent to a plant for generating hydrogen, which is used in the tar hydrotreater to produce liquid fuels.	Garrett Research and Development Co. has studied pyrolysis and gasification coal for years. Results to date indicate typical yields equal to 200 percent Fischer assay and significantly higher than fluidized-bed pyrolysis processes.
H-Coal	Hydrocarbon Research, Inc. (HRI) Trenton, N.J.  3 ton/day process development unit  600 ton/day pilot plant planned	Dried, pulverized coal is slurried with process-derived oil, then compressed hydrogen is added. The mixture is heated and fed to an ebullated-bed catalytic reactor. Vapor product from the reactor is cooled and cleaned to separate the heavier components as liquid. Light hydrocarbons, ammonia, and hydrogen sulfide are absorbed from the gas stream and sent to a separator and sulfur-recovery unit. Liquid-solid product from the reactor is fed into a flash separator. Material that boils off is distilled to produce light and heavy distillates. The bottoms product from the flash separator (solids and heavy oil) is further separated in a vacuum still to produce heavy distillates and residual fuel oil.	HRI has been developing the H-Coal process since 1964, based on experience with the H-Oil process. Various plant options and systems have been developed and tested. The cost of the 600 ton/day demonstration pilot plant is expected to exceed \$80 million; the government will provide two-thirds of the project cost.

Table XI-2  
LIQUEFACTION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor, Site, and Capacity	Process Description	Status
Intermediate Hydrogenation	University of Utah Salt Lake City, Utah 60 lb/hour bench-scale unit 5-10 ton/day pilot plant designed	Dry, pulverized coal is passed with catalyst stannous or zinc chloride into a reactor containing hydrogen at 2,000 to 2,500 psi. The coal is hydrogenated, and liquid fuels and gases are produced.	Successful research and development work on the process was conducted between 1969 and 1974. The University has also experimented (bench-scale) on catalytic hydrosolvolation of coal and lignite to synthetic crude in a single step.
Project SEACOKE	ARCO Chemical Co. Philadelphia, Pa. Laboratory unit 10,000 barrel/day pilot plant designed	Coal, usually blended with petroleum residuum as part of the feedstock, is pyrolyzed in multistage fluidized beds to produce char, liquids, fuels, and gas. After separation of the phases, the liquid products are further catalytically hydrotreated to produce gasoline. The gas can be used in the process or sold, and the char can be used for power generation on site.	This project was operational under government sponsorship during the 1960s. A 10,000 barrel/day plant was designed for converting coal and residual fuel oil to char, syncrude, and fuel gas. In 1970, the final report on the project was issued.
Solvent-Refined Coal (SRC)	Pittsburgh & Midway Coal Mining Co. (PAMCO) Merriam, Kansas 60 lb/hour continuous flow process development unit 6 ton/day pilot plant 60 ton/day pilot plant 1,000 ton/day demonstration plant planned	Pulverized coal is slurried with coal-derived solvent, then hydrogen (produced by other steps in the process) is added. The mixture is pumped through a fired preheater and passed into a dissolver where about 90 percent of the MAF coal is dissolved. Gas is then separated from the slurry of undissolved solids and coal solution. The raw gas is sent to a hydrogen-recovery and gas-desulfurization unit. The undissolved solids are separated from the coal solution in a filtration unit. The coal solution passes to the solvent recovery unit and the final liquid product, solvent-refined coal, is produced.	Beginning in 1972, Spencer Chemical Co. (subsequently PAMCO) conducted bench-scale evaluation of the Pott-Brecht process to find a clean fuel. The project has continued at an accelerated pace and much interest has been shown by both government and private companies. In 1974, Wheelabrator-Frye announced plans for a 1,000 ton/day demonstration plant costing \$80 million. If successful, the plant can be expanded, over 3 years at a cost of about \$360 million, to 10,000 tons/day.
Synthoil	U.S. Bureau of Mines, Pittsburgh Energy Research Center Pittsburgh, Pa. 6 lb/hour bench-scale unit 0.5 ton/day pilot plant 8-10 ton/day pilot plant under construction	Pulverized, dried coal is slurried with recycled oil. The slurry is pumped into a catalytic, fixed-bed reactor with hydrogen at high velocity to create turbulent flow conditions. The reactor is filled with immobilized catalyst pellets composed of cobalt molybdate on silica-activated alumina. The hydrogen, turbulent flow conditions, and catalytic action combine to liquefy and desulfurize the coal. The product passes through a high-pressure receiver where gas is separated and recycled after ammonia and hydrogen sulfide are removed. The raw oil is	Progressing from a bench-scale unit and a small pilot plant, the Bureau of Mines awarded a \$0.9 million contract to Foster Wheeler Corp. to procure equipment and construct an 8 to 10 ton/day pilot plant (producing 1,000 gallons of fuel oil per day). Bethlehem Steel Corp. will contribute \$1.1 million to the plant's cost and \$0.5 million for further research, and will operate the pilot plant for 2 years. If the project is successful, a 700 ton/day plant will probably be constructed.



Table XI-2

## LIQUEFACTION PROCESSES AND STATUS (Cont'd)

Process	Owner or Contractor, Site, and Capacity	Process Description	Status
Synthoil (cont'd)	700 ton/day demonstration plant being designed	centrifuged to remove ash and unreacted coal, providing a low-sulfur, low-ash fuel oil.	
Toscoal	The Oil Shale Corp. (TOSCO), Rocky Flats Research Center Golden, Colorado 25 ton/day pilot plant	Preheated coal from a dilute-phase fluidized bed is fed to a pyrolysis vessel where it is contacted with heated ceramic balls. The char produced in this reactor is screened, cooled, and stockpiled. The cooled ceramic balls pass over the screen and are reheated. The vaporized products of the pyrolysis step are condensed and fractionated. Offgas (600 Btu/scf) from the condenser can be used as a fuel gas heating the ceramic balls or processed for sale.	TOSCO has investigated the Toscoal process since 1970, drawing on experience and development work associated with the TOSCO II process for oil-shale retorting. The TOSCO II process was field tested in a 1,000 ton/day pilot plant, and construction engineering is under way on a 66,000 ton/day commercial oil-shale plant. The Toscoal process will probably parallel development of the TOSCO II process in the future.

Sources: I. Howard-Smith and G. J. Werner, *Coal Conversion Technology: A Review*, 1976.  
*Energy From Coal, A State-of-the-Art Review*, U.S. Energy Research and Development Administration, ERDA 76-67.  
*Fossil Energy Research Program of the Energy Research and Development Administration, FY 1977*, ERDA 76-63.

Table XI-3

## SYNTHESIS GAS PROCESS

Process	Reactor Bed Type	Temperature (° F)	Pressure (psig)	Reactants	Products
Fischer-Tropsch Synthesis					
M. W. Kellogg (SASOL)	Fluidized-bed catalytic	620	330	Synthesis gas Iron catalyst	Gasoline, alcohol, oil, gas
Arge-Arbeit (SASOL)	Fixed-bed catalytic	450	360	Synthesis gas Iron/cobalt catalyst	Gasoline, L.P.G., oil, wax, gas

Source: I. Howard-Smith and G. J. Werner, *Coal Conversion Technology: A Review*, 1975.

Table XI-4

## PYROLYSIS PROCESSES

Process	Reactor Bed Type	Temperature (° F)	Pressure (psig)	Reactants	Products
Char-Oil Energy Development (COED) (FMC Corp.)	Fluidized bed No. 1	600	5-10	Coal Heat	Char, oil, gas, liquor
	No. 2	850	5-10		
	No. 3	1,000	5-10		
	No. 4	1,500	5-10		
COGAS (COGAS Development Company)	Four fluidized beds	600-1,500	5-10	Coal Heat	Char, oil, gas, liquor
Garrett's Coal Pyrolysis (Garrett Research and Development Company)	Pyrolyzer	1,100	Atmospheric	Coal Hot char	Tar, product char, gas
Project SEACOKE (ARCO Chemical Company)	Five fluidized beds	600-1,600	Atmospheric	Coal Heat	Char, gas, oil
TOSCOAL (TOSCO)	Pyrolyzer	800-1,000	Atmospheric	Coal Heat	Char, gas, oil

Source: I. Howard-Smith and G. J. Werner, *Coal Conversion Technology: A Review*, 1975.

Table XI-5  
HYDROGENATION PROCESSES

Process	Process Type	Temperature (° F)	Pressure (psig)	Reactants	Products
Bergius (F. Bergius)	Solution Hydrogenation (Iron-oxide catalyst)	900	3,000—10,000	Coal Recycle oil Hydrogen	Light oils
Catalytic Coal Liquefaction (Gulf Research and Development Company)	Fixed-bed catalytic	900	2,000	Coal Oil Hydrogen	Synthetic crude oil, gas
Clean-Coke Process (U.S. Steel Corp.)	Carbonization  Extraction Hydrogenation	1,200—1,400  900	100  3,000—4,000		Liquid products, gas, char for coker Liquid products, gas, filter cake for gasifier
Coal-Oil-Gas (COG) (Pittsburg & Midway Coal Mining Company)	Extraction Hydrogenation	850	1,000	Coal slurry Synthesis gas Water	Naphtha, fuel, oil, SRC, fuel gas
Consol Synthetic Fuel (CSF) (Consolidation Coal Company)	Extraction Carbonization Hydrotreatment	765 925 800	150—400 10 3,000		Vapors, liquids, residue Char, pyrolysis, liquid, gas Naphtha, oil, gas, residue
Exxon Liquefaction (Exxon Research and Engineering Company)	Catalytic Hydrogenation	800	2,000	Coal H-Donor solvent Hydrogen	Naphtha, gas, distillate, heavy bottoms, recycle solvent
H-Coal (Hydrocarbon Research, Inc.)	Ebullated-bed catalytic	850	2,250—2,700	Coal Oil Hydrogen	Synthetic crude oil, gas
Intermediate Hydrogenation (University of Utah)	Entrained-flow catalytic	930—1,020	2,000—2,500	Coal Hydrogen	Liquid, gas
Solvent-Refined Coal (SRC) (Pittsburgh & Midway Coal Mining Company)	Dissolver	815	1,000	Coal Hydrogen Solvent	Solvent-refined coal
Synthoil (U.S. Bureau of Mines, Pitts- burgh Energy Research Center)	Fixed-bed catalytic	850	2,000—4,000	Coal Hydrogen Oil	Fuel oil, gas

Source: I. Howard-Smith and G. J. Werner, *Coal Conversion Technology: A Review*, 1975.

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## INTRODUCTION

The generation of power from nuclear reactions is accomplished by two quite distinct processes. The first (and most highly developed) is nuclear fission. In the fission process, heavy nuclei such as those of uranium and plutonium atoms are split into lighter nuclei by neutron absorption. The splitting of the heavy nuclei results in the release of additional neutrons (which sustain the fission process) and the conversion of a small fraction of mass into kinetic energy of the fission products. The kinetic energy is degraded into thermal energy and the fission process acts simply as a heat source used to make steam to generate electric power.

Although the basic process is conceptually simple, the engineering, control, and safety considerations make fission utilization a highly sophisticated industry requiring the integration of a great many technologies. As a result of the continuing development of each of the technologies involved and of each electric utility's special problems, there is little standardization of commercial nuclear power plants. On the other hand, there has been some degree of standardization in nuclear reactors for naval propulsion because of the specific requirements of marine propulsion systems and their space and structural limitations. Both commercial power generation and naval propulsion systems are discussed further in this chapter.

The second process for using nuclear reactions for power generation is fusion. Fusion is much the opposite of fission in that light nuclei such as those of the hydrogen isotopes deuterium and tritium are combined (or fused) into heavier nuclei such as those of helium. This is the process that occurs within the sun. Again, a small amount of mass is converted into kinetic energy that can be degraded into useful thermal energy. The process is conceptually simple but technically difficult because fusion can occur only under the stringent conditions of ultrahigh temperatures ( $100,000,000^{\circ}\text{K}$ ) for the appropriate fuel confinement time and density.

Basically two approaches are being taken to achieve the conditions necessary for fusion. The first is magnetic confinement of a heated plasma. Several magnetic configurations are under investigation with fusion temperatures now attainable. The second approach to fusion is production of microexplosions that can be achieved by subjecting pellets of a deuterium-tritium mixture to intense bombardment by electron beams or by laser beams. Again, the necessary temperatures can be reached.

Power generation by means of fusion is not a near-term possibility. Many basic problems remain to be solved that will require substantial private and public investments in research.

## NUCLEAR POWER GROWTH

Most of the commercial nuclear electric energy generating capacity in the United States is based on light water reactor (LWR) systems. As of June 30, 1976, there were 32 pressurized water reactors (PWR), 23 boiling water reactors (BWR) and one light water cooled, graphite moderated reactor (LGR) in commercial operation in the United States.<sup>1</sup> The total capacity of these plants was 39,030 MWe or about 8.5 percent of the total electric generating capacity in the United States. The growth rate for nuclear power is a function of the economic conditions of the utilities and of possible delays. Delays encountered by the electric utilities have stemmed from environmental objections, complex licensing procedures, and construction and supply limitations. Table XII-1 presents three estimates of nuclear power capacity in the United States through 2000, with the actual installed capacities for 1960 and 1970 listed.

For comparison, the 1974 year-end installed commercial nuclear capacity was 31,214 MWe and was 36,452 MWe for 1975.<sup>2</sup> The ability to meet nuclear capacity projections depends greatly upon the introduction of several new types of reactors. The reason for this limitation is the finite amount of uranium available from which the light water reactor fuel is obtained. The two most widely discussed alternative reactors are the liquid metal fast breeder reactor (LMFBR) and the high-temperature, gas-cooled reactor (HTGR). Both of these reactors can greatly extend the resource base. The United States has a demonstrated capacity for producing both of these reactors: one HTGR is commercially operational. The U.S. experience with LMFBRs dates back to 1946, and the first electric energy was produced by this kind of reactor in 1951.<sup>3</sup>

<sup>1</sup>Nuclear News, August 1976.

<sup>2</sup>Nuclear News Buyers Guide, Mid-February 1975, pp. 45-56 and Mid-February 1976, pp. 52-64.

<sup>3</sup>Draft Environmental Statement Liquid Metal Fast Breeder Reactor Program, U.S. Atomic Energy Commission WASH-1535, 1974.

Table XII-1

**YEAR-END PROJECTED NUCLEAR CAPACITY**  
(Thousands of MWe)

Estimate	1960	1970	1975	1980	1985	1990	2000
High	0.02	5.8	39	71	166	290	620
Medium	0.02	5.8	39	67	145	250	510
Low	0.02	5.8	39	50	127	195	380

Source: Information from ERDA, Vol. 2, No. 45, November 26, 1976.

### THE NUCLEAR FUEL CYCLE

The use of nuclear fuels differs from fossil fuels in two important ways:

- Before it can be used, the fuel must undergo a complex series of processing and fabrication steps to produce useful fuel elements.
- Nuclear fuels are not completely expended when used in a reactor but are removed, purified, replenished, and refabricated periodically.

These unique characteristics establish a fuel cycle that includes exploration, mining, milling, conversion, enrichment, fabrication, recovery and reprocessing, transportation, and waste disposal. Figure XII-1 shows fuel cycles for the LWR, HTGR, and LMFB. In each case, ERDA and the nuclear industry attempt to optimize the fuel cycle from the long-range economic point of view.

Uranium 235, U-233, and plutonium 239 are the three fissile materials capable of serving as fuels in fission reactors. Of these, only U-235 occurs naturally. The other two can be produced or bred from the fertile materials thorium 232 and U-238 by neutron absorption. Uranium, as it occurs naturally, is 99.284 percent U-238, 0.711 percent U-235, and 0.005 percent U-234. Although reactors such as the Canadian CANDU can operate on natural uranium, the LWRs in use in the United States are designed to operate on uranium that is 2.0 to 3.2 percent U-235.<sup>1</sup>

The fuel cycle for LWRs starts with the mining and milling of uranium ore to obtain yellowcake ( $U_3O_8$ ). The yellowcake is shipped from the mill to a conversion plant where it is converted into uranium hexafluoride ( $UF_6$ ), a solid at room temperatures. The  $UF_6$  is shipped to an ERDA-operated enrichment facility where the ratio of the uranium isotopes (U-235 and U-238) is changed. The portion of the  $UF_6$  that contains a higher than natural percentage (or assay) of U-235 is the enriched uranium and the portion that contains the lower assay is the de-

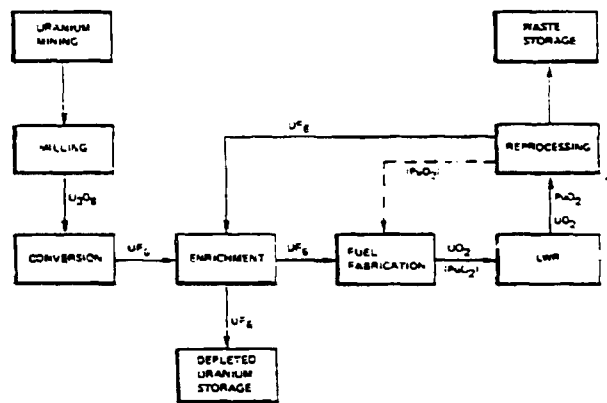
pleted uranium (or tails). The enriched uranium is sent to a fuel fabrication plant where the  $UF_6$  is converted into uranium oxide ( $UO_2$ ) powder and compacted into small cylindrical pellets. The fuel assembly consists of precisely aligned cylinders that contain the fuel pellets. In this form the uranium is ready for use in a reactor. Periodically (usually once a year) LWRs are shut down and refueled. At that time, 25 to 35 percent of the fuel is replaced. The spent fuel is intensely radioactive and is stored at the power plant site for several months before shipping to a reprocessing plant. The spent fuel contains, in addition to U-235 and U-238, isotopes of plutonium and other radioactive materials. The reprocessing procedure separates the uranium and plutonium from the spent fuel and prepares the remaining wastes for storage. The uranium is slightly enriched (0.84 to 0.94 percent) and is shipped back to the enrichment plant for recycling.

In the LWR fuel cycle shown in Figure XII-1, the dashed line indicates the path the plutonium would follow if it were to be recycled for use as LWR fuel. At the present time, plutonium is stockpiled for its anticipated future use in both LWRs and LMFBs. The Nuclear Regulatory Commission (NRC) has proposed to announce its position on plutonium recycle early in 1977.<sup>2</sup>

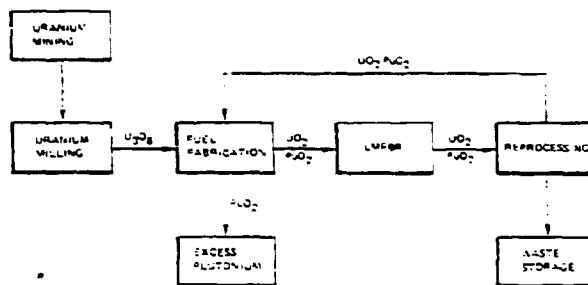
The HTGR fuel cycle in Figure XII-1 is based on the use of both thorium and uranium. The uranium used as a fuel in the HTGR is highly enriched (93.15 percent U-235) and is in the form of uranium carbide ( $UC_2$ ). Excess neutrons from the U-235 fission are absorbed by the thorium nuclei in  $ThC_2$  and U-233 produced. Th-233 is fissile and serves as a fuel for the HTGR.

<sup>1</sup>Nuclear Power Growth 1974-2000. U.S. Atomic Energy Commission, WASH-1139, 1974.

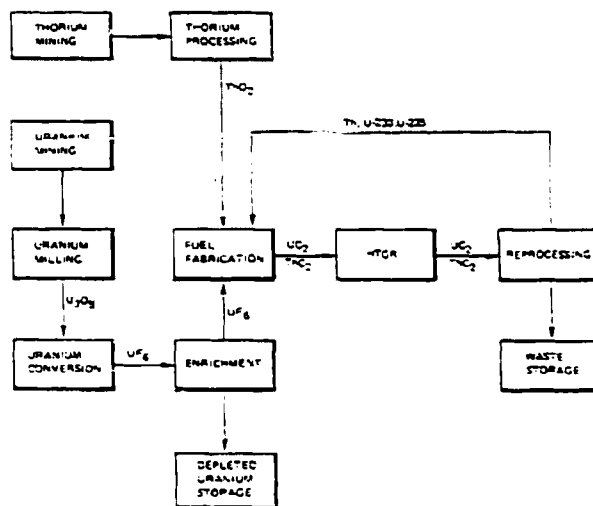
<sup>2</sup>Weekly Energy Report, November 12, 1975.



LIGHT WATER REACTOR FUEL CYCLE



LIQUID METAL FAST BREEDER REACTOR FUEL CYCLE



HIGH TEMPERATURE GAS-COOLED REACTOR FUEL CYCLE

Figure XII-1. LWR, LMFBR, AND HTGR FUEL CYCLES

The LMFBF fuel cycle in Figure XII-1 uses plutonium as a fuel. The U-238 in the natural uranium that serves as the resource base provides the fertile material from which the plutonium is bred. The unique feature of the LMFBF fuel cycle is that more plutonium is bred from the U-238

than is consumed in the reactor. In the sense that plutonium is the fissioning material, more fuel is produced than consumed and the excess plutonium can be used for other reactors such as the light water reactor.

## U.S. URANIUM AND THORIUM RESOURCES

The resource base of uranium and thorium for the nuclear industry is commonly expressed in terms of tons of the resource recoverable at a given cost. Recent estimates of the size of the U.S. nuclear resources are shown in Tables XII-2 and XII-3. The exact extent of thorium deposits is not well known, but thorium is probably a more abundant resource than uranium.

It has been estimated that unconventional supplies of

uranium present in the United States could be recovered at costs of \$100/lb  $U_3O_8$ . These include 2,700,000 tons in very low grade ore and an additional 2,500,000 tons in Chattanooga shale. Also, uranium may be recovered from seawater (0.0033 ppm U) at a recovery cost of approximately \$300/lb  $U_3O_8$ .<sup>1</sup>

<sup>1</sup> *Nuclear News*, July 1975, p. 37.

Table XII-2  
U.S. URANIUM RESOURCES  
(Thousands of tons  $U_3O_8$ )

Recovery Cost	Reserves	Probable	Possible	Speculative
to \$10/lb	270	440	420	145
to \$15/lb	430	655	675	290
to \$30/lb	640	1,060	1,270	590
Byproduct*	140			

\*Byproduct of phosphate and copper production.

Source: *Information from ERDA*,  
Vol. 2, No. 13, April 9, 1976, pp. 5-6.

Table XII-3  
U.S. THORIUM RESERVES

Recovery Cost (\$/lb)	Reasonably Assured Reserves (Tons $ThO_2$ )
to \$10	65,500
to \$30	200,000
to \$50	3,200,000

Source: *Draft Environmental Statement LMFBF Program*, U.S. Atomic Energy Commission, WASH-1535, 1974.

## U.S. ANNUAL DEMAND

The annual demand for yellowcake ( $U_3O_8$ ) depends on the types of reactors in operation, the availability or unavailability of reprocessing facilities and the plutonium recycle, and the assay of the depleted uranium at the enrichment facilities. Table XII-4 presents a variety of projections of uranium requirements for different nuclear power development cases and various assumptions about the fuel cycle. Cases B and D assume that the Barnwell, S.C., reprocessing facility will begin operation in 1981 and will reach a capacity of 1,500 metric tons per year in 1982. (In cases B and D recovered uranium and plutonium are recycled to LWRs after reprocessing unless the plutonium is required by breeder reactors.) It is assumed additional reprocessing facilities will become available as needed. Cases C and E assume that the Barnwell plant begins pilot operations in 1985 and reaches a capacity of 1,000 metric tons per year in 1986. (In cases C and E

recovered uranium is recycled, but the plutonium is used only in breeders.)

At the end of 1973, there were 15  $U_3O_8$  mills in operation or on standby in the United States with a total capacity of 28,450 tons of  $U_3O_8$  per year.<sup>1</sup> In 1975, the production of yellowcake was 12,300 tons with primary uranium demand for nuclear fuels estimated at 15,600 tons.<sup>2</sup> Because of the projections of demand for yellowcake, the existing mining and milling capacity will be exceeded by the late 1970s.

As a result of supply and demand for uranium, the price of yellowcake has doubled in the last year. At t

<sup>1</sup> *Statistical Data of the Uranium Industry*, U.S. Atomic Energy Commission, GJO-100, 1974.

<sup>2</sup> *Commodity Data Summaries 1976*, Bureau of Mines, U.S. Department of Interior, January 1976, p. 182.



Table XII-4

**U.S. URANIUM REQUIREMENTS**  
(Thousands of short tons of  $U_3O_8$ )

Tails Assay	Case A			Case B			Case C		
	0.20%	0.25%	0.35%	0.20%	0.25%	0.30%	0.20%	0.25%	0.30%
1976	10	11	12	11	12	13	11	12	13
1980	17	18	20	19	20	22	19	20	22
1985	29	32	35	31	34	37	36	39	43
1990	43	47	52	41	45	50	55	60	66
2000	74	81	89	65	71	80	82	90	99

Tails Assay	Case D			Case E		
	0.20%	0.25%	0.30%	0.20%	0.25%	0.30%
1976	12	13	14	12	13	14
1980	22	24	26	22	24	26
1985	36	40	44	42	45	50
1990	51	56	62	65	71	78
2000	74	82	92	86	94	105

Case A: Low projection Table XII-1; no recycle of uranium or plutonium.

Case B: Medium projection Table XII-1; uranium and plutonium recycled on constrained basis.

Case C: Medium projection Table XII-1; limited uranium recycle; plutonium not recycled in LWRs.

Case D: High projection Table XII-1; uranium and plutonium recycled on constrained basis.

Case E: High projection Table XII-1; limited uranium recycle; plutonium not recycled in LWRs.

Source: Information from ERDA, Vol. 2, No. 46, November 26, 1976.

end of 1975, the price of yellowcake was \$30/lb for immediate delivery with a price of \$40/lb for delivery in 1980.<sup>1</sup> However, the capital-intensive nature of the nuclear industry makes the cost of power produced almost independent of uranium costs. A \$10/lb increase in the price of yellowcake increases the total fuel cycle cost about 0.8 mill/kWh.<sup>2</sup> Also, uranium supplies have been committed to long-term procurement contracts within the nuclear industry so that the spot price is not an accurate indicator of actual costs to the buyer. The future estimated average delivery prices under contract as of July 1, 1976 are shown in Table XII-5. The prices are for purchases contracted for from 1967 through mid-1976 and do not represent prices at which uranium can be purchased now for delivery in the future. Since the delivery commitments for future years cover only a fraction of projected requirements, the average prices for those years will change as additional uranium is contracted for.

Table XII-5

**AVERAGE  $U_3O_8$  PRICES FOR  
PROCUREMENT CONTRACTS**

Year	Price/lb $U_3O_8$ <sup>a</sup>	Delivery Commitments (tons $U_3O_8$ )
1976	\$12.05	14,900
1977	12.60	13,800
1978	14.30	17,300
1979	16.10	18,000
1980	15.95	17,400
1981	18.60	16,000
1982	19.85	15,800
1983	19.80	12,600
1984	19.55	10,200
1985	19.90	7,900
1976-1985		143,900

<sup>a</sup>Current dollars.

Source: Information from ERDA, Vol. 2, No. 44, November 12, 1976, pp. 1-2.

<sup>1</sup>Nuclear News Buyers Guide, Mid-February 1976, p. 38.

<sup>2</sup>Task Force Report on Nuclear Energy, Project Independence, November 1974.

## CONVERSION, ENRICHMENT, AND FABRICATION

### Conversion

Conversion of the yellowcake ( $\text{U}_3\text{O}_8$ ) to uranium hexafluoride ( $\text{UF}_6$ ) takes place at two plants in the United States. These plants can process 22,400 tons per year of yellowcake and produce 28,100 tons per year of  $\text{UF}_6$ . Planned expansion of an existing facility and the construction of a new plant will double the U.S. conversion capacity.<sup>1</sup> The costs of conversion amount to about 1.5 percent of the cost of the total fuel cycle and have little effect on the cost of power produced.

### Enrichment

Enrichment is a major component of the fuel cycle. ERDA operates three gaseous diffusion plants that take  $\text{UF}_6$  from conversion plants and reprocessing plants and alter the isotopic mixture of U-235 and U-238. The gaseous diffusion process is both capital and power intensive. It is common practice to measure the capacity and productivity of the enrichment process in terms of separative work units. A separative work unit (SWU) is a measure of the effort expended in the plant to separate a quantity of uranium of a given assay into two components, one having a higher percentage of U-235 and one having a lower percentage. Separative work is generally expressed in kilograms to give it the same dimension as material quantities. However, it is common practice to refer to a kilogram SWU simply as an SWU. For example, if a single kilogram of uranium enriched to 3.0 percent U-235 were produced starting with natural uranium (0.711 percent U-235) and with depleted (or tails) uranium of 0.275 percent U-235, then 3.6 SWU would be required. If there was any change in the feed assay, the tails assay or the enrichment assay, the number of SWU would change. For the example cited, 6.25 kilograms of natural uranium are needed to produce a single kilogram of 3.0 percent enriched uranium.<sup>2</sup> Lowering the tails assay would decrease the demand for natural uranium but would increase the separation work required. ERDA operates its diffusion plants at 0.25 percent tails assay.<sup>3</sup>

The three enrichment plants—located at Oak Ridge, Tennessee; Paducah, Kentucky; and Portsmouth, Ohio—operate interdependently with the complex having a capacity of 17.2 million SWU per year in 1973. Operating at full capacity, the three plants consume 6,000 MWe. Because the demand for enrichment services will grow with the nuclear power industry, ERDA is pursuing two programs to increase the diffusion plant capacities. The Cascade Improvement Program (CIP) will increase capacity by 33 percent, and the Cascade Upgrading Program (CUP) will raise that another 21 percent for a total capacity of 27.7 million SWU per year by 1980. At this

capacity, the power demand of the complex will be about 7,400 MWe.<sup>4</sup>

Because of the limitations on electric power available, the enrichment facilities have been operating well below full capacity. The FY 1972 and FY 1973 power levels and production levels and the projected FY 1974 figures for the enrichment plants are shown in Table XII-6. Full production will not be achieved until about 1978.

The projected demands for separative work are shown in Table XII-7. These projections were made assuming a 0.30 percent tails assay with plutonium recycle in 1977. Without plutonium recycle, the demand for enrichment services will increase.

The current cost of enrichment is \$61.30/SWU for fixed-commitment, long-term contracts and \$66.75/SWU for requirements-type contracts. The cost of enrichment had been \$59.05/SWU for fixed-commitment contracts before October 1, 1976 and \$42.10/SWU before August 20, 1975. The price of requirements-type contracts will have increased to \$69.80/SWU on January 27, 1977.<sup>5</sup> By 1981, ERDA plans to increase the cost of enrichment services to about \$76/SWU.<sup>6</sup> An increase from \$42 to \$76/SWU increases the fuel cycle costs by about 0.9 mills/kWh.<sup>6</sup>

ERDA plans an expansion of its Portsmouth, Ohio, gaseous diffusion plant. After completion of CIP and CUP in 1981, the capacity will have been increased from 5.2 to 8.4 million SWU per year. The proposed increase in plant size will add 8.75 million SWU per year by the mid-1980s and will require 3,500 to 3,700 MWe of additional power.<sup>7</sup>

The future expansion of enrichment facilities in the United States is a matter of Congressional debate. Several proposals have been made by private industry to enter the enrichment market.

Two alternatives to gaseous diffusion are under investigation in the United States. The first, the gaseous centrifuge, is at the pilot-plant stage. This process consumes only 10 percent of the power of a gaseous diffusion plant

<sup>1</sup>"Task Force Report on Nuclear Energy," *Project Independence*, November 1974, and *Nuclear News*, April 1974.

<sup>2</sup>AEC Gaseous Diffusion Plant Operations, U.S. Atomic Energy Commission, ORO-684, 1972.

<sup>3</sup>*Energy Daily*, September 9, 1976.

<sup>4</sup>"Task Force Report on Nuclear Energy," *Project Independence*, November 1974 and Vincent V. Abajian and Alan M. Fishman, "Supplying Enriched Uranium," *Physics Today*, August 1973, pp. 23-29.

<sup>5</sup>Information from ERDA, Vol. 2, No. 30, August 6, 1976.

<sup>6</sup>"Task Force Report on Nuclear Energy," *Project Independence*, November 1974.

<sup>7</sup>Information from ERDA, Vol. 2, No. 41, October 22, 1976.

Table XII-6

## ENRICHMENT OPERATIONS

	MWe	Million SWU
FY 1972	2626	8.4
FY 1973	3227	10.3
FY 1974	4069	12.7

Source: *The Nuclear Industry, 1973*, U.S. Atomic Energy Commission WASH-1174-73 UC-2.

for the same separative work and has been demonstrated to be effective in both the United States and Europe. The second is isotope separation by lasers. This is still in the experimental stage and can only be considered to be a possible long-term enrichment method.

## Fabrication

There are five operating fuel fabrication plants in the United States with a total capacity of 3,025 tons of uranium per year. Industry plans will add a capacity of

Table XII-7

ANNUAL SEPARATIVE WORK DEMAND  
(Million SWU)

	1974	1977	1980	1985	1990	2000
High	4.6	7.2	13.9	28.5	53.4	97.4
Reasonable	3.3	7.2	14.1	26.4	46.0	84.0
Low	2.5	6.2	11.3	23.0	36.3	57.4

Source: *Nuclear Power Growth 1974-2000*, U.S. Atomic Energy Commission, WASH-1139, 1974.

6,000 tons of uranium per year by 1980.<sup>1</sup> The fabrication facilities convert the  $UF_6$  from the enrichment plant to  $UO_2$ . The  $UO_2$  is formed into pellets and sintered before loading into zircaloy or stainless steel tubes which are welded shut. The completed fuel rods are assembled into fuel element arrays before shipping to a nuclear power plant.

<sup>1</sup> "Task Force Report on Nuclear Energy," *Project Independence*, November 1974.

## NUCLEAR REACTORS

Both the boiling water reactor (BWR) and the pressurized water reactor (PWR) are fueled with slightly enriched  $UO_2$  and are cooled by ordinary water. In the BWR, the pressure is maintained at about 1,000 psig and steam is generated in the primary coolant loop at 545° F. The steam is passed directly through a turbine to drive an electric generator. In the PWR, the pressure in the reactor vessel is maintained at 2,050 psig and the water does not boil. The heated water passes through steam generators where the heat is transferred to water in a secondary loop at lower pressures and steam is formed for driving the turbines. Simplified diagrams of BWR and PWR systems are shown in Figure XII-2. Some of the significant characteristics of these reactor systems appear in Table XII-8.

The high-temperature gas-cooled reactor (HTGR) diagrammed in Figure XII-3 operates on the U-233, Th-232 cycle. The primary coolant is helium, which passes through the reactor core consisting of a mixed  $UC_2$ ,  $ThC_2$  fuel. The present generation of HTGRs is designed so that the helium coolant transfers the heat of reaction to a steam generator. The primary coolant reaches 1,400° F and the steam is generated at 950° F and 2,400

psig. The high operating temperatures of the HTGR give it a thermal efficiency of nearly 40 percent. If a direct-cycle, helium-driven turbine is developed, the efficiency could be increased to as much as 50 percent.<sup>1</sup> Because of the slowed growth rate of the electric power industry, most of the HTGRs that were on order have been cancelled and the HTGR has yet to demonstrate economic feasibility. One of the advantages of the HTGR over the BWR and PWR is its lower demand for natural uranium. (See Table XII-8.)

The liquid metal fast breeder reactor (LMFBR)<sup>2</sup> is being developed because of the limited size of the uranium resource base. The LMFBR utilizes a high percentage of the energy potentially available in the uranium. Light water reactors and HTGRs use only 1 to 2 percent

<sup>1</sup> *Draft Environmental Statement Liquid Metal Fast Breeder Reactor Program*, U.S. Atomic Energy Commission WASH-1535, 1974.

<sup>2</sup> In nuclear reactor terminology the term "fast" designates that the neutrons on the average have high velocities (i.e. fast neutron spectrum); slow (or thermal) neutrons have low velocities.

Table XII-8

NUCLEAR REACTOR CHARACTERISTICS<sup>a</sup>

Characteristic	BWR	PWR	HTGR	LMFBR
Thermal efficiency (percent)	34	33	40	40
Raw material demand U <sub>3</sub> O <sub>8</sub> (tons)	180	190	100	1.62 <sup>b</sup>
Raw material demand ThO <sub>2</sub> (tons)			8.6	
Enrichment demand <sup>c</sup> (SWU)	84000	94000	67000	
Fresh fuel assay (percent U-235)	2.7	3.2	93	
Spent fuel assay (percent U-235)	0.8	0.9		
Reprocessing demand (tons)	30	27	11	21
Plutonium production (tons)	0.18	0.19		0.31
Primary loop pressure (psig)	1000	2050	700	200
Primary loop temperature (° F)	545	600	1400	1000
Steam loop pressure (psig)	<i>d</i>	800	2400	1450
Steam loop temperature (° F)	<i>d</i>	500	950	900

<sup>a</sup>For 1000 MWe plant, steady state conditions, 75 percent plant factor, no plutonium recycle except in LMFBR.

<sup>b</sup>Uranium feed can consist of depleted tails in stockpile, no enrichment needed.

<sup>c</sup>Tails assay 0.30 percent.

<sup>d</sup>There is no secondary loop for a BWR.

Sources: *Nuclear Power Growth 1974-2000*, U.S. Atomic Energy Commission, WASH-1139, 1974; *AEC Gaseous Diffusion Plant Operations*, U.S. Atomic Energy Commission, ORO-684, 1972; *The Nuclear Industry 1973*, U.S. Atomic Energy Commission, WASH-1174-73 UC-2; and *Draft Environmental Statement Liquid Metal Fast Breeder Reactor Program*, U.S. Atomic Energy Commission, WASH-1535, 1974.

of the available energy while the LMFBR is designed to use 60 to 70 percent of that energy. As indicated in Table XII-8, the demand for U<sub>3</sub>O<sub>8</sub> for the breeder is about one hundredth of that for LWRs. This breeder reactor uses sodium as the primary coolant. A secondary sodium loop is used to transfer heat from the primary loop to the steam loop. The overall thermal efficiency of the LMFBR is expected to be about 40 percent.

The pressurized water reactor is generally accepted as the preferred nuclear power conversion system for ship propulsion. Nuclear reactors have proven successful in terms of safety and reliability on both submarines and surface ships. The U.S. Maritime Administration operated the *USS Savannah* from 1962 to 1970 to demonstrate the feasibility of commercial nuclear-powered vessels. The

reactor was a PWR that generated 20,000 shaft horsepower. Currently, there is only one operating commercial nuclear ship, the West German 10,000 shaft horsepower *Otto Hahn*. It uses an advanced PWR termed the Consolidated Nuclear Steam Generator (CNSG) in which the primary coolant flow is entirely within the reactor pressure vessel.<sup>1</sup> Economics in the maritime industry do not support commercial development of fleets of nuclear merchant ships.

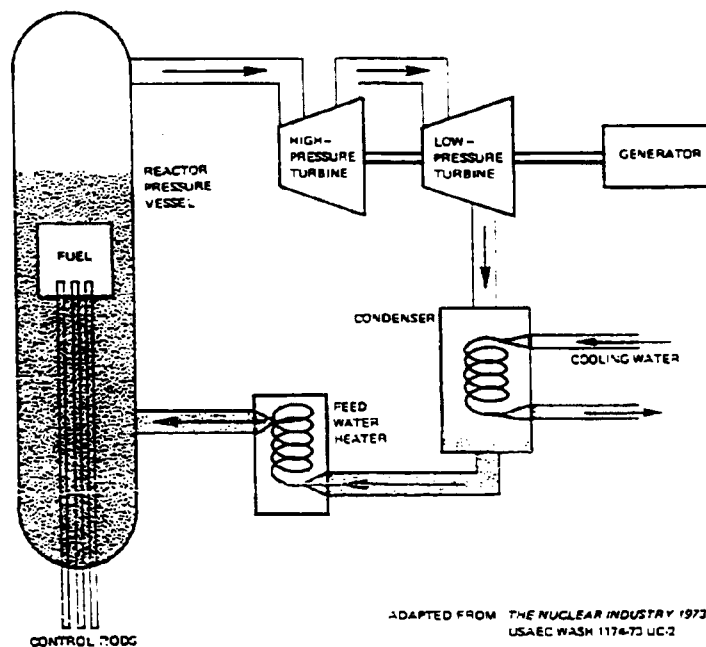
<sup>1</sup>*The Nuclear Industry, 1973*, U.S. Atomic Energy Commission, WASH-1174-73 UC-2, and R. A. Grams, W. L. Sage, and G. W. Geyer, "Fuels for Marine Steam Propulsion," The Society of Marine Port Engineers 22nd Annual Fort Schuyler Forum, March 1974.

## REPROCESSING AND WASTE MANAGEMENT

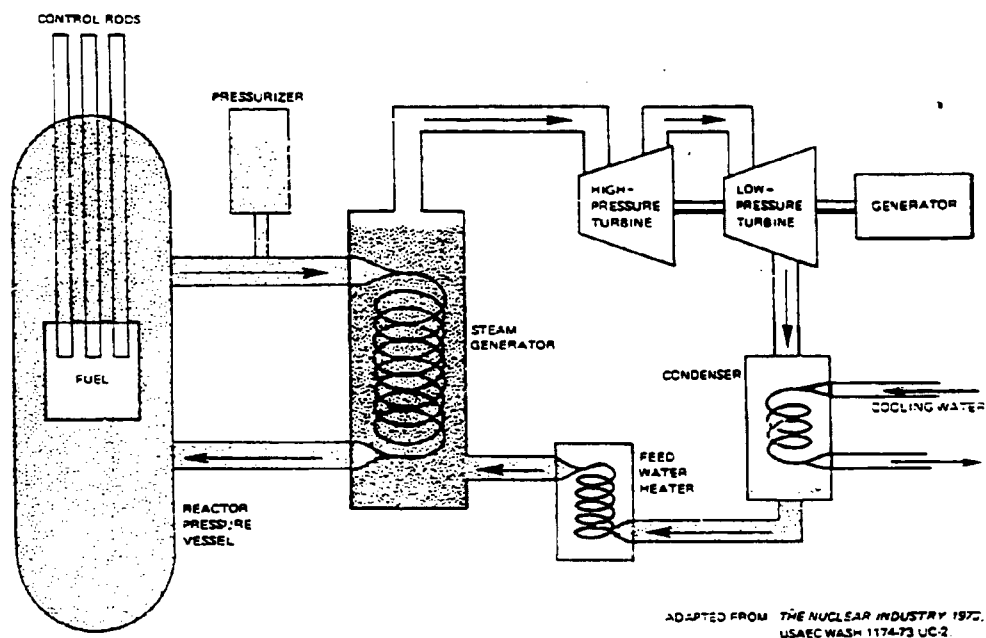
During reprocessing of spent fuel from nuclear power plants, the usable fissile materials are recovered and the waste materials are separated for storage. For a light water reactor, the recovered uranium is still slightly enriched and is shipped to an enrichment facility where it

serves as feedstock. For each ton of uranium reprocessed, approximately 3 grams of plutonium are recovered and stored.

No fuel reprocessing plants are in commercial operation, and power plants are storing spent fuel at their plant

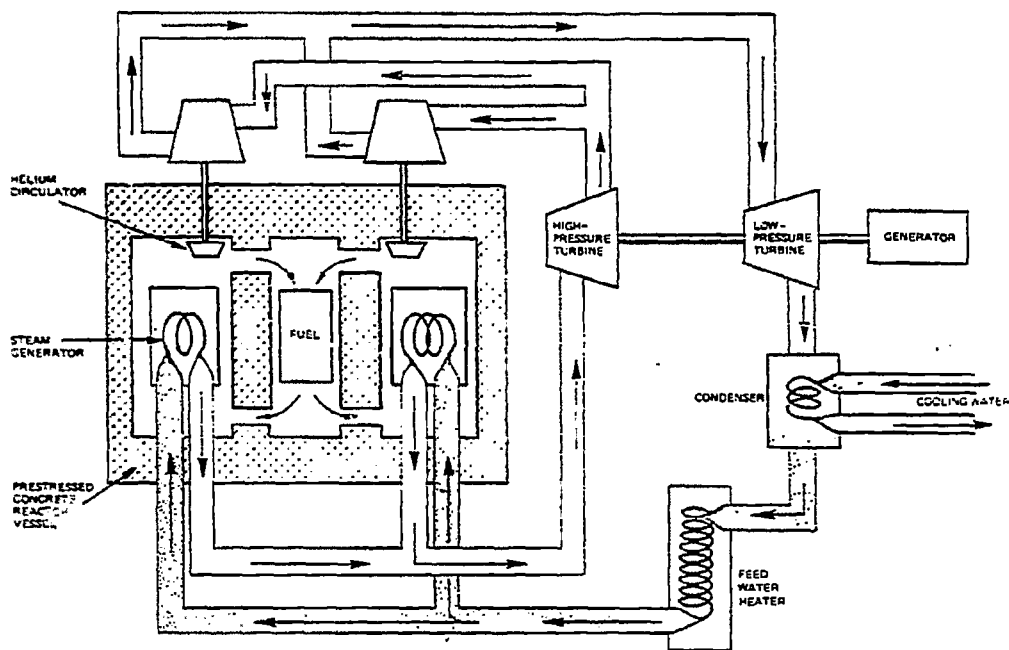


BOILING WATER REACTOR



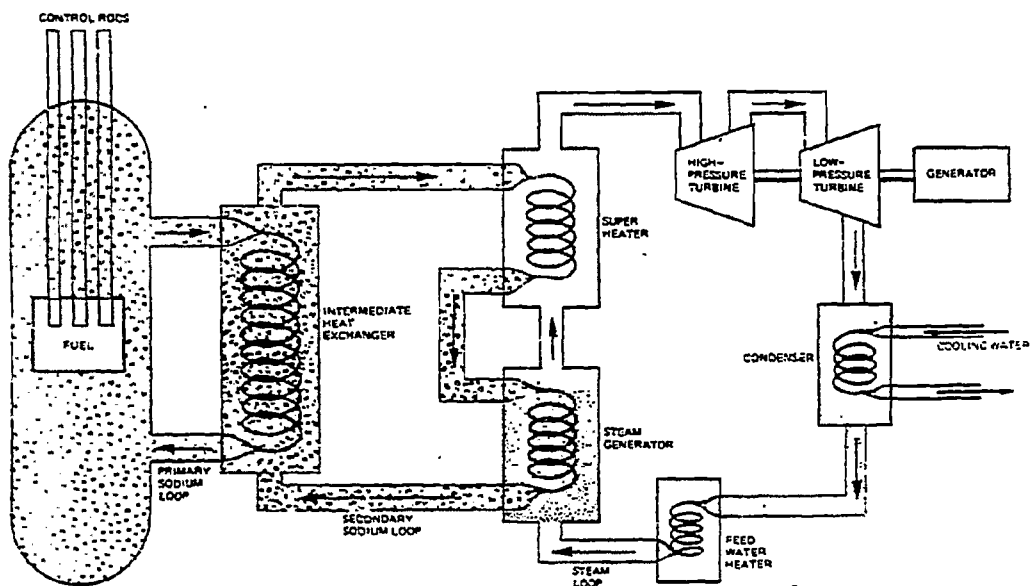
PRESSURIZED WATER REACTOR

Figure XII-2. SCHEMATIC DIAGRAMS FOR BOILING WATER  
AND PRESSURIZED WATER REACTORS



ADAPTED FROM THE NUCLEAR INDUSTRY 1972,  
USAEC WASH 1176-73 UCQ

HIGH-TEMPERATURE, GAS-COOLED REACTOR



ADAPTED FROM DRAFT ENVIRONMENTAL STATEMENT  
LIQUID METAL FAST BREEDER REACTOR  
PROGRAM USAEC WASH 1525-74

LIQUID METAL FAST BREEDER REACTOR

Figure XII-3. SCHEMATIC DIAGRAMS FOR HGTR AND LMFBR REACTORS

sites until reprocessing plants enter operation. The Nuclear Fuel Services plant in West Valley, New York, was in operation from 1966 to 1971 when it was shut down for modification and expansion. It is not expected to reopen. The Barnwell Nuclear Fuel Plant in South Carolina may be able to start operating in 1981. The Barnwell plant has a projected capacity of 1,500 metric tons per year. While in operation, the Nuclear Fuel Services plant charged about \$35,000 per ton of uranium processed. The reprocessing costs are likely to increase fourfold, increasing the fuel cycle cost by about 0.4 mills/kWh.

The management of nuclear wastes is an unsettled

issue. Commercial high-level wastes are stored in liquid form in underground tanks. ERDA is continuing its investigations into methods of storage of these wastes, including solidification. In February 1976, ERDA dropped plans for a Retrievable Surface Storage Facility (RSSF), a nonpermanent solution to the high level waste storage problem. Waste management is now geared to solidification with geologic isolation. The current program calls for the construction of a Bedded Salt Pilot Plant (BSPP) for safe, terminal storage. This is the approach that has been taken in Europe.

## RESEARCH PROGRAMS

The lead agency in nuclear power research and development is ERDA. Of the ERDA-sponsored programs, the urgent are those supporting development of the LMFBR. One of the key elements in that program is the Fast Flux Test Facility (FFTF) at the Hanford Engineering Development Laboratory (HEDL). The purpose of the FFTF is to provide a neutron environment similar to that anticipated in a fast breeder reactor to test fuel elements and reactor components. Cost of the FFTF was originally estimated to be \$87 million; the entire FFTF program is now expected to approach \$1 billion. The second major element of the LMFBR program is the construction of a demonstration breeder, the Clinch River Breeder Reactor (CRBR), near Oak Ridge, Tennessee. The cost estimate of the CRBR program has grown to \$1.7 billion, with possible start of operation in 1982. However, before starting construction, ERDA must issue a final environmental impact statement for the entire breeder program, must await the Nuclear Regulatory Commission (NRC) final environmental statement on the CRBR, and must obtain NRC authorization.

ERDA also sponsors several other breeder programs, including the Light Water Breeder Reactor (LWRB). An LWRB core is planned for the Shippingport, Pennsylvania, Atomic Power Station to demonstrate the technical feasibility of this concept in PWRs. This reactor had its core installed in 1976 and should demonstrate the feasibility of converting PWR systems to breeders. Another breeder concept under investigation is the gas-cooled, fast reactor (GCFR), which would operate on the thorium-uranium fuel cycle.

ERDA continues to support research on thermal (non-breeder) reactors. Experimental work is being funded on the HTGR and on the very high temperature gas-cooled

reactor (VTGR). Closely associated with these programs are the development of a direct-cycle gas turbine and the thorium-uranium fuel cycle. For existing LWR systems, ERDA is investigating ways of improving reliability and efficiency. Related to these programs are improvements in the enrichment facilities and the support of advanced isotope separation technologies (gaseous centrifugation and laser separation).

Fusion research is split into two basic areas. The laser fusion program is included in the ERDA weapons activities because of possible military applications. A portion of the laser fusion funds has been designated for KMS Industries, a corporation that has shown considerable expertise in laser fusion. The major element of the magnetic confinement approach to fusion is the construction of a Tokamak fusion test reactor at the Princeton Plasma Physics Laboratory. Two related programs are the intense neutron source projects at Los Alamos Scientific Laboratory (LASL) and at the Lawrence Livermore Laboratory (LLL). These programs will investigate anticipated materials problems that may occur with intense neutron fluxes at 14 MeV.

ERDA's Division of Naval Reactors is directing its efforts toward development of improved nuclear propulsion plants and reactor cores for nuclear-powered warships.

DOD has supported development of small nuclear power plants for remote bases. The Army has the lead for development of this type of reactor and currently has a 20 MW plant in operation in the Panama Canal Zone.<sup>1</sup>

<sup>1</sup> "A Study of the Navy's Energy Research Needs—From the Viewpoint of NRL Involvement," *NRL Memorandum Report 3027*, November 1974.

**WORLD LIST OF NUCLEAR POWER PLANTS**  
**OPERABLE, UNDER CONSTRUCTION, OR ON ORDER (30 MWe AND OVER)**  
**AS OF JUNE 30, 1976**

	Net MWe	Type	Commercial Operation
<b>ARGENTINA</b>			
Comision Nacional de Energia Atomica			
Atucha (Lima, Buenos Aires)	319	PHWR	6/74
Rio Tercero (Embalse, Cordoba)	600	PHWR	12/79
<b>AUSTRIA</b>			
Gemeinschaftskernkraftwerk Tullnerfeld (GKT)			
Tullnerfeld 1 (Vienna area)	692	BWR	10/76
<b>BELGIUM</b>			
Societe Belgo-Francaise d'Energie Nucleaire Mosane (SEMO)			
Tihange 1 (Huy, Liege)	870	PWR	9/75
Societes Reunies d'Energie du Bassin de l'Escaut (EBES)			
Doel 1 (Antwerp)	390	PWR	2/75
Doel 2 (Antwerp)	390	PWR	11/75
Doel 3 (Antwerp)	897	PWR	2/80
CNW 1 (undesignated)	1,000	PWR	12/81
Societe Intercommunale Belge de Gaz et d'Electricite (INTERCOM)			
Tihange 2 (Huy, Liege)	910	PWR	4/80
CNW 2 (undesignated)	1,000	PWR	4/82
<b>BRAZIL</b>			
Furnas			
Angra 1 (Itaorna)	626	PWR	9/78
Angra 2 (Itaorna)	1,245	PWR	12/82
Angra 3 (Itaorna)	1,245	PWR	6/84
<b>BULGARIA</b>			
Kozloduy 1 (Kozloduy)	440	PWR	12/74
Kozloduy 2 (Kozloduy)	440	PWR	12/75
Kozloduy 3 (Kozloduy)	440	PWR	7/78
Kozloduy 4 (Kozloduy)	440	PWR	7/79
<b>CANADA</b>			
New Brunswick Electric Power Commission			
Point Lepreau (Bay of Fundy, N.B.)	600	PHWR	10/79
Ontario Hydro			
Douglas Point (Tiverton, Ont.)	206	PHWR	9/68
Pickering 1 (Pickering, Ont.)	514	PHWR	7/71
Pickering 2 (Pickering, Ont.)	514	PHWR	12/71
Pickering 3 (Pickering, Ont.)	514	PHWR	6/72
Pickering 4 (Pickering, Ont.)	514	PHWR	6/73
Pickering 5 (Pickering, Ont.)	516	PHWR	4/81
Pickering 6 (Pickering, Ont.)	516	PHWR	1/82
Pickering 7 (Pickering, Ont.)	516	PHWR	10/82
Pickering 8 (Pickering, Ont.)	516	PHWR	7/83
Bruce 1 (Tiverton, Ont.)	746	PHWR	6/77
Bruce 2 (Tiverton, Ont.)	746	PHWR	9/76
Bruce 3 (Tiverton, Ont.)	746	PHWR	6/73
Bruce 4 (Tiverton, Ont.)	746	PHWR	6/79
Bruce 5 (Tiverton, Ont.)	769	PHWR	10/83
Bruce 6 (Tiverton, Ont.)	769	PHWR	7/84
Bruce 7 (Tiverton, Ont.)	769	PHWR	4/85
Bruce 8 (Tiverton, Ont.)	769	PHWR	1/86
Hydro Quebec			
Gentilly 1 (Becancour, Que.)	250	SLWR	5/72
Gentilly 2 (Becancour, Que.)	600	PHWR	7/79
<b>CZECHOSLOVAKIA</b>			
Bohunice 1A	110	GCHWR	7/72
Bohunice 2A	440	PWR	12/77
Bohunice 2B	440	PWR	12/78
Czechoslovakian 3	440	PWR	12/79
Czechoslovakian 4	440	PWR	12/80



# WORLD LIST OF NUCLEAR POWER PLANTS (continued)

	Net MWe	Type	Commercial Operation
<b>FINLAND</b>			
Imatran Voima Osakeyhtio			
Loviisa 1 (Loviisa)	420	PWR	12/76
Loviisa 2 (Loviisa)	420	PWR	8/78
Teollisuuden Voima Osakeyhtio			
TVO 1 (Olkiluoto)	660	BWR	8/78
TVO 2 (Olkiluoto)	660	BWR	8/80
<b>FRANCE</b>			
Electricite de France			
Marcoule G2 (Marcoule)	40	GCR	4/59
Marcoule G3 (Marcoule)	40	GCR	5/60
Chinon 2 (Avoine)	210	GCR	2/65
Chinon 3 (Avoine)	400	GCR	8/67
Monts d'Arrée (Brennilis)	70	GCHWR	7/67
Saint-Laurent-des-Eaux 1 (Orleans)	460	GCR	3/69
Saint-Laurent-des-Eaux 2 (Orleans)	515	GCR	8/71
Phenix (Marcoule)	233	LMFBR	12/73
Bugey 1 (St-Vulbas)	540	GCR	4/72
Fessenheim 1 (Haut Rhin)	890	PWR	3/77
Fessenheim 2 (Haut Rhin)	890	PWR	4/77
Bugey 2 (Ain)	925	PWR	3/77
Bugey 3 (Ain)	925	PWR	8/77
Saint-Laurent-des-Eaux 3 (Orleans)	954	BWR	1/79
Saint-Laurent-des-Eaux 4 (Orleans)	954	BWR	1/80
Bugey 4 (Ain)	905	PWR	5/78
Bugey 5 (Ain)	905	PWR	11/78
Dampierre 1 (Loiret)	905	PWR	7/79
Dampierre 2 (Loiret)	905	PWR	1/80
Dampierre 3 (Loiret)	905	PWR	7/80
Dampierre 4 (Loiret)	905	PWR	4/81
Gravelines B1 (Nord)	925	PWR	5/79
Gravelines B2 (Nord)	925	PWR	10/79
Gravelines B3 (Nord)	925	PWR	6/80
Gravelines B4 (Nord)	925	PWR	2/81
Tricastin 1 (Drome)	925	PWR	2/79
Tricastin 2 (Drome)	925	PWR	8/79
Tricastin 3 (Drome)	925	PWR	3/80
Tricastin 4 (Drome)	925	PWR	12/80
Blayais 1 (Gironde)	925	PWR	2/81
Blayais 2 (Gironde)	925	PWR	9/81
Chinon B1 (Loiret)	905	PWR	1/81
Chinon B2 (Loiret)	905	PWR	1/82
Fessenheim 3 (Haut Rhin)	905	PWR	1/82
Fessenheim 4 (Haut Rhin)	905	PWR	1/83
Undesignated	905	PWR	-
Undesignated	905	PWR	-
Paluel 1 (Calvados)	1,300	PWR	1/82
Undesignated	1,300	PWR	-
Undesignated	1,300	PWR	-
Undesignated	1,300	PWR	-
Societe d'Energie Nucleaire Franco-Belge des Ardennes (SENA)			
SENA (Chooz)	310	PWR	4/67
<b>GERMANY (DEMOCRATIC REPUBLIC)</b>			
Rheinsberg 1 (Rheinsberg, Gransee region)	70	PWR	5/66
Nord 1-1 (Lubmin, Greifswald region)	440	PWR	12/73
Nord 1-2	440	PWR	1/75
Nord 2-1	440	PWR	1/77
Nord 2-2	440	PWR	1/78
Magdeburg 1	440	PWR	1/80
Magdeburg 2	440	PWR	1/80
<b>GERMANY (FEDERAL REPUBLIC)</b>			
Gemeinschaftskernkraftwerk Neckar (GKN)			
GKN 1 (Neckarwestheim)	905	PWR	8/76
GKN 2 (Neckarwestheim)	905	PWR	1/81

# WORLD LIST OF NUCLEAR POWER PLANTS (continued)

	Net MWe	Type	Commercial Operation
<b>GERMANY (FEDERAL REPUBLIC) (continued)</b>			
Kern kraftwerk Krummel GmbH (KKK)			
Krummel KKK (Geesthacht-Krummel/Elbe)	1,260	BWR	3/79
Hochtemperatur Kernkraftwerk GmbH (HKG)			
THTR 300 (Hamm-Uentrop)	300	THTR	/77
Kernforschungszentrum Karlsruhe			
Karlsruhe MZFR (Karlsruhe)	52	PHWR	10/62
Kernkraftwerk Brokdorf GmbH			
Brokdorf (River Elbe)	1,300	PWR	-
Kernkraftwerk Brunsbüttel GmbH (KKB)			
Brunsbüttel (Brunsbüttel/Elbe)	771	BWR	9/75
Kernkraftwerk Hamm GmbH (KKH)			
Hamm (Hamm-Uentrop)	1,300	PWR	/81
Kernkraftwerk Isar (KKI)			
Isar KKI (Ohu)	870	BWR	5/77
Kernkraftwerk Lingen GmbH (KWL)			
Lingen KWL (Lingen)	256	BWR	10/68
Bayernwerk AG			
KKG (Grafenrheinfeld)	1,225	PWR	9/79
Kernkraftwerk Obrigheim GmbH (KWO)			
Obrigheim KWO (Obrigheim)	328	PWR	3/69
Kernkraftwerk Philippsburg (KKP)			
KKP 1 (Philippsburg)	864	BWR	/77
KKP 2 (Philippsburg)	1,250	PWR	/82
Kernkraftwerk RWE-Bayernwerk GmbH (KRB)			
KRB I Block A (Gundremmingen)	237	BWR	4/67
KRB II Block B (Gundremmingen)	1,249	BWR	7/62
KRB II Block C (Gundremmingen)	1,249	BWR	7/81
Kernkraftwerk Stade GmbH (KKS)			
Stade KKS (Stade)	630	PWR	5/72
Kernkraftwerk Sud GmbH (KWS)			
Upper Rhine	1,300	PWR	6/79
Preussische Elektrizitäts AG (PREAG)			
KWW (Wuergassen)	640	BWR	3/72
Kernkraftwerk Unterwieser GmbH			
KKU (Esenshamm)	1,230	PWR	1/77
Gemeinschaftskernkraftwerk Grohnde GmbH			
KWG (Grohnde)	1,294	PWR	2/81
Rheinisch-Westfälisches Elektrizitätswerk AG (RWE)			
Biblis A (Worms/Rhein)	1,146	PWR	6/74
Biblis B (Worms/Rhein)	1,240	PWR	8/76
Biblis C (Worms/Rhein)	1,228	PWR	/81
Kaerlich	1,228	PWR	5/78
Schnell-Brüter-Kernkraftwerksgesellschaft (SBK)			
Kalkar SNR 300 (Kalkar)	282	LMFBR	9/81
<b>HUNGARY</b>			
Hungarian Electrical Works			
Paks 1 (Paks)	440	PWR	/80
Paks 2 (Paks)	440	PWR	/80
Paks 3 (Paks)	440	PWR	-
Paks 4 (Paks)	440	PWR	-
<b>INDIA</b>			
Atomic Energy Commission, Department of Atomic Energy			
Tarapur 1 (Bombay)	200	BWR	10/69
Tarapur 2 (Bombay)	200	BWR	10/69
RAPS 1 (Kota, Rajasthan)	202	PHWR	12/73
RAPS 2 (Kota, Rajasthan)	202	PHWR	3/77
MAPP 1 (Kalpakkam, Tamil Nadu)	220	PHWR	/78
MAPP 2 (Kalpakkam, Tamil Nadu)	220	PHWR	/79
Narora 1 (Uttar Pradesh)	220	PHWR	/81
Narora 2 (Uttar Pradesh)	220	PHWR	/82
<b>IRAN</b>			
Iran 1	1,200	PWR	/80
Iran 2	1,200	PWR	/81

# WORLD LIST OF NUCLEAR POWER PLANTS (continued)

	Net t/We	Type	Commercial Operation
<b>IRAN (continued)</b>			
Iran 3	900	PWR	/82
Iran 4	900	PWR	/83
<b>ITALY</b>			
Ente Nazionale per l'Energia Elettrica (ENEL)			
Latina (Borgo Sabotino)	150	GCR	1/64
Garigliano (Sessa Aurunca)	150	BWR	5/64
Trino Vercellese (Vercelli)	247	PWR	1/65
Cirene (Latina)	40	LWCHW	/79
Caorso (Caorso, Piacenza)	840	BWR	12/75
ENEL 5 (site not yet approved)	952	PWR	/81
ENEL 6 (site not yet approved)	982	BWR	/81
ENEL 7 (undesignated)	952	PWR	/82
ENEL 8 (undesignated)	982	BWR	/82
<b>JAPAN</b>			
Tohoku Electric Power Co.			
Hamaoka 1 (Hamaoka-cho)	516	BWR	3/76
Hamaoka 2 (Hamaoka-cho)	814	BWR	3/78
Chugoku Electric Power Co., Inc.			
Shimane (Kashima-cho, Shimane-Pref.)	439	BWR	3/74
Japan Atomic Power Co. Ltd. (JAPC)			
Tokai 1 (Tokai Mura)	159	GCR	7/66
Tsuruga (Tsuruga)	340	BWR	3/70
Tokai 2 (Tokai Mura)	1,067	BWR	12/77
Kansai Electric Power Co., Inc.			
Mihama 1 (Mihama-cho)	320	PWR	11/70
Mihama 2 (Mihama-cho)	470	PWR	7/72
Takahama 1 (Takahama-cho)	781	PWR	11/74
Takahama 2 (Takahama-cho)	781	PWR	11/75
Ohi 1 (Ohi-cho)	1,122	PWR	6/78
Mihama 3 (Mihama-cho)	781	PWR	12/76
Ohi 2 (Ohi-cho)	1,122	PWR	12/78
Kyushu Electric Power Corp.			
Genkai 1 (Genkai, Saga)	559	PWR	10/75
Genkai 2 (Genkai, Saga)	559	PWR	3/81
Power Reactors & Nuclear Fuel Development Corp.			
Fugen, ATR (Tsuruga)	200	LWCHR	7/77
Monju	300	LMFBR	10/82
Shikoku Electric Power Co.			
Ikata (Ikata-cho-Ehime prefecture)	538	PWR	4/77
Tohoku Electric Power Co., Inc.			
Onagawa (Oshikagun)	500	BWR	8/80
Tokyo Electric Power Co.			
Fukushima 1 (Fukushima)	460	BWR	3/71
Fukushima 2 (Fukushima)	784	BWR	5/73
Fukushima 3 (Fukushima)	784	BWR	3/76
Fukushima 4 (Fukushima)	784	BWR	10/78
Fukushima 5 (Fukushima)	784	BWR	4/78
Fukushima 6 (Fukushima)	1,100	BWR	10/79
<b>KOREA (SOUTH)</b>			
Korea Electric Co.			
Ko-Ri 1 (Ko-Ri, near Pusan City)	564	PWR	11/77
Ko-Ri 2 (Ko-Ri)	605	PWR	/83
Wolsung 1 (near Ulsan)	629	PWR	1/82
<b>LUXEMBOURG</b>			
Luxembourg Nuclear Power Company (SENU)			
Remerschen (upper Mosel River)	1,300	PWF	-
<b>MEXICO</b>			
Comision Federal de Electricidad			
Laguna Verde 1 (Laguna Verde, Veracruz)	654	BWR	3/80
Laguna Verde 2 (Laguna Verde, Veracruz)	654	BWR	3/81

# WORLD LIST OF NUCLEAR POWER PLANTS (continued)

	Net MWe	Type	Commercial Operation
<b>NETHERLANDS</b>			
Gemeenschappelijke Kernenergiecentrale Nederland NV (GKN) Dordrecht (Dordrecht, Betuwe)	55	BWR	3/69
NV Provinciale Zeeuwse Energie Maatschappij (PZEM) Borssele (Borssele)	477	PWR	10/73
<b>PAKISTAN</b>			
Pakistan Atomic Energy Commission Kanupp (near Karachi)	125	PHWR	12/72
<b>PHILIPPINES</b>			
Philippine National Power Corp. Philippines 1 (Bagac, N. Luzon)	626	PWR	1/82
Philippines 2 (Bagac, N. Luzon)	626	PWR	1/82
<b>POLAND</b>			
Zarnowieckie	440	PWR	1/83
<b>ROMANIA</b>			
Romania-1 (Olt)	440	PWR	1/80
<b>SPAIN</b>			
Centrales Nucleares del Norte, SA (NUCLENOR) Santa Maria de Garona (Santa Maria de Garona, Burgos)	440	BWR	3/71
Compania Sevillana de Electricidad SA, Hidroelectrica Espanola SA Valdecaballeros 1 (Badajoz)	937	BWR	1/81
Valdecaballeros 2 (Badajoz)	937	BWR	1/82
Compania Sevillana de Electricidad SA, Hidroelectrica Espanola SA, and Union Electrica SA Almaraz 1 (Almaraz, Caceres)	900	PWR	6/77
Almaraz 2 (Almaraz, Caceres)	900	PWR	1/78
Central Nuclear de Asco Asco 1 (Asco, Tarragona)	890	PWR	12/78
Asco 2 (Asco, Tarragona)	890	PWR	6/79
Hidroelectrica Espanola, SA Cofrentes (Valencia)	930	BWR	4/80
Cabo Cope (Murcia)	930	BWR	Indef.
Hispano-Francesa de Energia Nuclear, SA (HIFRENSA) Vandellos (Tarragona)	480	GCR	7/72
Iberduero SA Lemoniz 1 (Lemoniz, Vizcaya)	900	PWR	3/78
Lemoniz 2 (Lemoniz, Vizcaya)	900	PWR	4/79
Union Electrica (UE) Jose Cabrera (near Madrid)	153	PWR	8/69
Electricas Reunidas de Zaragoza SA, Energia e Industrias Aragonesas SA, Union Electrica SA Trillo 1 (Trillo, Guad.)	997	PWR	6/82
<b>SWEDEN</b>			
Oskarshamnverkets Kraftgrupp AB (OKG) Oskarshamn 1 (Oskarshamn)	440	BWR	2/72
Oskarshamn 2 (Oskarshamn)	580	BWR	12/74
Oskarshamn 3 (Oskarshamn)	1,060	BWR	12/83
Statens Vattenfallsverk (SSPB) Ringhals 1 (Varberg)	760	BWR	2/76
Ringhals 2 (Varberg)	809	PWR	5/75
Forsmark 1 (Uppsala)	900	BWR	7/78
Ringhals 3 (Varberg)	900	PWR	12/77
Ringhals 4 (Varberg)	900	PWR	7/79
Forsmark 2 (Uppsala)	900	BWR	7/80
Forsmark 3 (Uppsala)	1,000	BWR	1/82
Sydsvenska Kraft AB Barsebeck 1 (Malmo)	580	BWR	7/75
Barsebeck 2 (Malmo)	580	BWR	7/77
<b>SWITZERLAND</b>			
Bernische Kraftwerke AG (BKW) Mühleberg (near Bern)	306	BWR	10/72
Graben 1 (Graben)	1,140	BWR	12/79

# WORLD LIST OF NUCLEAR POWER PLANTS (continued)

	Net MWe	Type	Commercial Operation
<b>SWITZERLAND (continued)</b>			
Kernkraftwerk Leibstadt AG			
Leibstadt (Leibstadt)	955	BWR	10/78
Nordostschweizerische Kraftwerke AG (NOK)			
Beznau 1 (Doettingen)	350	PWR	12/69
Beznau 2 (Doettingen)	350	PWR	3/72
Kaiseraugst (Kaiseraugst)	932	BWR	12/76
Ruthi (Ruthi)	900	-	-
Kernkraftwerk Goesgen-Daniken AG			
Goesgen (Daniken, SO)	920	PWR	4/78
<b>TAIWAN</b>			
Taiwan Power Co.			
Chin-shan 1 (Shinmin Hsiang)	604	BWR	7/77
Chin-shan 2 (Shihmin Hsiang)	604	BWR	7/78
Kuosheng 1 (Kuosheng)	951	BWR	4/80
Kuosheng 2 (Kuosheng)	951	BWR	4/81
Nuclear No. 5	907	PWR	4/83
Nuclear No. 6	907	PWR	4/84
<b>UNITED KINGDOM</b>			
Central Electricity Generating Board (CEGB)			
Berkeley 1 (Gloucestershire)	138	GCR	6/62
Berkeley 2 (Gloucestershire)	138	GCR	10/62
Bradwell 1 (Essex)	150	GCR	6/62
Bradwell 2 (Essex)	150	GCR	11/62
Trawsfynydd 1 (Wales)	250	GCR	2/65
Trawsfynydd 2 (Wales)	250	GCR	2/65
Dungeness A1 (Kent)	275	GCR	9/65
Dungeness A2 (Kent)	275	GCR	12/65
Sizewell A1 (Suffolk)	290	GCR	1/66
Sizewell A2 (Suffolk)	290	GCR	3/66
Hinkley Point A1 (Somerset)	250	GCR	5/65
Hinkley Point A2 (Somerset)	250	GCR	5/65
Oldbury 1 (Gloucestershire)	300	GCR	1/68
Oldbury 2 (Gloucestershire)	300	GCR	1/68
Wylfa 1 (Anglesey)	590	GCR	11/71
Wylfa 2 (Anglesey)	590	GCR	1/72
Hinkley Point B1 (Somerset)	625	AGR	7/76
Hinkley Point B2 (Somerset)	625	AGR	7/76
Dungeness B1 (Kent)	600	AGR	7/78
Dungeness B2 (Kent)	600	AGR	7/78
Hartlepool 1 (Durham)	625	AGR	7/78
Hartlepool 2 (Durham)	625	AGR	7/79
Heysham 1 (Lancashire)	625	AGR	7/79
Heysham 2 (Lancashire)	625	AGR	7/79
South of Scotland Electricity Board			
Hunterston A-R1 (Ayrshire)	160	GCR	5/64
Hunterston A-R2 (Ayrshire)	160	GCR	9/64
Hunterston B-R3 (Ayrshire)	525	AGR	7/76
Hunterston B-R4 (Ayrshire)	625	AGR	7/76
British Nuclear Fuels Ltd.			
Calder Hall 1 (Cumberland)	50	GCR	9/56
Calder Hall 2 (Cumberland)	50	GCR	9/56
Calder Hall 3 (Cumberland)	50	GCR	9/56
Calder Hall 4 (Cumberland)	50	GCR	9/56
Chapel Cross 1 (Dumfriesshire)	50	GCR	11/58
Chapel Cross 2 (Dumfriesshire)	50	GCR	11/58
Chapel Cross 3 (Dumfriesshire)	50	GCR	11/58
Chapel Cross 4 (Dumfriesshire)	50	GCR	11/58
United Kingdom Atomic Energy Authority			
Windscale (Cumbria)	32	AGR	2/63
Winfrith SCHWR (Dorset)	92	HWLWR	2/68
Dounreay PFR (Highland)	250	LMFBR	7/76

**WORLD LIST OF NUCLEAR POWER PLANTS (continued)**

	Net MWe	Type	Commercial Operation
<b>UNITED STATES</b>			
<b>NORTHEAST</b>			
Baltimore Gas & Electric Co.			
Calvert Cliffs 1 (Lusby, Md.)	850	PWR	5/75
Calvert Cliffs 2 (Lusby, Md.)	850	PWR	1/77
Boston Edison Co.			
Pilgrim 1 (Plymouth, Mass.)	670	BWR	12/72
Pilgrim 2 (Plymouth, Mass.)	1,180	PWR	10/82
Central Main Power Company			
Sears Island Project (Searsport, Me.)	1,150	PWR	Indef.
Connecticut Yankee Atomic Power Co.			
Haddam Neck (Haddam Neck, Conn.)	575	PWR	1/68
Consolidated Edison Co.			
Indian Point 1 (Indian Point, N.Y.)	265	PWR	10/62
Indian Point 2 (Indian Point, N.Y.)	873	PWR	7/74
Indian Point 3 (Indian Point, N.Y.)	965	PWR	7/76
Duquesne Light Co.			
Beaver Valley 1 (Shippingport, Pa.)	852	PWR	4/76
Beaver Valley 2 (Shippingport, Pa.)	852	PWR	4/81
Jersey Central P&L Co.			
Oyster Creek 1 (Toms River, N.J.)	640	BWR	12/69
Forked River 1 (Forked River, N.J.)	1,168	PWR	5/82
Long Island Lighting Co.			
Shoreham (Brookhaven, N.Y.)	820	BWR	7/79
Jamesport 1 (undesignated)	1,150	PWR	7/83
Jamesport 2 (undesignated)	1,150	PWR	7/85
Maine Yankee Atomic Power Co.			
Maine Yankee (Wiscasset, Me.)	790	PWR	12/72
Metropolitan Edison Co.			
Three Mile Island 1 (Goldsboro, Pa.)	818	PWR	9/74
Three Mile Island 2 (Goldsboro, Pa.)	906	PWR	5/78
Portland 5 (undesignated)	1,251	PWR	5/94
New England Power Company			
NEP-1 (Charleston, R.I.)	1,150	PWR	7/84
NEP-2 (Charleston, R.I.)	1,150	PWR	7/86
New York State Electric & Gas Corp.			
Somerset 1 (Somerset, N.Y.)	1,200	BWR	7/87
Somerset 2 (Somerset, N.Y.)	1,200	BWR	7/89
Niagara Mohawk Power Corp.			
Nine Mile Point 1 (Scriba, N.Y.)	610	BWR	12/69
Nine Mile Point 2 (Scriba, N.Y.)	1,100	BWR	10/82
Niagara Mohawk Power Corp. and Power Authority of the State of New York			
James A. FitzPatrick (Scriba, N.Y.)	821	BWR	7/75
Northeast Utilities			
Millstone 1 (Waterford, Conn.)	652	BWR	12/70
Millstone 2 (Waterford, Conn.)	828	PWR	12/75
Millstone 3 (Waterford, Conn.)	1,150	PWR	5/82
Montague 1 (Montague, Mass.)	1,150	BWR	4/86
Montague 2 (Montague, Mass.)	1,150	BWR	1/88
Pennsylvania Power & Light			
Susquehanna 1 (Berwick, Pa.)	1,050	BWR	11/80
Susquehanna 2 (Berwick, Pa.)	1,050	BWR	5/82
Philadelphia Electric Co.			
Peach Bottom 2 (Peach Bottom, Pa.)	1,065	BWR	7/74
Peach Bottom 3 (Peach Bottom, Pa.)	1,065	BWR	12/74
Limerick 1 (Pottstown, Pa.)	1,055	BWR	2/81
Limerick 2 (Pottstown, Pa.)	1,055	BWR	7/82
Potomac Electric Power Co.			
Douglas Point 1 (Douglas, Md.)	1,178	BWR	3/85
Douglas Point 2 (Douglas, Md.)	1,178	BWR	3/87
Power Authority of the State of New York			
Green County (Cementon, N.Y.)	1,200	PWR	9/84
Public Service Co. of New Hampshire			
Seabrook 1 (Seabrook, N.H.)	1,200	PWR	6/81
Seabrook 2 (Seabrook, N.H.)	1,200	PWR	11/83

# WORLD LIST OF NUCLEAR POWER PLANTS (continued)

	Net MWe	Type	Commercial Operation
<b>NORTHEAST (continued)</b>			
Public Service Electric & Gas Co.			
Salem 1 (Salem, N.J.)	1,090	PWR	9/76
Salem 2 (Salem, N.J.)	1,115	PWR	5/79
Hope Creek 1 (Salem, N.J.)	1,067	BWR	12/82
Hope Creek 2 (Salem, N.J.)	1,067	BWR	5/84
Atlantic 1 (off Little Egg Inlet, N.J.)	1,150	PWR	5/85
Atlantic 2 (off Little Egg Inlet, N.J.)	1,150	PWR	5/87
Undesignated Floating Plant 1	1,150	PWR	/90
Undesignated Floating Plant 2	1,150	PWR	/92
Rochester Gas & Electric Co.			
Robert E. Ginna (Ontario, N.Y.)	490	PWR	3/70
Sterling (Sterling, N.Y.)	1,150	PWR	4/84
Vermont Yankee Nuclear Power Corp.			
Vermont Yankee (Vernon, Vt.)	514	BWR	11/72
Yankee Atomic Electric Co.			
Yankee (Rowe, Mass.)	175	PWR	6/61
<b>MIDWEST</b>			
Cincinnati Gas & Electric Co.			
Zimmer 1 (Moscow, Ohio)	810	BWR	/79
Zimmer 2 (Moscow, Ohio)	1,150	BWR	/86
The Cleveland Electric Illuminating Co.			
Perry 1 (North Perry, Ohio)	1,205	BWR	/80
Perry 2 (North Perry, Ohio)	1,205	BWR	/82
Commonwealth Edison Company			
Dresden 1 (Morris, Ill.)	200	BWR	8/60
Dresden 2 (Morris, Ill.)	800	BWR	8/70
Dresden 3 (Morris, Ill.)	800	BWR	10/71
LaSalle 1 (Seneca, Ill.)	1,078	BWR	10/78
LaSalle 2 (Seneca, Ill.)	1,078	BWR	10/79
Zion 1 (Zion, Ill.)	1,100	PWR	6/73
Zion 2 (Zion, Ill.)	1,100	PWR	12/73
Byron 1 (Byron, Ill.)	1,120	PWR	10/80
Byron 2 (Byron, Ill.)	1,120	PWR	10/82
Braidwood 1 (Braidwood, Ill.)	1,120	PWR	10/81
Braidwood 2 (Braidwood, Ill.)	1,120	PWR	10/82
Commonwealth Edison Co. and Iowa-Illinois Gas & Electric Co.			
Quad-Cities 1 (Cordova, Ill.)	800	BWR	8/72
Quad-Cities 2 (Cordova, Ill.)	800	BWR	10/72
Consumers Power Co.			
Big Rock Point (Big Rock Point, Mich.)	70	BWR	12/62
Palisades (South Haven, Mich.)	700	PWR	12/71
Midland 1 (Midland, Mich.)	492	PWR	3/82
Midland 2 (Midland, Mich.)	818	PWR	3/81
Dairyland Power Cooperative			
La Crosse BWR (Genoa, Wis.)	42	BWR	11/69
Detroit Edison Co.			
Fermi 2 (Newport, Mich.)	1,093	BWR	9/80
Greenwood 2 (St. Clair County, Mich.)	1,208	PWR	3/84
Greenwood 3 (St. Clair County, Mich.)	1,208	PWR	3/86
Illinois Power Co.			
Clinton 1 (Clinton, Ill.)	950	BWR	6/81
Clinton 2 (Clinton, Ill.)	950	BWR	6/84
Indiana & Michigan Electric Co.			
Donald C. Cook 1 (Bridgman, Mich.)	1,054	PWR	8/75
Donald C. Cook 2 (Bridgman, Mich.)	1,054	PWR	4/78
Iowa Electric Light & Power Co.			
Duane Arnold (Palo, Iowa)	545	PWR	5/74
Iowa Power & Light Co.			
Central Iowa (Vandalia, Iowa)	1,300	PWR	/85
Kansas Gas & Electric Co.			
Wolf Creek (Burlington, Kan.)	1,150	PWR	4/82
Nebraska Public Power District			
Cooper (Brownville, Neb.)	778	BWR	7/74
Northern Indiana Public Service Co.			
Bailly N-1 (Dune Acres, Ind.)	645	BWR	undef.

# WORLD LIST OF NUCLEAR POWER PLANTS (continued)

	Net MWe	Type	Commercial Operation
<b>MIDWEST (continued)</b>			
Northern States Power Co.			
Monticello (Monticello, Minn.)	548	BWR	7/71
Prairie Island 1 (Red Wing, Minn.)	530	PWR	12/73
Prairie Island 2 (Red Wing, Minn.)	530	PWR	12/74
Tyrone 1 (Durand, Wis.)	1,150	PWR	5/85
Omaha Public Power District			
Fort Calhoun 1 (Fort Calhoun, Neb.)	457	PWR	9/73
Fort Calhoun 2 (Fort Calhoun, Neb.)	1,150	PWR	1/83
Public Service Indiana			
Marble Hill 1 (Jefferson County, Ind.)	1,130	PWR	/82
Marble Hill 2 (Jefferson County, Ind.)	1,130	PWR	/84
Toledo Edison Co.			
Davis-Besse 1 (Oak Harbor, Ohio)	906	PWR	4/77
Davis-Besse 2 (Oak Harbor, Ohio)	906	PWR	/83
Davis-Besse 3 (Oak Harbor, Ohio)	906	PWR	/85
Union Electric Co.			
Callaway 1 (Fulton, Mo.)	1,150	PWR	10/81
Callaway 2 (Fulton, Mo.)	1,150	PWR	4/83
Wisconsin Electric Power Co. and Wisconsin Michigan Power Co.			
Point Beach 1 (Two Creeks, Wis.)	497	PWR	12/70
Point Beach 2 (Two Creeks, Wis.)	497	PWR	10/72
Wisconsin Electric Power Co. (with three other Wisconsin utilities)			
Koshkonong 1 (Ft. Atkinson, Wis.)	900	PWR	/83
Koshkonong 2 (Ft. Atkinson, Wis.)	900	PWR	/84
Wisconsin Public Service Corporation			
Kewaunee (Carlton, Wis.)	540	PWR	6/74
<b>SOUTH</b>			
Alabama Power Company			
Joseph M. Farley 1 (Dothan, Ala.)	860	PWR	6/77
Joseph M. Farley 2 (Dothan, Ala.)	860	PWR	4/79
Alan R. Barton 1 (Verbena, Ala.)	1,200	BWR	Indef.
Alan R. Barton 2 (Verbena, Ala.)	1,200	BWR	Indef.
Arkansas Power & Light Co.			
Nuclear One 1 (Russellville, Ark.)	836	PWR	12/74
Nuclear One 2 (Russellville, Ark.)	912	PWR	3/78
Carolina Power & Light Co.			
Brunswick 1 (Southport, N.C.)	821	BWR	3/77
Brunswick 2 (Southport, N.C.)	790	BWR	11/75
Shearon Harris 1 (Newhill, N.C.)	900	PWR	3/84
Shearon Harris 2 (Newhill, N.C.)	900	PWR	3/86
Shearon Harris 3 (Newhill, N.C.)	900	PWR	3/90
Shearon Harris 4 (Newhill, N.C.)	900	PWR	3/88
Robinson 2 (Hartsville, S.C.)	665	PWR	3/71
SR 1 (undesignated)	1,150	PWR	3/87
SR 2 (undesignated)	1,150	PWR	3/89
Duke Power Co.			
Oconee 1 (Seneca, S.C.)	871	PWR	7/73
Oconee 2 (Seneca, S.C.)	871	PWR	9/74
Oconee 3 (Seneca, S.C.)	871	PWR	12/74
McGuire 1 (Terrell, N.C.)	1,180	PWR	1/78
McGuire 2 (Terrell, N.C.)	1,180	PWR	1/79
Catawba 1 (Clover, S.C.)	1,153	PWR	1/81
Catawba 2 (Clover, S.C.)	1,153	PWR	1/82
Perkins 1 (Mocksville, N.C.)	1,280	PWR	1/83
Perkins 2 (Mocksville, N.C.)	1,280	PWR	1/85
Perkins 3 (Mocksville, N.C.)	1,280	PWR	1/87
Cherokee 1 (Gaffney, S.C.)	1,280	PWR	1/84
Cherokee 2 (Gaffney, S.C.)	1,280	PWR	1/86
Cherokee 3 (Gaffney, S.C.)	1,280	PWR	1/88
Florida Power & Light Co.			
Turkey Point 3 (Florida City, Fla.)	666	PWR	12/72
Turkey Point 4 (Florida City, Fla.)	666	PWR	9/73
St. Lucie 1 (Hutchinson Island, Fla.)	802	PWR	6/76
St. Lucie 2 (Hutchinson Island, Fla.)	802	PWR	/81



# WORLD LIST OF NUCLEAR POWER PLANTS (continued)

	Net MWe	Type	Commercial Operation
<b>SOUTH (continued)</b>			
South Dade 1 (Dade County, Fla.)	1,150	PWR	mid 80s
South Dade 2 (Dade County, Fla.)	1,150	PWR	mid 80s
Florida Power Corporation			
Crystal River 3 (Red Level, Fla.)	855	PWR	12/76
Georgia Power Co.			
Edwin I. Hatch 1 (Baxley, Ga.)	786	BWR	12/75
Edwin I. Hatch 2 (Baxley, Ga.)	786	BWR	4/79
Vogtle 1 (Waynesboro, Ga.)	1,100	PWR	4/83
Vogtle 2 (Waynesboro, Ga.)	1,100	PWR	4/84
Gulf States Utility Co. (See also Southwest)			
River Bend 1 (St. Francisville, La.)	940	BWR	10/81
River Bend 2 (St. Francisville, La.)	940	BWR	10/83
Louisiana Power & Light Co.			
Waterford 3 (Taft, La.)	1,165	PWR	4/81
Mississippi Power & Light			
Grand Gulf 1 (Port Gibson, Miss.)	1,250	BWR	6/80
Grand Gulf 2 (Port Gibson, Miss.)	1,250	BWR	9/84
Puerto Rico Water Resources Authority			
NORCO 1 (Barrio Isote, Arecibo, P.R.)	583	PWR	Indef.
South Carolina Electric & Gas Co.			
Virgil C. Summer 1 (Parr, S.C.)	900	PWR	5/79
Tennessee Valley Authority			
Browns Ferry 1 (Decatur, Ala.)	1,067	BWR	8/74
Browns Ferry 2 (Decatur, Ala.)	1,067	BWR	3/75
Browns Ferry 3 (Decatur, Ala.)	1,067	BWR	11/76
Sequoyah 1 (Daisy, Tenn.)	1,148	PWR	5/78
Sequoyah 2 (Daisy, Tenn.)	1,148	PWR	1/79
Watts Bar 1 (Spring City, Tenn.)	1,177	PWR	6/79
Watts Bar 2 (Spring City, Tenn.)	1,177	PWR	3/80
Belefonte 1 (Scottsboro, Ala.)	1,213	PWR	6/80
Belefonte 2 (Scottsboro, Ala.)	1,213	PWR	3/81
Hartsville A1 (Hartsville, Tenn.)	1,233	BWR	2/83
Hartsville A2 (Hartsville, Tenn.)	1,233	BWR	2/84
Hartsville B1 (Hartsville, Tenn.)	1,233	BWR	8/83
Hartsville B2 (Hartsville, Tenn.)	1,233	BWR	8/84
Phipps Bend 1 (undetermined)	1,233	BWR	4/84
Phipps Bend 2 (undetermined)	1,233	BWR	4/85
Yellow Creek 1 (undetermined)	1,300	PWR	3/85
Yellow Creek 2 (undetermined)	1,300	PWR	3/86
Tennessee Valley Authority, Commonwealth Edison Co., and ERDA			
Clinch River Breeder Reactor Plant (Oak Ridge, Tenn.)	350	LMFBR	/83
Virginia Electric & Power Co.			
Surry 1 (Gravel Neck, Va.)	788	PWR	12/72
Surry 2 (Gravel Neck, Va.)	788	PWR	5/73
North Anna 1 (Mineral, Va.)	934	PWR	4/77
North Anna 2 (Mineral, Va.)	934	PWR	11/77
North Anna 3 (Mineral, Va.)	938	PWR	4/81
North Anna 4 (Mineral, Va.)	938	PWR	11/81
Surry 3 (Gravel Neck, Va.)	900	PWR	4/86
Surry 4 (Gravel Neck, Va.)	900	PWR	4/87
<b>SOUTHWEST</b>			
Arizona Public Service Co.			
Palo Verde 1 (Wintersburg, Ariz.)	1,270	PWR	5/82
Palo Verde 2 (Wintersburg, Ariz.)	1,270	PWR	5/84
Palo Verde 3 (Wintersburg, Ariz.)	1,270	PWR	5/86
Gulf States Utility Co. (See also South region)			
Blue Hills 1 (Newton County, Tex.)	930	PWR	Indef.
Blue Hills 2 (Newton County, Tex.)	930	PWR	Indef.
Houston Lighting & Power Company			
Allens Creek 1 (Wallis, Tex.)	1,200	BWR	Indef.
Allens Creek 2 (Wallis, Tex.)	1,200	BWR	Indef.
South Texas Project 1 (Palacios, Tex.)	1,250	PWR	10/80
South Texas Project 2 (Palacios, Tex.)	1,250	PWR	3/82
Public Service Co. of Oklahoma			
Black Fox 1 (Inola, Okla.)	1,150	BWR	/83
Black Fox 2 (Inola, Okla.)	1,150	BWR	/85

# WORLD LIST OF NUCLEAR POWER PLANTS (continued)

	Net MWe	Type	Commercial Operation
<b>SOUTH (continued)</b>			
Texas Utilities Company			
Comanche Peak 1 (Glen Rose, Tex.)	1,150	PWR	1/80
Comanche Peak 2 (Glen Rose, Tex.)	1,150	PWR	1/82
<b>WEST AND NORTHWEST</b>			
Pacific Gas & Electric Co.			
Humboldt Bay 3 (Humboldt Bay, Cal.)	68	BWR	8/63
Diablo Canyon 1 (Diablo Canyon, Cal.)	1,084	PWR	8/76
Diablo Canyon 2 (Diablo Canyon, Cal.)	1,106	PWR	8/77
Portland General Electric Co.			
Trojan (Prescott, Ore.)	1,130	PWR	5/76
Pebble Springs 1 (Arlington, Ore.)	1,260	PWR	7/85
Pebble Springs 2 (Arlington, Ore.)	1,260	PWR	7/88
Public Service Company of Colorado			
Fort St. Vrain (Platteville, Colo.)	330	HTGR	7/76
Puget Sound Power & Light Co.			
Skagit 1 (Sedro Wooley, Wash.)	1,288	BWR	1/83
Skagit 2 (Sedro Wooley, Wash.)	1,288	BWR	1/86
Sacramento Municipal Utility District			
Rancho Seco (Clay Station, Cal.)	913	PWR	4/75
San Diego Gas & Electric Co.			
Sundesert 1 (Blythe, Cal.)	950	PWR	4/85
Sundesert 2 (Blythe, Cal.)	950	PWR	4/88
Southern California Edison and San Diego Gas & Electric Co.			
San Onofre 1 (San Clemente, Cal.)	430	PWR	1/68
San Onofre 2 (San Clemente, Cal.)	1,100	PWR	10/81
San Onofre 3 (San Clemente, Cal.)	1,100	PWR	1/83
Washington Public Power Supply System			
Hanford-N (Richland, Wash.)	860	LGR	7/66
WPPSS 2 (Richland, Wash.)	1,100	BWR	12/79
WPPSS 1 (Richland, Wash.)	1,220	PWR	3/81
WPPSS 3 (Satsop, Wash.)	1,240	PWR	3/82
WPPSS 4 (Richland, Wash.)	1,220	PWR	3/82
WPPSS 5 (Satsop, Wash.)	1,240	PWR	4/84
<b>U.S. Total (211 units)</b>	<b>206,835</b>		
<b>USSR</b>			
Ministry of Electric Power			
Troitsk (Siberia)	600	LGR	12/58
Beloyarsk 1 (Sverdlovsk region)	100	LGR	4/64
Beloyarsk 2 (Sverdlovsk region)	200	LGR	10/67
Novo-Voronezh 1 (Voronezh)	210	PWR	10/64
Novo-Voronezh 2 (Voronezh)	365	PWR	12/69
Novo-Voronezh 3 (Voronezh)	440	PWR	12/71
Kola 1 (near Murmansk)	440	PWR	10/73
Kola 2 (near Murmansk)	440	PWR	12/74
Novo-Voronezh 4 (Voronezh)	440	PWR	7/76
Novo-Voronezh 5 (Voronezh)	1,000	PWR	—
BN-600 (Sverdlovsk region)	600	LMFBR	7/78
Armenia 1 (Ararat Valley)	400	PWR	7/78
Armenia 2 (Ararat Valley)	400	PWR	7/78
Leningrad 1 (near Leningrad)	1,000	LGR	10/75
Leningrad 2 (near Leningrad)	1,000	LGR	12/76
Koursk 1	1,000	LGR	12/76
Koursk 2	1,000	LGR	7/77
Bilibinsk	450	PWR	5/77
South Ukrainian 1	1,000	PWR	—
South Ukrainian 2	1,000	PWR	—
West Ukrainian 1	440	PWR	—
West Ukrainian 2	440	PWR	—
West Ukrainian 3	1,000	PWR	—
Scientific Research Institute for Atomic Reactors			
VK-50 (Dimitrovgrad)	50	BWR	10/65
State Committee on Atomic Energy			
BN-350 (Shevchenko)	350	LMFBR	6/72

# WORLD LIST OF NUCLEAR POWER PLANTS (continued)

		Net MWe	Type	Commercial Operation
<b>YUGOSLAVIA</b>				
Savske Electrane (Slovenia) and Elektropivreda (Croatia)				
Krsko (Krsko)		615	PWR	12/78
U.S. TOTAL (211 units)	206,835			
NON-U.S. TOTAL (292 units)	184,662			
WORLD TOTAL (503 units)	391,497			

## ABBREVIATIONS USED IN THIS TABLE:

AGR	— advanced gas-cooled reactor
BWR	— boiling water reactor
GCHWR	— gas-cooled, heavy-water-moderated reactor
GCR	— gas-cooled reactor
HTGR	— high-temperature gas-cooled reactor
HWLWR	— heavy-water-moderated, boiling light-water-cooled reactor
LGR	— light-water cooled, graphite-moderated reactor
LMFBR	— liquid metal fast breeder reactor
LWCHW	— light-water-cooled, heavy-water-moderated reactor
PHWR	— pressurized heavy-water-moderated and -cooled reactor
PWR	— pressurized water reactor
THTR	— thorium high-temperature reactor

Source: *Nuclear News*, August 1976.

## CHAPTER XIII

### FUEL CELLS

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## INTRODUCTION

The fuel cell is a device in which the chemical energy of a fuel is converted directly into electrical power. As illustrated in Figure XIII-1, the reactants (fuel and oxidant) are fed continuously from the outside and the products of the reaction are continuously removed. Since it is not limited to the efficiency of the Carnot cycle as are heat engines, the fuel cell is capable of very high efficiencies.

The first hints of a fuel cell concept occurred in the early 1800s when Sir Humphrey Davy reported on the construction of simple galvanic combinations.<sup>1</sup> However, the first discovery of the fuel cell is usually credited to Sir William Grove in the late 1830s.<sup>2</sup> In his experiments, Grove demonstrated that the electrolysis of water was a reversible process and that hydrogen and oxygen could be recombined in an electrochemical cell to produce electrical power.

The first serious attempt to produce a practical device was made by Mond and Langer in the 1880s.<sup>3</sup> Their aim was to use a cheaper fuel than hydrogen and to replace the expensive platinum electrodes used by Grove with a much cheaper metal, such as nickel. It was during these experiments that they discovered the carbonyl process for refining nickel; this diverted their attention away from fuel cells, but led to the founding of a large nickel industry.

In the early 1900s, Bauer did work on high-temperature fuel cells with the prime objective of obtaining electricity directly from coal.<sup>4</sup> However, this objective was too ambitious for the time.

Among the most important work in the development of fuel cells was that started by F. T. Bacon in the 1930s. His original objective was to develop a practical energy storage device. Although the work on his hydrogen-oxygen fuel cell was interrupted by World War II, he returned to the task

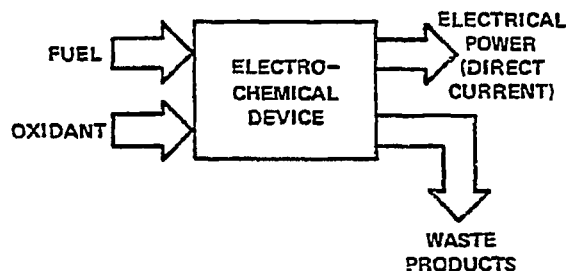


Figure XIII-1. THE BASIC FUEL CELL

afterwards and, in 1959, demonstrated a 6 KW unit.<sup>5</sup> It was the Bacon cell that was later further developed for use in Project Apollo by Pratt and Whitney Aircraft (now the Power Utility Division of United Aircraft Corporation-PUD/UAC).

Today much of the fuel cell research and development is being directed toward reducing costs and making fuel cells more practical. The focus of many of these programs is either to achieve high power densities for application in transportation (cars, trains, ships, buses, and trucks) or to achieve high efficiencies with available fuels for use in electrical power generation.

<sup>1</sup> H. Davy, *Journal of Natural Philosophy, Chemistry and the Arts*, Vol. 1 (edited by W. Nicholson), 1802, pp. 144-145.

<sup>2</sup> W. R. Grove, *Philosophical Magazine*, Vol. 3 Nr. 14, 1959, p. 139.

W. R. Grove, "On Gaseous Voltaic Battery," *Philosophical Magazine*, Vol. 3 Nr. 21, Dec. 1842, p. 417.

<sup>3</sup> L. Mond and C. Langer, *Proceedings of the Royal Society*, Vol. 46, 1889, p. 296.

<sup>4</sup> E. Bauer and H. Ehrenberg, *Z. Elektrochem*, Vol. 10, 1912, p. 697.

<sup>5</sup> F. T. Bacon, et al. "Fuel Cells," *American Institute of Chemical Engineering* (a C.E.P. technical manual), 1963, p. 63.

## BASIC HYDROGEN-OXYGEN FUEL CELL

The principle of hydrogen-oxygen fuel cell operation is shown in Figure XIII-2. Two platinum foil electrodes are immersed in a conductive acid electrolyte. One electrode is supplied with hydrogen, bubbled around it through the solution, and the other electrode is similarly supplied with oxygen. A diaphragm in the solution allows the hydrogen ions to pass through but prevents the hydrogen and oxygen from coming into direct contact with one another.

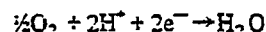
This chemical reaction occurs at the negative electrode:



Each hydrogen molecule that contacts the negative electrode surface is dissociated into two atoms by virtue of the catalytic properties of the surface. These enter the

solution as hydrogen ions, leaving behind two electrons, which pass through the external electrical circuit.

This chemical reaction takes place at the positive electrode:



At the positive electrode, the oxygen combines with the free hydrogen ions from the electrolyte and gains two electrons to form water. A "cold" electrochemical reaction occurs at two separated reaction sites to replace the normal single combustion process that occurs in a hydrogen-oxygen "flame."

The simple fuel cell illustrated in Figure XIII-2 does not provide a way to remove the water that is generated as a waste product and, therefore, is not of practical value. A

fuel cell that does allow the water to be removed in shown in Figure XIII-3. This fuel cell incorporates porous electrodes that allow them to be "wet" by the electrolyte.

The gas pressures must be selected carefully to avoid flooding or drying the electrode pores, either of which would impede the reaction rate and limit the current flow.

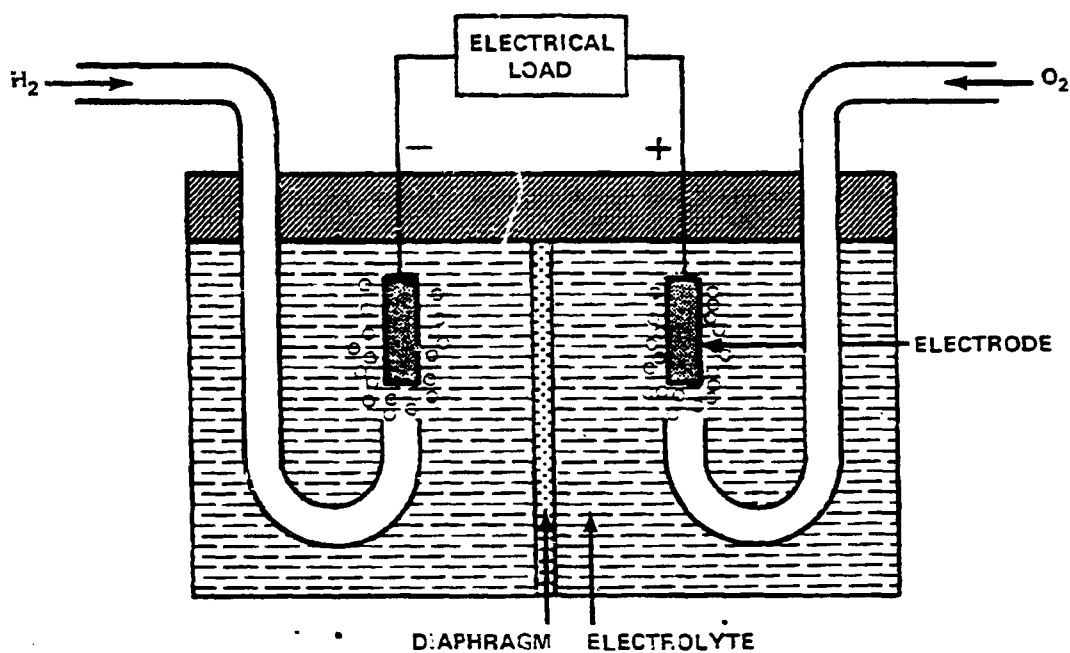
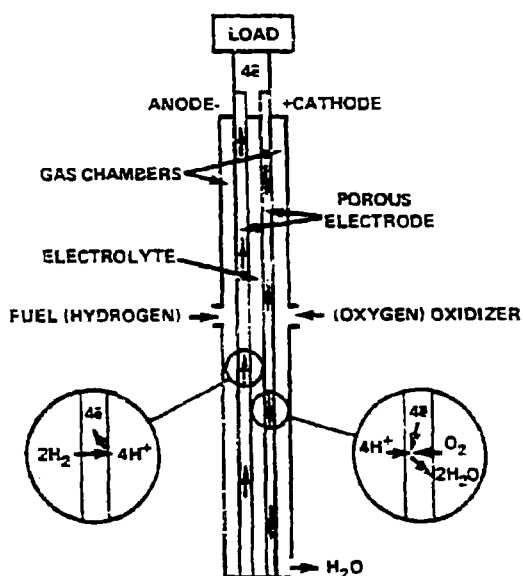


Figure XIII-2. SIMPLE HYDROGEN-OXYGEN FUEL CELL



Source: General Electric Publication GEA-7978, 1964.

Figure XIII-3. FUEL CELL WITH POROUS ELECTRODES

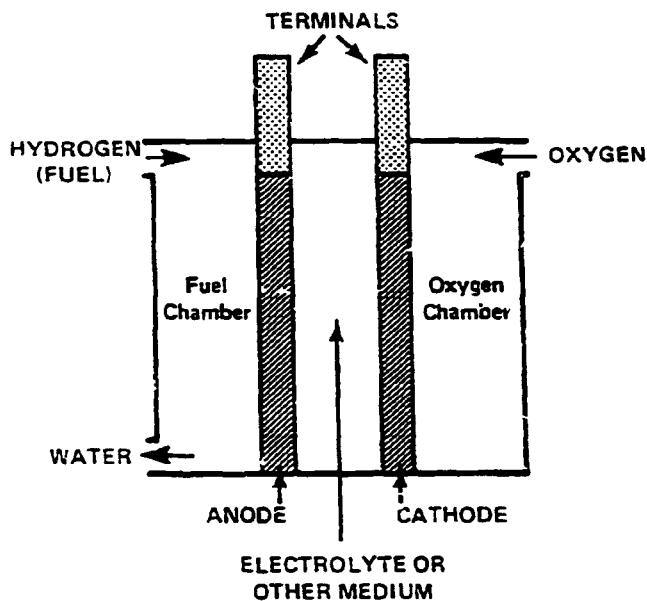


Figure XIII-4. DIRECT TYPE FUEL CELL

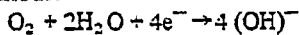
## FUEL CELL DESIGNS

Many different and varied designs are possible with fuel cells. The selection is usually dictated by size, weight, and performance requirements, or environmental and economic considerations. The more common types of fuel cells are described below.

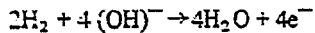
### Direct Type, Alkaline Electrolyte

The basic structure of this type of fuel cell is shown in Figure XIII-4. The electrodes are made of porous conductors. A 20 to 40 percent solution of potassium hydroxide (KOH) is a typical electrolyte. The electrochemical reactions with hydrogen as a fuel are:

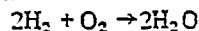
At the cathode:



At the anode:

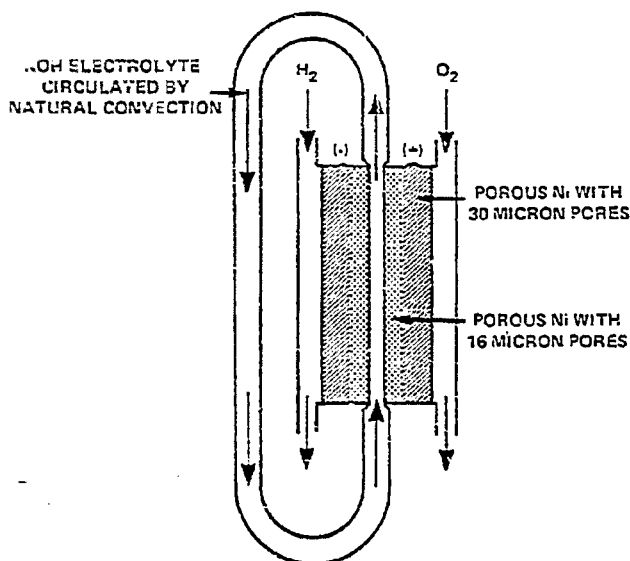


Overall reaction:



### Bacon Cell

The Bacon cell, using an alkaline electrolyte and invented by Francis T. Bacon of Great Britain in 1951, was among the first of the high-performance cells. It operates at about 500° K to support the reaction and at 400 to 1000 psi to prevent the electrolyte from boiling. Although this fuel cell has the disadvantage of requiring a pressurization system, it



Source: S. S. L. Chang, *Energy Conversion*, Englewood Cliffs: Prentice-Hall, 1963.

Figure XIII-5. TYPICAL BACON CELL

provides high current densities of about 750 amperes per square foot of electrode at 0.7 volt. Figure XIII-5 illustrates one Bacon cell design used by the Patterson Moos Division of the Leeson Corporation. The electrodes are made of sintered nickel with finer pores near the electrolyte. FUD/UAC purchased the rights to the Bacon cell in 1960; after extensive redesign, it became the mainstay of the company's fuel cell designs, among which was the very successful Project Apollo design.

### Union Carbide Cell

The Union Carbide cell uses activated carbon electrodes, which are treated with a substance to repel the alkaline electrolyte (Figure XIII-6). The electrodes have a highly developed surface area and fine pores. The reactions, which are of the direct alkaline electrolyte types, take place on the outer surfaces of the electrodes. This cell design has the advantage of operating at room temperature at a fairly high current density of about 100 amperes per square foot of electrode at 0.7 volt.

### Ion-Exchange Membrane Cell

The ion-exchange membrane fuel cell illustrated in Figure XIII-7 was developed at General Electric. The

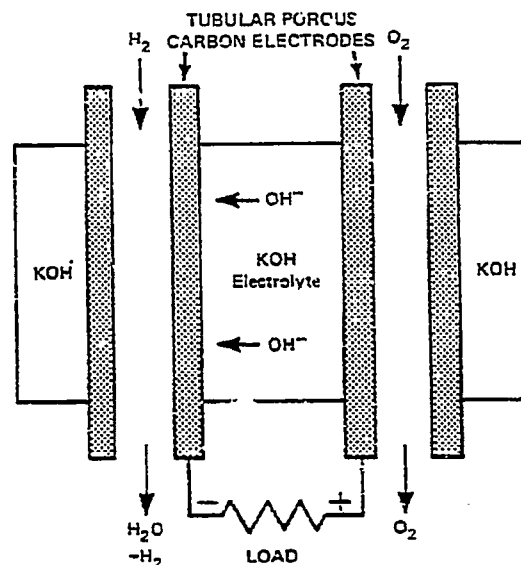


Figure XIII-6. UNION CARBIDE FUEL CELL



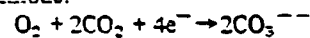
ion-exchange membrane performs the function of an acid electrolyte but in a quasisolid state. Hydrogen ions can move from one side of the membrane to the other, but other types of ions and neutral atoms cannot. Each side of the membrane is coated with a layer of platinum or palladium, which serves as an electrode as well as an electrocatalyst. These cells have current densities of about 30 to 50 amperes per square foot at 0.7 volt.

### High-Temperature Cell

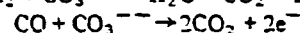
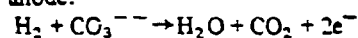
Hydrocarbon fuels can usually be converted into a mixture of hydrogen and carbon monoxide in a reversible

process. High-temperature fuel cells that use these two fuels have been developed. CO does not react as readily as  $H_2$  and also causes problems with many of the acid and alkaline electrolytes. Thus, carbonates are used as a weak alkali at high temperatures and the electrode reactions are

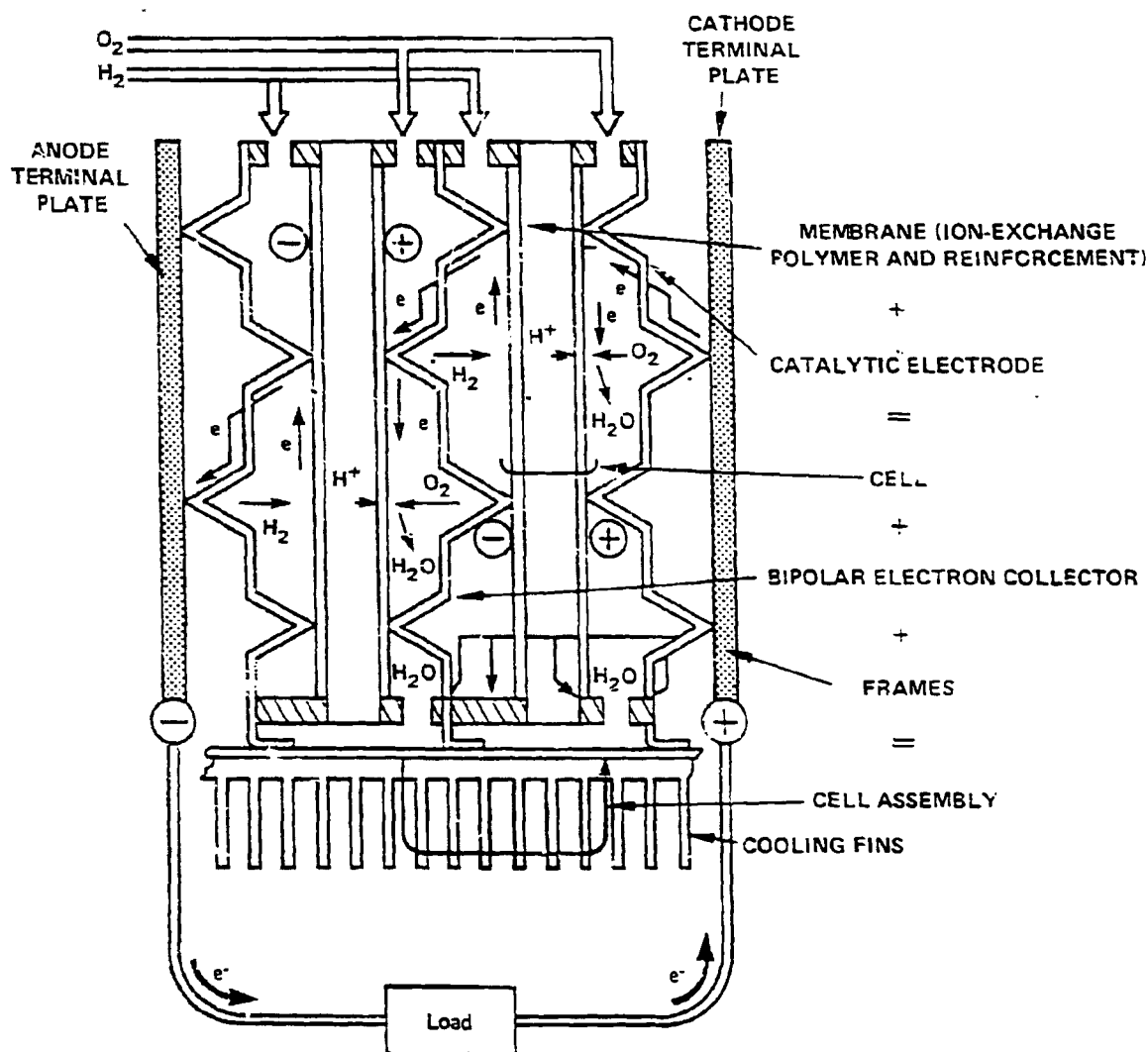
At the cathode:



At the anode:



Typical current densities range from 20 to 100 amperes per square foot at 0.7 volt.



Source: Reprinted from G. A. Phillips, "Status of the Ion-Exchange Membrane Fuel Cell" Electrical Engineering, Vol. 81, No. 3, March 1962, pp. 194-201.

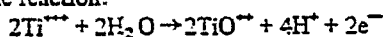
Figure XIII-7. ION-EXCHANGE MEMBRANE FUEL CELL

## Redox Cell

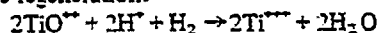
The Redox cell is illustrated in Figure XIII-8. It is different from the normal fuel cell because the fuel and oxidant are used to regenerate two electrolytic fluids instead of reacting at the electrodes directly. The cell is divided by a diaphragm, which allows free passage of the hydrogen ions. Two typical examples of Redox cells are:

General Electric Company with  $\text{H}_2$  fuel and  $\text{O}_2$  oxidant

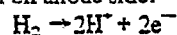
Anode reaction:



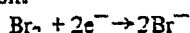
Anode regeneration:



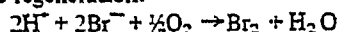
Overall reaction on anode side:



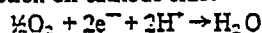
Cathode reaction:



Cathode regeneration:



Overall reaction on cathode side:



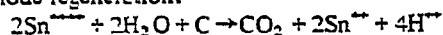
King's College, London, with coal powder fuel and air oxidant

[This has a low current density cell of 10 amperes per square foot at 0.62 volts.]

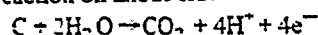
Anode reaction:



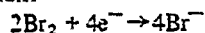
Anode regeneration:



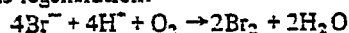
Overall reaction on anode side:



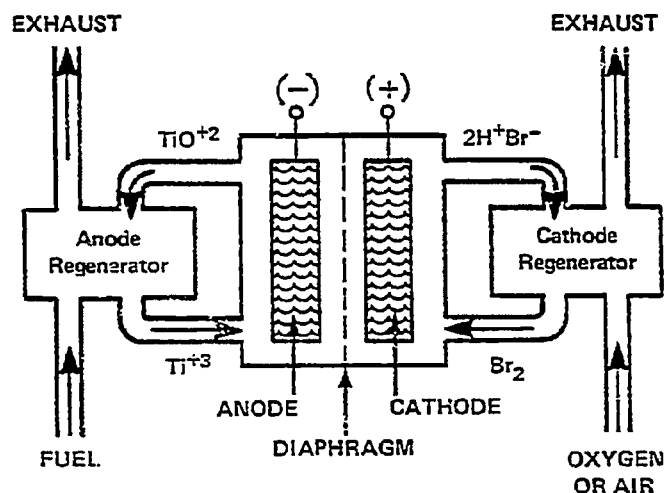
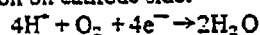
Cathode reaction:



Cathode regeneration:



Overall reaction on cathode side:



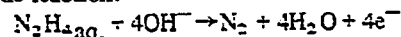
Source: S. S. L. Chang, *Energy Conversion*, Englewood Cliffs: Prentice-Hall, 1963.

Figure XIII-8. REDOX CELL

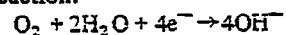
## Hydrazine Fuel Cells

Hydrazine fuel cells are used where high energy density with respect to volume and weight is required. These constraints often exist in military applications. Hydrazine, noted for its remarkable electrochemical activity, does not require the use of noble metals as anode catalysts. Further, its reaction products do not contaminate the electrolyte. Unfortunately hydrazine is very expensive. A typical electrochemical reaction in an alkaline solution is:

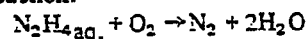
Anode reaction:



Cathode reaction:



Overall reaction:



## FUEL CELL EFFICIENCY

The potential for very high efficiency is one of the strong selling points for fuel cells. Many energy systems using fuel cells require modification of the fuel to a form that is compatible with the fuel cell. For example, a system using natural gas would normally require a "reformer," and a system using coal would require that it be gasified,

liquefied, or finely ground. Next, the electrical power leaves the fuel cell as a direct current, but this would have to be converted to mechanical power to drive a vehicle or be converted to alternating current for a utility. Thus the real efficiencies that must be considered are the overall efficiencies of converting the fuel available to output power

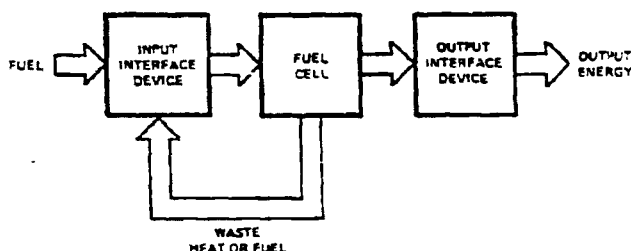


Figure XIII-9. FUEL CELL EFFICIENCY IMPROVEMENT - CONFIGURATION I

in the form required, or:

$$\left( \text{Overall Efficiency} \right) = \left( \text{Efficiency Of The Input Interface Device} \right) \times \left( \text{Ideal Efficiency} \right) \times \left( \text{Voltage Efficiency} \right) \\ \times \left( \text{Reaction Efficiency} \right) \times \left( \text{Efficiency Of The Output Interface Device} \right)$$

There are at least two configurations that would require a modification of the simple product efficiency calculation. These are shown in Figures XIII-9 and 10. In the first of these, waste heat or waste fuel from the fuel cell is used by the input interface device; in the second, waste heat or fuel is converted to useful power by a heat engine.

#### Input Interface Device Efficiency

Typical input interface devices would be coal gasifiers and reformers. Efficiencies from about 60 percent to nearly 100 percent are attainable for gasification processes (see Coal Gasification, Chapter X of this Fact Book, for efficiency tabulations). A gas or liquid fuel reformer would normally have efficiencies of 80 to 90 percent. Pages 151-167, of N. I. Palmer, et al., "A Comparison Between External and Internal Reforming Methanol Fuel Cell Systems," *Hydrocarbon Fuel Cell Technology*, Academic Press: New York, 1965, provides a method for computing reformer-fuel cell efficiencies.

#### Ideal Efficiency

The ideal efficiency is defined as the ratio of the maximum amount of electrochemical energy ( $\Delta F$ ) that can be obtained from a chemical reaction to the heat energy of the reaction ( $\Delta H$ ).

$$(\text{IDEAL EFFICIENCY}) = \frac{\Delta F}{\Delta H}$$

Representative ideal efficiencies for several chemical reactions are shown in Table XIII-1. (Note that the efficiencies are for 25° C. These efficiencies change with temperature.)

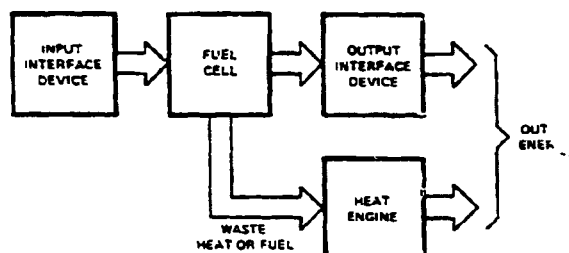


Figure XIII-10. FUEL CELL EFFICIENCY IMPROVEMENT - CONFIGURATION II

#### Voltage Efficiency

Voltage efficiency is defined as:

$$\left( \text{Voltage Efficiency At A Given Load} \right) = \frac{\left( \text{Terminal Voltage At A Given Load} \right)}{\left( \text{Ideal No-Load Voltage} \right)}$$

The voltage efficiency is a function of current flow. It includes all of the irreversible losses occurring in the cell under a specific load condition. These losses include cell resistance and voltage drops in electrode potential due, for example, to a side reaction. Voltage efficiency strongly depends on the electrode materials, electrolyte conductance, and cell geometry. The value of voltage efficiency can vary from nearly 100 percent at low load factors to near 0 percent at very high loads, but typically ranges from 50 to 90 percent.

#### Reaction Efficiency

Not all of the fuel and oxidizer supplied to a fuel cell is used to generate electricity. For example, some of the liquid reactants (e.g., hydrazine and hydrogen peroxide) are lost by spontaneous decomposition. Also, some fuels, such as methanol, cannot always be brought into complete reaction because they are oxidized in several steps, the last of which may proceed slower than the others. The fuel may then fail to be oxidized to the expected end product. Reaction efficiency is the ratio of the fuel consumed electrochemically to the fuel supplied. These efficiencies are normally 95 percent or higher.

#### Output Interface Device Efficiencies

The power supplied by the fuel cell is in the form of direct current (DC). This power may provide mechanical outputs through the use of DC motors, which have an efficiency of 80 to 90 percent when operated at rated loads. DC heating grids will operate at nearly 100 percent

### IDEAL EFFICIENCY VALUES FOR $H_2$ , $N_2H_4$ AND SOME COMMON HYDROCARBON FUELS

REACTANT Half-Cell Reaction Complete-Cell Reaction	$\Delta F^\circ/\Delta H^\circ$ , Ideal Efficiency (percent)
HYDROGEN $\text{H}_2 \rightleftharpoons 2\text{H}^+ + 2\text{e}^-$ $\text{H}_2 + \frac{1}{2}\text{O}_2 \rightleftharpoons \text{H}_2\text{O}$	83.0
METHANE $\text{CH}_4 + 2\text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + 8\text{H}^+ + 8\text{e}^-$ $\text{CH}_4 + 2\text{O}_2 \rightleftharpoons \text{CO}_2 + 2\text{H}_2\text{O}$	91.9
METHANOL (aq) $\text{CH}_3\text{OH (aq)} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + 6\text{H}^+ + 6\text{e}^-$ $\text{CH}_3\text{OH (aq)} + 1\frac{1}{2}\text{O}_2 \rightleftharpoons \text{CO}_2 + 2\text{H}_2\text{O}$	97.1
CARBON MONOXIDE $\text{CO} + \text{H}_2\text{O} \rightleftharpoons \text{CO}_2 + 2\text{H}^+ + 2\text{e}^-$ $\text{CO} + \frac{1}{2}\text{O}_2 \rightleftharpoons \text{CO}_2$	90.9
ETHANE $\text{C}_2\text{H}_6 + 4\text{H}_2\text{O} \rightleftharpoons 2\text{CO}_2 + 14\text{H}^+ + 14\text{e}^-$ $\text{C}_2\text{H}_6 + 3\frac{1}{2}\text{O}_2 \rightleftharpoons 2\text{CO}_2 + 3\text{H}_2\text{O}$	94.1
ETHANOL (aq) $\text{C}_2\text{H}_5\text{OH (aq)} + 3\text{H}_2\text{O} \rightleftharpoons 2\text{CO}_2 + 12\text{H}^+ + 12\text{e}^-$ $\text{C}_2\text{H}_5\text{OH (aq)} + 3\text{O}_2 \rightleftharpoons 2\text{CO}_2 + 3\text{H}_2\text{O}$	97.5
HYLENE $\text{C}_2\text{H}_4 + 4\text{H}_2\text{O} \rightleftharpoons 2\text{CO}_2 + 12\text{H}^+ + 12\text{e}^-$ $\text{C}_2\text{H}_4 + 3\text{O}_2 \rightleftharpoons 2\text{CO}_2 + 2\text{H}_2\text{O}$	94.3

REACTANT Half-Cell Reaction Complete-Cell Reaction	$\Delta F^\circ / \Delta H^\circ$ Ideal Efficiency (percent)
<b>ACETYLENE</b> $C_2H_2 + 4 H_2O \rightleftharpoons 2 CO_2 + 10 H^+ + 10 e^-$ $C_2H_2 + 2\frac{1}{2} O_2 \rightleftharpoons 2 CO_2 + H_2O$	95.0
<b>PROPANE</b> $C_3H_8 + 6 H_2O \rightleftharpoons 3 CO_2 + 20 H^+ + 20 e^-$ $C_3H_8 + 5 O_2 \rightleftharpoons 3 CO_2 + 4 H_2O$	95.0
<b>PROPYLENE</b> $C_3H_6 + 6 H_2O \rightleftharpoons 3 CO_2 + 18 H^+ + 18 e^-$ $C_3H_6 + 4\frac{1}{2} O_2 \rightleftharpoons 3 CO_2 + 3 H_2O$	95.1
<b>BENZENE</b> $C_6H_6 + 12 H_2O \rightleftharpoons 6 CO_2 + 30 H^+ + 30 e^-$ $C_6H_6 + 7\frac{1}{2} O_2 \rightleftharpoons 6 CO_2 + 3 H_2O$	97.2
<b>HYDRAZINE (aq)</b> $N_2H_4 (aq) + 4 OH^- \rightleftharpoons N_2 + 4 H_2O + 4 e^-$ $N_2H_4 (aq) + O_2 \rightleftharpoons N_2 + 2 H_2O$	99.4

The symbols used in the table are:

$\Delta F^\circ$  Standard-state free energy of reaction at 25°C.

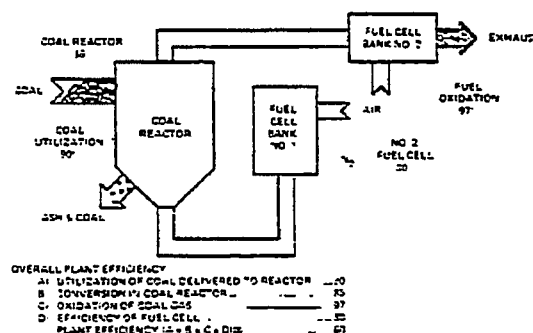
$\Delta H^\circ$  Standard-state heat of reaction at 25°C.

Source: Carl Berger (ed.), *Handbook of Fuel Cell Technology*.  
Englewood Cliffs, New Jersey: Prentice-Hall, 1968.

efficiency. DC may be converted to AC by either a motor-generator or solid-state inverter. Both these devices are capable of 80 to 90 percent efficiencies. Output interface device efficiency may be defined as a measure of the ratio of delivered power divided by DC power delivered by the fuel cell.

### al Fueled Power Efficiency Example

The efficiency estimates for a proposed Westinghouse multimegawatt coal-fueled fuel cell power plant with DC output are shown in Figure XIII-11.



Source: E. F. Sverdrup, et al, "A Fuel Cell Power System for Central-Station Power Generation Using Coal As a Fuel," *From Electrolysis to Fuel Cells*, Seattle: University of Washington Press, 1972.

**Figure XIII-11. EFFICIENCIES OF A  
SOLID ELECTROLYTE FUEL  
CELL POWER PLANT**

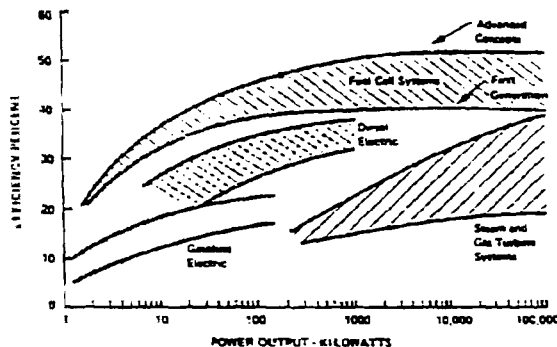
## Comparison of Power System Efficiencies

PUD/UAC has determined the efficiencies of a range of power plants that use gas or liquid hydrocarbon fuels to provide AC power (Figure XIII-12).

These efficiencies of a fuel cell also vary as a function of load, as shown in Figure XIII-13. The curves in that figure do not include the input or output interface efficiencies.

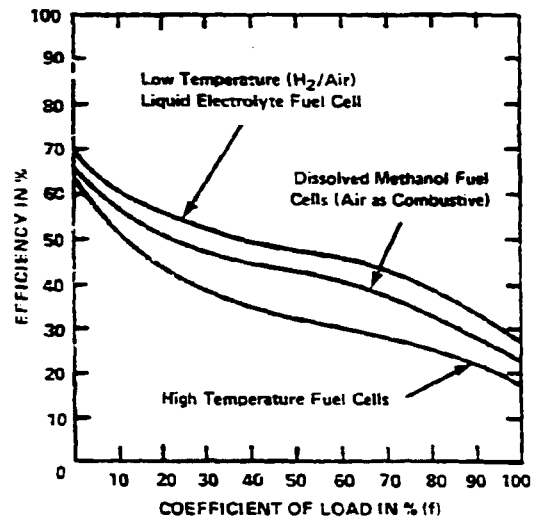
PUD/UAC plotted similar data for a fuel cell with input and output interface devices in Figure XIII-14 and compared the fuel cell with some other electrical power generation devices.

The two important observations to be made about the efficiency of fuel cells relative to other conventional energy systems are that, first, they usually offer higher efficiencies; second, their efficiencies improve with decreasing load over wide variations.



Source: Power Utility Division, United Aircraft Corp., Testimony Before Subcommittee on Energy Research, Development and Demonstration, Committee on Science and Technology, U.S. House of Representatives 27 Feb. 1975

Figure XIII-12. COMPARISON OF POWER SYSTEM EFFICIENCIES



Source: Carl Berger (ed), *Handbook of Fuel Cell Technology*, Englewood Cliffs: Prentice-Hall, 1968.

Figure XIII-13. EFFICIENCY AS A FUNCTION OF LOAD

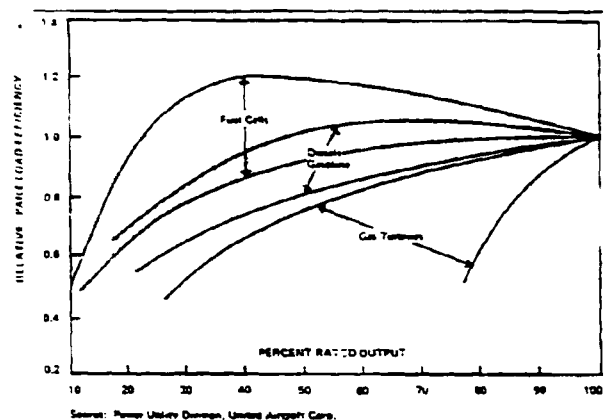


Figure XIII-14. COMPARISON OF PART LOAD EFFICIENCIES

## TECHNICAL CHARACTERISTICS

### Size

Space requirements for typical fuel cells, compared with conventional power sources, are shown in Table XIII-2. Although volume is normally the important size parameter, area is the most important one in large utility power plants. Also, volume with fuel and oxidant is the important consideration in spacecraft.

### Weight

Table XIII-3 lists some typical power density values for fuel cells, compared with conventional power plants.

In spacecraft, weight per kilowatt-hour is more important than weight per kilowatt; thus, fuel cell weights should be considered with their fuel and oxidant included. Figure XIII-15 shows weights of fuel cells and batteries for

Table XIII-2  
SPACE REQUIREMENTS FOR FUEL CELLS AND OTHER POWER SOURCES

U.S. Units		MKS Units		Remarks
Value	Units	Value	Units	
2.64	FT <sup>3</sup> /KW	0.075	M <sup>3</sup> /KW	Provisional specifications for PUD/UAC's PC-16 12.5 fuel cell using natural gas for propane for fuels; complete power system (reformer, liquid electrolyte fuel cell, and inverter) to supply AC power for remote site, portable or emergency applications.
0.21	FT <sup>3</sup> /KW	5.95x10 <sup>-3</sup>	M <sup>3</sup> /KW	Alstom's 1 KW hydrazine-hydrogen peroxide unit.
0.115 <sup>c</sup>	FT <sup>3</sup> /KW	3.26x10 <sup>-3</sup>	M <sup>3</sup> /KW	Westinghouse solid electrolyte fuel cell power unit optimization study (for fuel cell only).
0.2	FT <sup>3</sup> /KW	5.66x10 <sup>-3</sup>	M <sup>3</sup> /KW	Westinghouse study on central-station power generation (for fuel cell only, operating at 80 percent efficiency). <sup>a</sup>
0.71-1.06	FT <sup>3</sup> /KW	0.02-.03	M <sup>3</sup> /KW	Fuel cell only; low temperature hydrogen with liquid electrolyte.
0.18-0.53	FT <sup>3</sup> /KW	0.005-.015	M <sup>3</sup> /KW	Fuel cell only; low temperature hydrogen with solid electrolyte.
2.12-3.18	FT <sup>3</sup> /KW	0.06-.09	M <sup>3</sup> /KW	Fuel cell only; low temperature dissolved methanol.
0.53-0.88	FT <sup>3</sup> /KW	0.015-.025	M <sup>3</sup> /KW	Fuel cell only; low temperature dissolved hydrazine.
0.50	FT <sup>3</sup> /KW	0.0142	M <sup>3</sup> /KW	Fuel cell only; 11.2 KW electric automobile design study; hydrogen fuel.
0.20 <sup>b</sup>	FT <sup>2</sup> /KW	0.0186 <sup>b</sup>	M <sup>2</sup> /KW	Estimates for PUD/UAC 20 MW TARGET power plant.
0.106	FT <sup>3</sup> /KW	3.01x10 <sup>-3</sup>	M <sup>3</sup> /KW	Internal combustion engine.
1.766	FT <sup>3</sup> /KW	0.05	M <sup>3</sup> /KW	Gasoline engine with an alternator unit (10 KW size).
2.119	FT <sup>3</sup> /KW	0.06	M <sup>3</sup> /KW	Diesel engine with an alternator unit (100 KW size).
11.654	FT <sup>3</sup> /KW	0.33	M <sup>3</sup> /KW	Lead/acid batteries used to 0.1 of their capacity.
3.531	FT <sup>3</sup> /KW	0.10	M <sup>3</sup> /KW	Ni-Cad batteries used to 0.2 of their capacity.

<sup>a</sup>The coal gasification bed volume requirements are 0.25 to 0.4 FT<sup>3</sup>/KW.

<sup>b</sup>Area per KW.

Sources: A. D. S. Tantram, "Fuel Cells: Past, Present and Future," *Energy Policy*, Vol. 2, No. 1, March 1974.

E. F. Sverdrup, et al, "Design of High Temperature Solid-Electrolyte Fuel-Cell Batteries for Maximum Power Output Per Unit Volume," *Energy Conversion an International Journal*, Pergamon Press, Vol. 13, No. 4, December 1973.

E. F. Sverdrup, et al, "A Fuel-Cell Power System for Central-Station Power Generation Using Coal as a Fuel," *From Electrocatalysis to Fuel Cells*, Seattle, Washington, University of Washington Press, 1972.

Carl Berger (ed.), *Handbook of Fuel Cell Technology*, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1968.

W. T. Reid, "Fuel Cells for Practical Energy Conversion Systems," *From Electrocatalysis to Fuel Cells*, Seattle, Washington, University of Washington Press, 1972.

W. J. Lueckel, et al, "Fuel Cells for Dispersed Power Generation," *IEEE Winter Meeting*, New York, N. Y., Jan. 30 - Feb. 4, 1974, Paper T-72.

J. Verstrate, et al, "Fuel Cell Economics and Commercial Applications," *Handbook of Fuel Cell Technology*, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1968.

a 200 W unit. Table XIII-4 lists some weight comparisons between competing power sources considered for the Apollo space missions.

## Noise

While the basic fuel cell is a quiet device, there are some potentially noisy devices that can be part of a fuel cell system—for example, reformers, coal gasification plants, cooling fans, transformers, etc. Preliminary design noise estimates, not including transformer noise, for PUD/UAC 20 MW TARGET fuel cell power plant indicate that it will

be inaudible at 100 feet in a residential neighborhood. Although this system has some sound-proofing, the noise level could be further reduced by additional acoustical baffling.

## Exhaust Emissions

Fuel cells usually have low levels of exhaust emissions because the chemical reaction takes place at low temperatures. The results of PUD/UAC fuel cell experiments using natural gas are contained in Table XIII-5.

Table XIII-3

## POWER DENSITIES OF FUEL CELLS AND OTHER POWER SOURCES

Power Density (lb/kw)	Power Density (kg/kw)	Remarks
17.0	7.71	PUD/UAC PC15A-1 space system fuel cell; also two of these used in the Deep Submergence Rescue Vehicle (DSRV).
19.0	8.62	PUD/UAC space shuttle orbiter fuel cell.
80.0	36.29	Provisional specifications for PUD/UAC PC-16 fuel cell; based on total system weight including reformer, fuel cell and DC to AC inverter. System designed to use natural gas or propane.
33.1 to 44.1	15 to 20	Low temperature hydrogen fuel cells with liquid electrolyte (fuel cell only).
22.0 to 33.1	10 to 15	Low temperature hydrogen fuel cell with solid electrolyte (fuel cell only).
66.1 to 99.2	30 to 45	Low temperature dissolved methanol fuel cells (fuel cell only).
22.0 to 33.1	10 to 15	Low temperature dissolved hydrazine fuel cells (fuel cell only).
6.61	3.00	Internal combustion engines.
8.82	4.00	Gasoline engines with transmission.
17.64	8.00	Diesel engines with transmission.
55.12	25.00	Gasoline engines with alternator unit (10 KW size).
77.16	35.00	Diesel engines with alternator unit (100 KW size).
1322.77	600.00	Lead/acid batteries used to 0.1 of their capacity.
440.92	200.00	Ni Cd batteries used to 0.1 of their capacity.
3.31	1.50	Wankel engine (projection).

Sources: PUD/UAC data.

A. D. S. Tantram, "Fuel Cell Economics and Commercial Applications," *Handbook of Fuel Cell Technology*, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1968.

## ECONOMICS

The economic evaluation<sup>1</sup> of competing energy conversion systems in its simplest form requires the combination of fixed and proportional costs to determine a cost per kilowatt-hour (KWH). A typical situation for fuel cells is shown in Figure XIII-16. In the example shown, the most economical operation would occur at a 53 percent load factor. If, for example, a power plant were required to provide an average 53 KW load, it would be desirable, from an economics point of view, to build a 100 KW power plant. The resulting power plant would thus have a large reserve capacity. It could also economically provide power for at least a 40 percent reduction in its 53 KW nominal load.

In a conventional (e.g., a steam turbogenerator) electrical power generation system, the proportional costs curve would have a reversed slope and a somewhat different shape.<sup>2</sup> As a result, the combined costs curve would have an optimum economic load factor near 100 percent and the relative cost per KWH would rise rapidly for lower load factors. Thus the optimum plant would have a (1) small reserve capacity and (2) energy at the lower load factors would be relatively expensive. However, the initial capital costs would usually be much lower than the competing fuel cell power plant.

PUD/UAC, in testimony before Congress,<sup>3</sup> stated that technology has progressed to the point that a mass pro-

duction selling price of \$200 to \$350 per kilowatt can be projected. These costs include both input (for fuel conditioning) and output (to convert from DC to AC power) interface devices for the fuel cell.

In summary, fuel cells compare most favorably economically when:

- DC power is the required output.
- Hydrogen is the required fuel.
- A power plant has a large peaking requirement relative to its nominal load.
- One of the favorable factors listed below could be exploited.

There are several favorable factors involved in the use of fuel cells:

<sup>1</sup>For more details on the methodology for making economic evaluations of fuel cells relative to other power systems consult J. Verstraete, et al., "Fuel Cell Economics and Commercial Applications," *Handbook of Fuel Cell Technology*, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1968 and F. Courtoy, "La tarification EREFKA—son application au règlement des échanges dans groupements de centrales électriques," *Revue Universelle Mines*, 7ème série, XI, No. 2, 7-15-1926.

<sup>2</sup>The primary cause of the change would be the differing efficiency characteristics.

<sup>3</sup>Testimony by Mr. William H. Podolsky before the Subcommittee on Energy Research, Development, and Demonstration, Committee on Science and Technology, United States House of Representatives on February 27, 1975.

Table XIII-4

## COMPARISONS OF WEIGHTS FOR POWER SOURCES FOR THE APOLLO MISSION

Power Source	Approximate Weight for Mission <sup>1</sup> (lb)	Command and Service Module <sup>2</sup> (percent)
Lead-acid batteries	44,000	70
Silver-zinc batteries	12,000	15
Hydrogen-oxygen engine generator	6,500	10
Ion exchange fuel cell (General Electric)	2,500	4
Sacon fuel cell (PUD/UAC)	1,600	2-6

<sup>1</sup>The weights are all up weights including fuel, oxidant, tankage, electrolyte, etc., for the Apollo mission requirements.

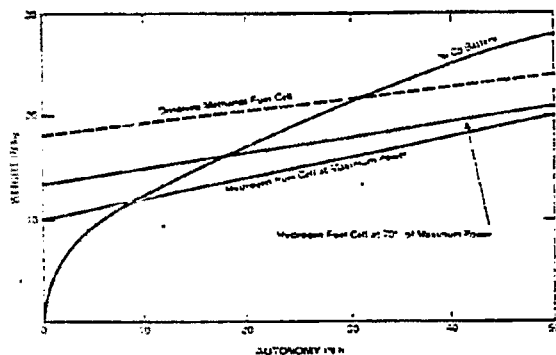
Mission time: Up to 400 hours

Peak power: About 3 KW

Energy storage: About 800 kWh

<sup>2</sup>Command module + service module = 62,720 lb

Source: A. D. S. Tantram, "Fuel Cells: Past, Present and Future," *Energy Policy*, Vol. 2, No. 1, March 1974, pages 55-66.



Source: J. Verstraete, et al, "Fuel Cell Economics and Commercial Applications," *Handbook of Fuel Cell Technology*, Englewood Cliffs: Prentice-Hall, 1968.

Figure XIII-15. WEIGHT OF BATTERY AND FUEL CELLS FOR 200 W UNIT

- Fuel cells lend themselves to modular construction, which allows:
  - a utility to purchase the power capacity needed today with the flexibility to add capacity later as required
  - good space utilization (e.g., in naval ships).
- Higher efficiencies result in lower fuel consumption and costs.
- Fuel cells can be located near application sites, thus reducing electrical distribution costs.

Table XIII-5

## COMPARISON OF POLLUTION LEVELS

Pollutant	Gas-Fired Central Station (lb/mWh)	Fuel Cells <sup>a</sup> (lb/mWh)
Sulfur dioxide	0.3	0.0003
Nitrogen oxides	4	0.24
Hydrocarbons	2.8	0.23
Particulates	0.1	0.00003

<sup>a</sup>Based on experimental data from natural gas fuel cells.

Source: PUD/UAC data.

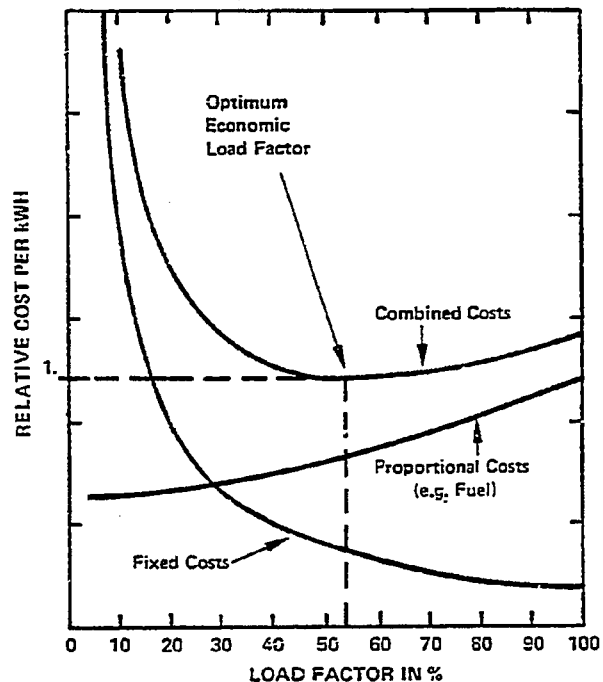


Figure XIII-16. COST VARIATIONS AS A FUNCTION OF LOAD FACTOR

- Fuel cell modules are made up of components that can be mass produced.
- Fuel cells can meet many of the noise, air pollution, and other environmental requirements with only minimum modifications.

There are also several unfavorable factors:

- It is a new technology with uncertainties in data on production and operation costs and other economic factors.
- The anticipated life of some fuel cell system components is less than that of conventional power sources.



## RESEARCH AND DEVELOPMENT

An inventory of fuel cell R&D programs is contained in U.S. House of Representatives *Inventory of Current Energy Research and Development*.<sup>1</sup> This section lists a few of the most significant fuel cell programs.

**TITLE:** Electrochemical In-House Study  
**RESEARCH GROUP:** U.S. Dept. of Defense, Aero Propulsion Laboratory  
**SPONSOR(S):** U.S. Dept. of Defense, Aero Propulsion Laboratory  
**DURATION:** July 1971 through June 1972  
**DESCRIPTION:** Implementation of advanced R&D programs on electrochemical power sources for air force use and application.

**TITLE:** Electrochemical Research Related to Batteries and Fuel Cells  
**RESEARCH GROUP:** U.S. Dept. of Defense, Air Force Cambridge Research Laboratories  
**SPONSOR(S):** U.S. Dept. of Defense, Air Force  
**DURATION:** February 1968 through June 1972  
**DESCRIPTION:** Study of the basic processes occurring in electrolyte solutions and at electrode surfaces in systems which show promise as new power sources.

**TITLE:** Electrical Power Research/Advanced Electrical Generating Systems  
**RESEARCH GROUP:** U.S. Dept. of Defense, Army Mobility Equipment Research & Development Center  
**SPONSOR(S):** U.S. Dept. of Defense, Army  
**DURATION:** Continuing  
**DESCRIPTION:** Perform applied research on those problems which are impeding the development of silent and tactical electrical power sources.

**TITLE:** Hydrocarbon Fuel Cells  
**RESEARCH GROUP:** Argonne National Laboratory, Chemical Engineering Division  
**SPONSOR(S):** U.S. Dept. of Defense, Army Mobility Equipment Command  
**DURATION:** 1972 to Indefinite  
**DESCRIPTION:** Developing an electrolyte superior to phosphoric acid for use in fuel cells with platinum electrodes and propane as the anode reactant.

**TITLE:** Evaluation of Phosphoric Acid Matrix Fuel Cells  
**RESEARCH GROUP:** Engelhard Minerals & Chemicals Corp.  
**SPONSOR(S):** U.S. Dept. of Defense, Army Mobility Equipment Command

**DURATION:** January 1967 through January 1972  
**DESCRIPTION:** Reduce the catalysts cost/kw of H<sub>2</sub>-air fuel cells and examination of other reactants such as methanol and propane.

**TITLE:** Natural Gas Fuel Cell Development  
**RESEARCH GROUP:** PUD/UAC  
**SPONSOR(S):** PUD/UAC  
**DURATION:** January 1967 through December 1975  
**DESCRIPTION:** The natural gas fuel cell power plant which PUD/UAC is investigating for TARGET produces electrical power directly from natural gas by an electrochemical reaction. The fuel cell uses natural gas and air to produce power directly at the site—without the intermediate steps.

**TITLE:** The Coal Energized Fuel Cell  
**RESEARCH GROUP:** Westinghouse Electric Corp.  
**SPONSOR(S):** U.S. Dept. of Interior, Office of Coal Research  
**DURATION:** July 1971 through June 1972  
**DESCRIPTION:** Development of a commercial fuel-cell power generating system, using coal as fuel.

**TITLE:** Twenty Watt-Hour/Lb Regenerative Fuel Cell  
**RESEARCH GROUP:** PUD/UAC  
**SPONSOR(S):** U.S. Dept. of Defense, Aero Propulsion Laboratory  
**DURATION:** June 1970 through June 1972  
**DESCRIPTION:** Build a base of exploratory development which will support advanced development of a rechargeable fuel cell for space applications.

**TITLE:** Electric Power — Generation  
**RESEARCH GROUP:** Institute of Gas Technology  
**SPONSOR(S):** Utilities, Unspecified  
**DURATION:** Continuing  
**DESCRIPTION:** Fuel cell research—details proprietary.

**TITLE:** Fuel Cell Generator  
**RESEARCH GROUP:** Long Island Lighting Co.  
**SPONSOR(S):** Long Island Lighting Co.  
**DURATION:** 1972 through 1975  
**DESCRIPTION:** Investigate the use of the Fuel Cell Generator on the LILCO system.

**TITLE:** Heat Rejection Systems for Electrochemical Equipment  
**RESEARCH GROUP:** National Aeronautics & Space Administration  
**SPONSOR(S):** National Aeronautics & Space Administration

**DURATION:** July 1969 through 1973  
**DESCRIPTION:** Perform basic R&D tasks related to optimization of a heat rejection system for an alkaline, hydrogen-oxygen fuel cell.

<sup>1</sup> Prepared by Atomic Energy Commission's Oak Ridge Laboratory and RANN for the Subcommittee on Energy of the Committee of Science and Astronautics U.S. House of Representatives, Washington, D.C., January 1974, pp. 1056 to 1151.

**TITLE:** Fuel Cell Reactant Purification

**RESEARCH GROUP:** National Aeronautics & Space Administration

**SPONSOR(S):** National Aeronautics & Space Administration

**DURATION:** July 1970 through June 1974

**DESCRIPTION:** To determine the effects of impurities in the reactant gases of fuel cells and then determine methods of removing detrimental impurities.

**TITLE:** Energy Conversion and Storage

**RESEARCH GROUP:** Oklahoma State University

**SPONSOR(S):** Arkansas Power & Light Co.

**DURATION:** 1964 to Undetermined

**DESCRIPTION:** Develop an economical commercial electrolysis-fuel cell, the purpose of which would be to utilize off-peak electric energy and water in the electrolysis mode to produce oxygen and hydrogen which would be stored.

**TITLE:** Pollution-Free Electrochemical Energy Generation from Fuel

**RESEARCH GROUP:** Stanford Research Institute

**SPONSOR(S):** National Science Foundation

**DURATION:** May 1972 through July 1973

**DESCRIPTION:** Development of an electrochemical conversion system to oxidize fuel under pollutant-free conditions and generate electrical energy.

**TITLE:** Aerospace Fuel Cells

**RESEARCH GROUP:** U.S. Dept. of Defense, Aero. Propulsion Laboratory

**SPONSOR(S):** U.S. Dept. of Defense, Air Force

**DURATION:** Indefinite

**DESCRIPTION:** This task develops the fuel cell technology required by the Air Force to fulfill its needs for both primary and secondary power in aerospace applications.

**TITLE:** Fuel Cell Power Plant

**RESEARCH GROUP:** U.S. Dept. of Defense, Army Mobility Equipment Command

**SPONSOR(S):** U.S. Dept. of Defense, Army Materiel Command

**DURATION:** July 1971 through June 1972

**DESCRIPTION:** Develop, checkout, test and deliver two development models of 1.5 KW 28 V.D.C. fuel cell power unit, to operate on regular automotive gasoline for powering communications equipment.

**TITLE:** Evaluation of New Fuel Cell Concepts

**RESEARCH GROUP:** U.S. Dept. of Defense, Army Mobility Equipment Command

**SPONSOR(S):** U.S. Dept. of Defense, Army Mobility Equipment Command

**DURATION:** April 1970 to indefinite

**DESCRIPTION:** Continued evaluation and comparison to determine whether new fuel cell concepts are advances in the state-of-the-art for military

applications. This requires experimental efforts for new concepts and often for new technology when the military application differs from that of the initial development.

**TITLE:** Fuel Cell Power Plant

**RESEARCH GROUP:** U.S. Dept. of Defense, Army Satellite Communications Agency

**SPONSOR(S):** U.S. Dept. of Defense, Army Materiel Command

**DURATION:** July 1971 through June 1972

**DESCRIPTION:** Develop, fabricate, checkout, test and deliver two development models of a 1.5 KW 28 V.D.C. fuel cell power unit, to operate on regular automotive gasoline for powering communications equipment.

**TITLE:** Fuel Cell Materials for Underwater Power Sources

**RESEARCH GROUP:** U.S. Dept. of Defense, Naval Ship Research & Development Center

**SPONSOR(S):** U.S. Dept. of Defense, Naval Ship Systems Command

**DURATION:** November 1965 through June 1974

**DESCRIPTION:** Study the electrochemical and compatibility behavior of plants operating in deep-sea pressures as high as 10,000 psi.

**TITLE:** Containment of High Pressure Hydrogen, Underwater Fuel Cell Systems

**RESEARCH GROUP:** U.S. Dept. of Defense, Naval Ship Research & Development Center

**SPONSOR(S):** U.S. Dept. of Defense, Naval Ship Systems Command

**DURATION:** January 1973 through June 1974

**DESCRIPTION:** Determine the performance characteristics of high strength steel and titanium alloys in high pressure gaseous hydrogen environments anticipated in the underwater containment of hydrogen fuel for naval fuel cell power systems.

**TITLE:** Hydrogen-Oxygen Fuel Cells for Underwater Applications

**RESEARCH GROUP:** U.S. Dept. of Defense, Naval Ship Research & Development Center

**SPONSOR(S):** U.S. Dept. of Defense, Naval Ship Systems Command

**DURATION:** July 1969 through June 1974

**DESCRIPTION:** Exploratory development of naval hydrogen-oxygen fuel cell power plant modules over the range of 2 to 20 KW with capabilities reaching 20 lb. and 0.2 cu. ft. per KW rated output, 0.8 lb. consumables per kWh, and a maintenance free life of 3000 hours.

**TITLE:** Hydrazine-Hydrogen Peroxide Fuel Cells for Underwater Applications

**RESEARCH GROUP:** U.S. Dept. of Defense, Naval Ship Research & Development Center

**SPONSOR(S):** U.S. Dept. of Defense, Naval Ship Systems Command

**DURATION:** July 1967 through June 1974

**DESCRIPTION:** Investigate operational characteristics and overall feasibility of pressure-compensated hydrazine-hydrogen peroxide fuel cells at simulated submergence depths down to 30,000 feet.

**TITLE:** Non-Gaseous Reactants, Pressure Equilibrated Operation

**RESEARCH GROUP:** U.S. Dept. of Defense, Naval Ship Research & Development Center

**SPONSOR(S):** U.S. Dept. of Defense, Naval Ship Research & Development Center

**DURATION:** July 1971 through September 1973

**DESCRIPTION:** Assess the feasibility of non-gaseous-reactant, high-energy density electrochemical energy sources, particularly the lithium-water system, for underwater naval applications requiring low weight and volume.

**TITLE:** Deep Submergence Vehicle (DSV) Fuel Cell Power System Supporting R&D

**RESEARCH GROUP:** U.S. Dept. of Defense, Naval Ship Research & Development Center

**SPONSOR(S):** U.S. Dept. of Defense

**DURATION:** July 1967 through June 1974

**DESCRIPTION:** In-house laboratory research and development on critical components of a fuel cell power system for a deep submergence vehicle, associated support equipment and program management technical support being provided to the Naval Ship Systems Command (PMS 395).

**TITLE:** Fuel Cell Research and Hydrogen Storing Electrodes

**RESEARCH GROUP:** U.S. Dept. of Defense, Naval Underwater Systems Center

**SPONSOR(S):** U.S. Dept. of Defense, Naval Underwater Systems Center

**DURATION:** July 1972 to Indefinite

**DESCRIPTION:** Develop information for fuel cell design concepts in which the oxidizer and the fuel are more compatible with the submarine environment than the hydrazine and hydrogen peroxide of presently available fuel cells.

**TITLE:** Materials for Conversions and Storage of Energy

**RESEARCH GROUP:** U.S. Dept. of Interior, Bureau of Mines

**SPONSOR(S):** U.S. Dept. of Interior, Bureau of Mines

**DURATION:** July 1972 through June 1976

**DESCRIPTION:** To develop rare-earth-based catalysts as low-cost substitutes for precious-metal catalysts, and develop fuel-gas storage systems having improved absorption capacity.

**TITLE:** Advanced Technology Fuel Cell System

**RESEARCH GROUP:** PUD/UAC

**SPONSOR(S):** National Aeronautics & Space Administration

**DURATION:** June 1971 through June 1976

**DESCRIPTION:** To develop an advanced technology fuel cell system for future space applications and provide technology fallout for ongoing mission oriented programs.

**TITLE:** Fuel Cells Research

**RESEARCH GROUP:** PUD/UAC

**SPONSOR(S):** Edison Electric Institute; Electric Power Research Institute

**DURATION:** 1959 to indefinite

**DESCRIPTION:** Commencing in 1967, PUD/UAC with the sponsorship of 28 natural gas utilities, embarked on a program to develop fuel cell power plants for on-site utility service. This group called TARGET (Team to Advance Research for Gas Energy Transformation) has since expanded to include gas utilities and combination gas and electric companies in the United States, Canada, and Japan. Planned as an overall nine-year program to be conducted in three phases, the program has as its goal the development of natural gas fuel cells for a competitive, environmentally sound energy service offering for natural gas customers.

**TITLE:** Development of a Family of Fuel Cell Power Plants

**RESEARCH GROUP:** PUD/UAC

**SPONSOR(S):** U.S. Dept. of Defense, Army Mobility Equipment Command

**DURATION:** June 1970 through January 1973

**DESCRIPTION:** Conduct advanced development on a family of fuel cell power sources to establish their suitability for the slipstream system and to ultimately provide a more cost effective power source than the present DOD standard generators.

**TITLE:** Mass Transfer in Fuel Cells

**RESEARCH GROUP:** University of Florida

**SPONSOR(S):** National Aeronautics & Space Administration

**DURATION:** Continuing

**DESCRIPTION:** Research in progress is directed toward improved structural characterization of all elements of a fuel cell, a study of the processes by which electrolyte wets and penetrates a heterogeneous, porous wet-proofed electrode, measurement of effective transport properties for reactants and products in fuel cells, and a study of water transport in fuel cells.

**TITLE:** Fuel Cell Research - Electrocatalysis

**RESEARCH GROUP:** University of Idaho

**SPONSOR(S):** University of Idaho

**DURATION:** 1971 to Continuing

**DESCRIPTION:** Eliminating the need of a noble metal catalyst by using some external means of conditioning the electrode surface, the fuel, or both.

**TITLE:** Hydrogen Generator for 0.5 KW Fuel Cell system

**RESEARCH GROUP:** Energy Research Corp.

**SPONSOR(S):** U.S. Dept. of Defense, Army Mobility Equipment Command

**DURATION:** May 1971 through January 1972

**DESCRIPTION:** Design, construction and testing of a hydrogen generator capable of steam reforming JP-4 and water, to generate sufficient hydrogen to sustain the operation of a 0.5 KW fuel cell system.

### RECENT APPLICATIONS

Recent fuel cell applications include:

**MODEL:** U.S. Navy Deep Submergence Rescue Vehicle (DSRV) Fuel Cell

**MANUFACTURER:** Power Utility Division of United Aircraft Corp. (PUD/UAC), formerly Pratt and Whitney Aircraft

**STATUS:** Scheduled for delivery to U.S. Navy July 1975

**SPECIFICATIONS:**

maximum rated power—22 kilowatts

nominal regulation—100 to 140 vdc

energy delivery—700 kWh

total system weight—less than 9500 lb

**DISCUSSION:** The fuel cell is being constructed for the Navy under contract number N00024-74-C-1073 for installation on the DSRV. The power system consists of two PC15A-1 fuel cell power plants installed in containment vessels and a reactant supply system consisting of containment vessels for the storage of gaseous hydrogen, gaseous oxygen, and fuel-cell generated product water. The fuel cell power system will be capable of automatic continuous operation in sea water depths to 5000 feet. (Source: PUD/UAC)

**MODEL:** ASEA Submarine Power Plant

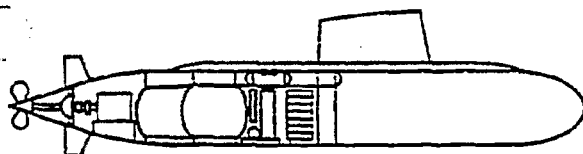
**MANUFACTURER:** ASEA of Sweden

**STATUS:** Unknown

**SPECIFICATIONS:**

maximum power—200 KW

**DISCUSSION:** Figure XIII-17 shows an outline of the Swedish submarine power plant. It is made up of ten 20 KW modules. The ammonia is cracked and the hydrogen formed is supplied to the hydrogen-oxygen battery. The nitrogen is condensed in a refrigeration system. The cells operate with nickel boride and silver catalysts. (Source: Vielstich, Wolf, *Fuel Cells Modern Processes for the Electrochemical Production of Energy*, New York, Wiley Interscience, 1965)



Source: Wolf Vielstich, *Fuel Cells*, New York: Wiley, 1965.

Figure XIII-17. ASEA SUBMARINE

**MODEL:** Gemini Spacecraft Fuel Cell

**MANUFACTURER:** General Electric

**STATUS:** Past development

**SPECIFICATIONS:**

maximum power

complete system—2 KW

per fuel cell battery—1KW

nominal voltage—27 volts DC

water production per kWh—1 pint

**DISCUSSION:** These fuel cells were designed for simplicity, reliability and light weight rather than high conversion efficiency. The basic cell has the electrolyte confined in an ion-exchange membrane based on sulphonated polystyrene. The electrodes, which contain 10-40 mg/cm<sup>2</sup> of platinum and palladium, are directly in contact with the membrane. Thirty-two cells in series make a stack; three stacks in parallel compose a battery; the system is composed of two batteries. A diagram of the system is shown in Figure XIII-18. For more technical discussion on the construction of this fuel cell system consult pages 439 to 441 of Vielstich, Wolf, *Fuel Cells Modern Processes for the Electrochemical Production of Energy*, New York, Wiley Interscience, 1965. (Source: Hart, A. B. and Womack, G. J., *Fuel Cells Theory and Application*, London, Chapman and Hall, 1967 and Vielstich, Wolf, *Fuel Cells Modern Processes for the Electrochemical Production of Energy*, New York, Wiley Interscience, 1965)

**MODEL:** PC3A-2 Project Apollo Fuel Cell

**MANUFACTURER:** PUD/UAC

**STATUS:** Project completed

**SPECIFICATIONS:**

maximum power—2.295 KW

normal power range—0.563 to 1.420 KW

voltage range—27 to 31 volts

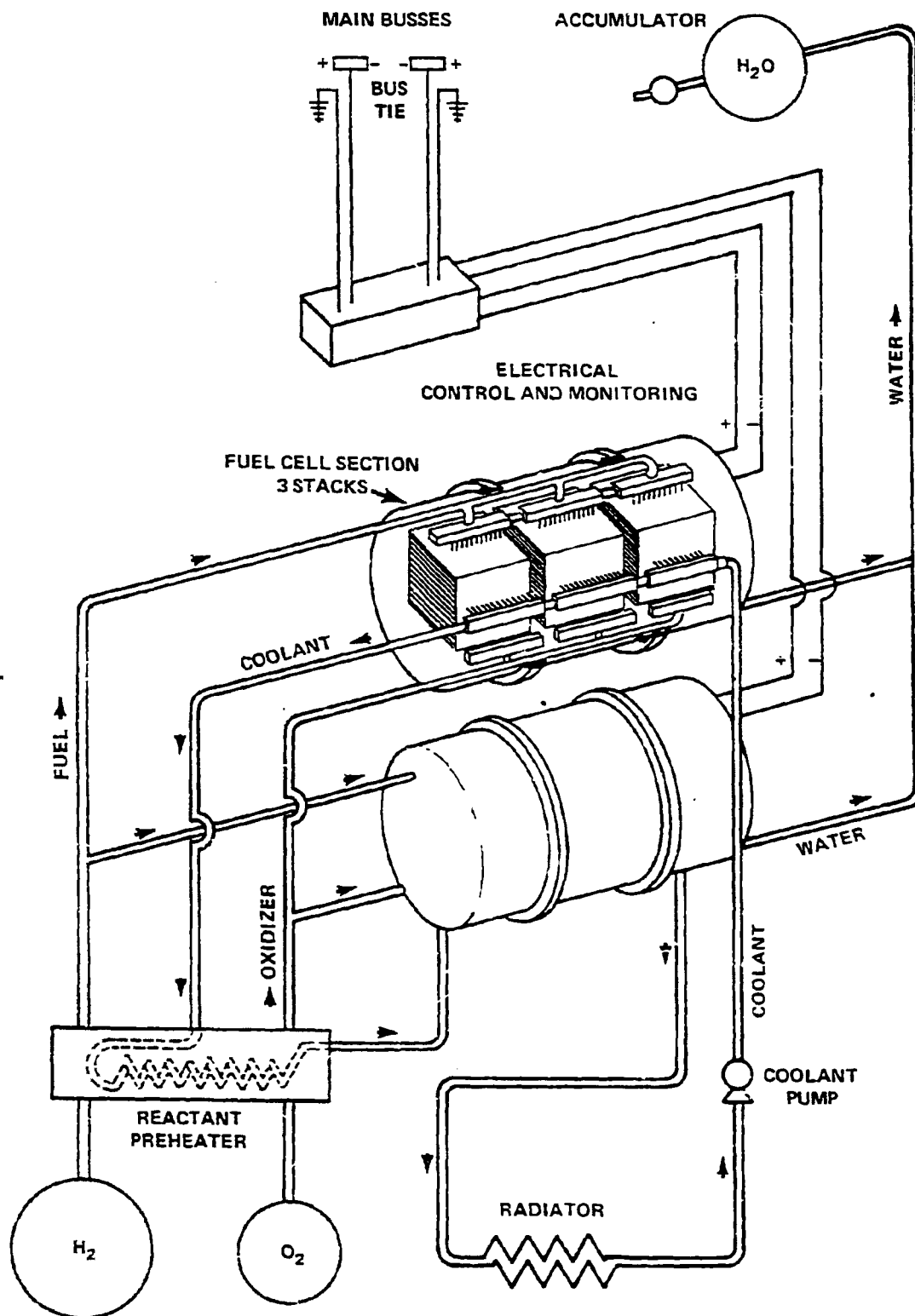
reactant consumption at 1.42 KW—1.166 lb/hr (maximum)

power plant weight—200 lb (exclusive of mounting provisions)

product water pH—6 to 8

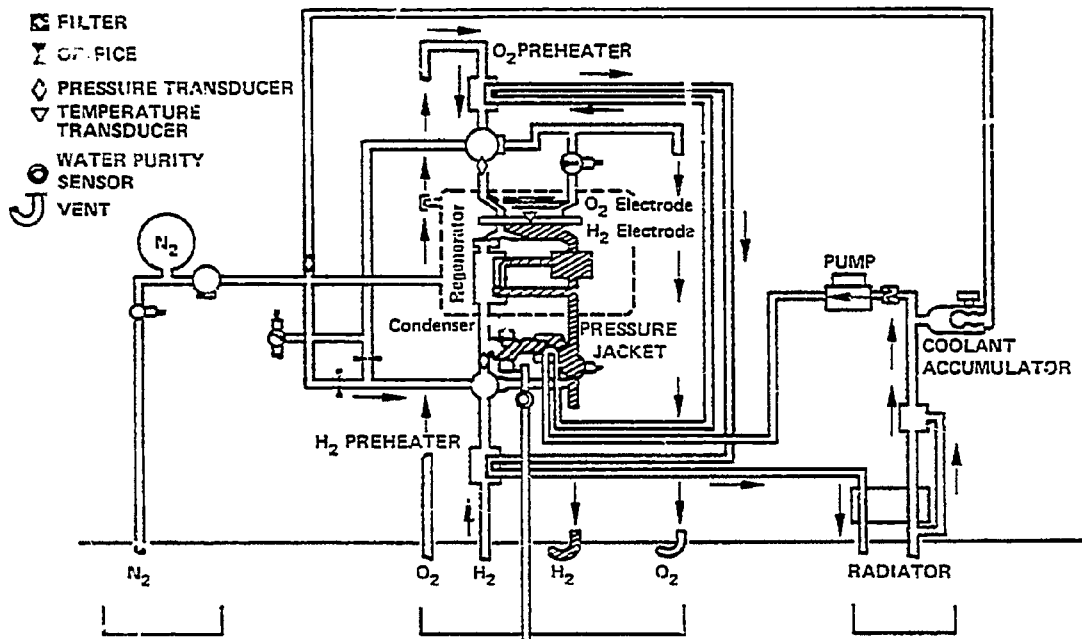
life—well in excess of 400 hours

**DISCUSSION:** This fuel cell is based on the Bacon Cell design. This was a considerable redesign of the original Bacon Cell to allow weightlessness operation and lower



Source: Wolf Vielstich, *Fuel Cells*, New York: Wiley, 1965.

Figure XIII-18. GE/GEMINI FUEL CELL



Source: A. B. Hart and G. J. Womack, *Fuel Cells Theory and Application*, London: Chapman and Hall, 1967.

Figure XIII-19. APOLLO FUEL CELL MODEL PC3A-2

operating pressures. The operating pressure was reduced from 600 lb/in<sup>2</sup> to 50 lb/in<sup>2</sup> to reduce the need for heavy components. This was achieved by increasing the potassium hydroxide concentration from 45 to 85 percent and operating the cell at 250° C instead of 200° C. Figure XIII-19 contains a diagram of the Apollo fuel cell system. (Source: Hart, A. B. and Womack, G. J., *Fuel Cells Theory and Application*. London, Chapman and Hall, 1967)

#### MODEL: PC11

MANUFACTURER: PUD/UAC

STATUS: 65 units built between 1970 and 1972

#### SPECIFICATIONS:

maximum power—12.5 KW

DISCUSSION: Sixty-five of these experimental power plants were installed at 35 sites. These units were installed, operated and serviced by utility company personnel in apartments, stores, single-family homes, small industrial plants and electrical utility substations. (Source: PUD/UAC)

#### MODEL: PC16

MANUFACTURER: PUD/UAC

STATUS: Proposed Development

#### SPECIFICATIONS:

continuous rated power—12.5 KW at 120 vac

dimensions—28 in x 41 in x 50 in

volume—33 ft<sup>3</sup>

weight—1000 lb

endurance, at rated power—2000 hours

endurance, at 10 KW—4000 hours

overall operating efficiency—about 30 percent

start-up time from a cold start—15 minutes

fuel—natural gas or propane

DISCUSSION: The PC16 is a proposed follow-on to the PC11 power plant. It is intended for remote site generation and portable or emergency power. In these applications it will compete with the diesel generator. The power plant system is composed of three main subsystems. The reformer subsystem processes the fuel to produce a hydrogen-rich feed for the fuel cell subsystem. The DC output from the fuel cell is then converted to a stable AC output in the electrical subsystem. The fuel cell subsystem uses a concentrated acid electrolyte with electrodes about one foot square and operates at around 130°-150° C. This temperature of operation enables the waste heat from the fuel cell stack to be used for creating the steam required for the reformer input. In conjunction with the concentrated acid electrolyte this operating temperature also allows direct use of the reformer gas without any intermediate purification and makes for easy control of the water balance in the cell stacks. The reformer is heated by burning the tail gases from the fuel cell stack. (Source: Tantram, A. D. S., "Fuel Cells: Past, Present and Future." *Energy Policy*, Vol. 2, No. 1, March 1974, Pages 55-66)

**MODEL:** PC17 Fuel Cell for Space Shuttle Orbiter

**MANUFACTURER:** PUD/UAC

**STATUS:** 15 power plants to be delivered between July 1976 and December 1980

**SPECIFICATIONS:**

maximum rated power—12 KW

voltage regulation—28.5 to 32.5 vdc

useful life—5000 hours

weight—228 lb

**DISCUSSION:** These fuel cells are being developed under contract number M4JTXMB-483025 with Rockwell International Corporation. A set of three power plants will be delivered for each Orbiter Vehicle. (Source: PUD/UAC)

**MODEL:** GM Electrovan Power Plant

**MANUFACTURER:** General Motors/Union Carbide

**STATUS:** R&D project, completed

**SPECIFICATIONS:**

maximum power—32 KW

peak electric motor rating—160 KW

fuel—liquid hydrogen (6 kg max.)

oxidizer—liquid oxygen (48 kg max.)

vehicle maximum range—150 miles

**DISCUSSION:** A minibus built by the General Motors Corporation was equipped with a 32 KW Union Carbide fuel cell. The liquid reactants were carried in vacuum tanks. In spite of a doubling of vehicle weight a speed of 60 mph could be attained from rest in 30 seconds. This compared favorably with the 23 seconds for the original 225 hp vehicle. (Source: Vielstich, Wolf, *Fuel Cells Modern Processes for the Electrochemical Production of Energy*. New York, Wiley Interscience, 1965)

## CHAPTER XIV

### GEOTHERMAL ENERGY



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## INTRODUCTION

Geothermal energy is heat from the earth's interior. This energy is mostly generated from the slow decay of naturally occurring radioactive elements present in all rocks. The heat escapes very slowly from the earth's core to the crust by conductive flow through solid rocks, by convective flow in circulating fluids, and by mass transfer of magma (molten rock generated from within the earth, termed lava when expelled at the earth's surface).

Thermal gradient describes the rate at which temperature increases with depth below the earth's surface and is expressed as degrees per unit of depth. Normally, the earth's heat is diffuse, the thermal gradient averaging about 25° C/km. In many areas, though, geologic conditions have created local thermal gradients much higher than the average. These thermal reservoirs contain enough concentrated heat to make up a potential energy source.

## TYPES OF GEOTHERMAL SYSTEMS

Geothermal systems are classified according to the mode of heat transfer and the temperature and pressure of the system.

In hydrothermal-convection systems, Figure XIV-1, heat is transferred from a deeper igneous source (magma) to the circulation of water or a vapor. Vapor-dominated systems,<sup>1</sup> meaning that pressure is controlled by vapor rather than by liquid, produce saturated or slightly superheated steam containing little or no liquid water and a small percentage of other gases such as CO<sub>2</sub> and H<sub>2</sub>S.

Temperatures in these systems can reach 240° C. Unfortunately, this type of system occurs only rarely, since the steam can be easily used directly in turbines to generate electricity. As a matter of fact, steam geothermal systems have been the most successfully and widely used to date in the Geysers Field, California; Lardarello, Italy; and Matsukawa, Japan.

In liquid-dominated systems, hot water transfers heat from deep sources to a geothermal reservoir at depths shallow enough to be tapped by drill holes. Most liquid-dominated systems occur as hot springs, although other types exist. Hot water convection systems have been arbitrarily divided into three temperature ranges according to their potential end-use: above 150° C for generation of electricity;<sup>2</sup> 90° C to 150° C for space and process heating; and below 90° C for local use where better energy sources do not exist.<sup>3</sup>

Hot water systems are about 20 times more common than steam systems and are usually found in areas of volcanic origin and high seismic activity; for example, in the western United States and along the mid-Atlantic Ridge. (See Figure XIV-2.) Their brine (dissolved salts) content varies widely. Hydrothermal convection systems in the United States have been studied for years by U.S. Geological Survey (USGS). More details on the characteristics of these, as well as other systems, can be found in numerous USGS publications, including the most recent summary.<sup>4</sup>

When used for space heating, hot water from geothermal resources can be piped directly to the point of

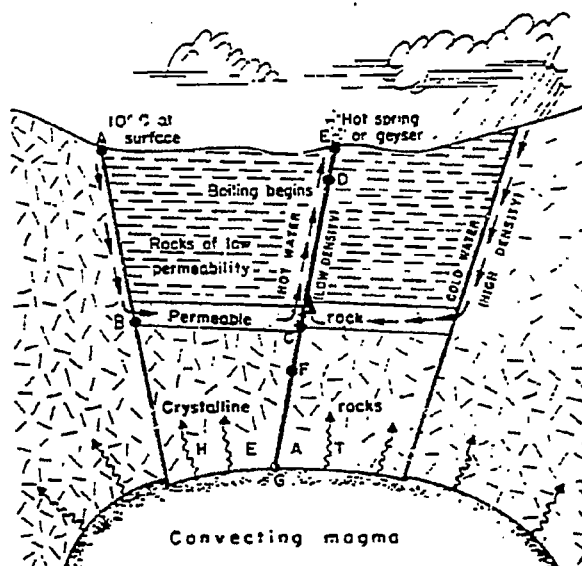
use. If the hot water is a highly corrosive brine, heat exchangers could be used. Other uses for such hot water include heating greenhouses, fish farming, pulp and paper processing, and as a source for extractable minerals. Desalination of geothermal hot waters might also provide fresh

<sup>1</sup> Sometimes inappropriately called "dry-steam deposits."

<sup>2</sup> Binary systems may allow use of somewhat lower temperatures for electricity generation.

<sup>3</sup> D. E. White, "Characteristics of Geothermal Resources," *Geothermal Energy*, P. Kruger and C. Otte (ed), Stanford University Press, 1973.

<sup>4</sup> *Assessment of Geothermal Resources of the United States—1975*, Circular No. 726, U.S. Geological Survey, Washington.



Source: D. E. White, "Characteristics of Geothermal Resources," *Geothermal Energy*, F. Kruger and C. Otte (ed), Stanford University Press, 1973.

Figure XIV-1. HYDROTHERMAL CONVECTION SYSTEM

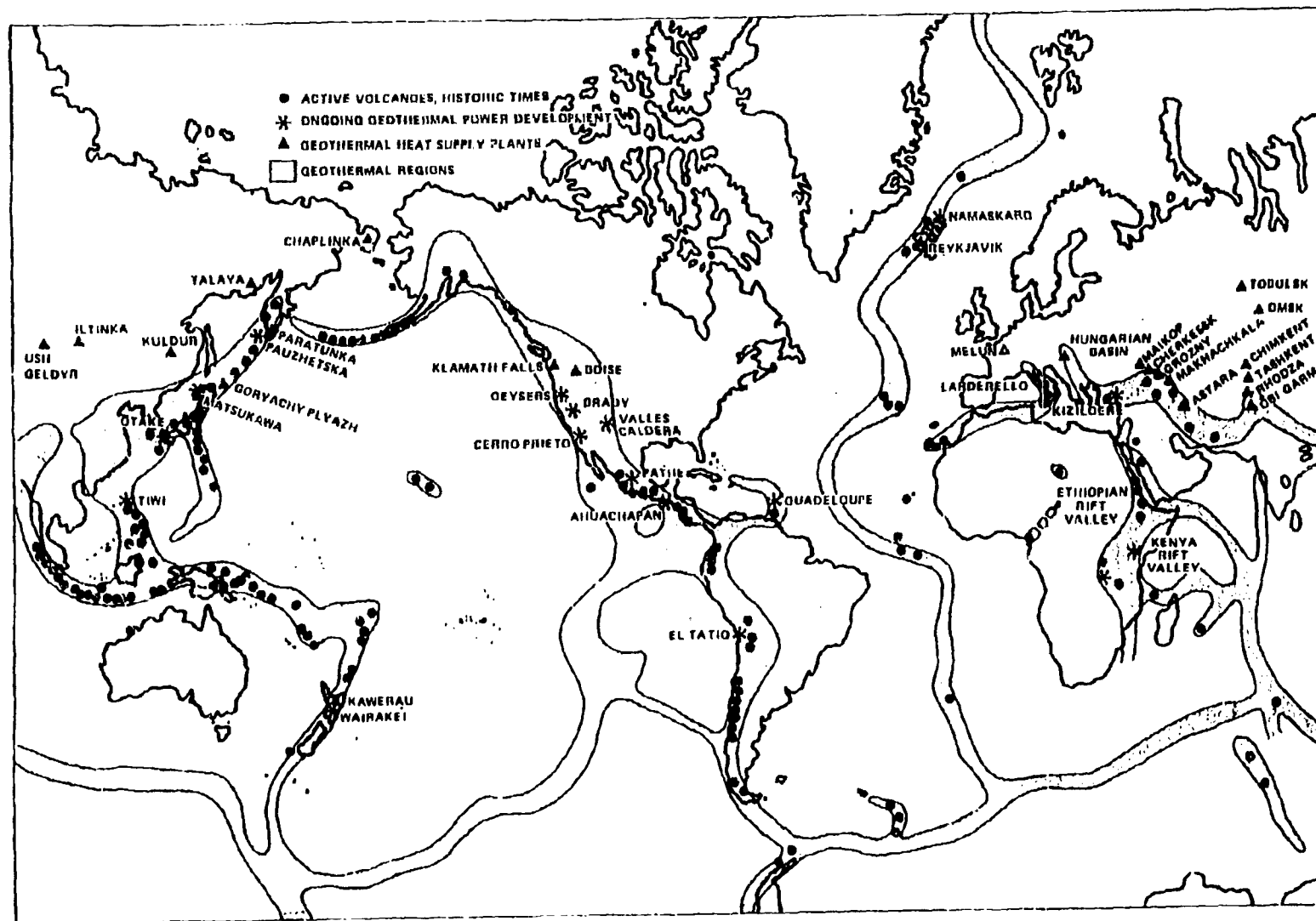


Figure XIV-2. GEOTHEMAL REGIONS OF THE WORLD

water needed in water-deficient areas, such as the Imperial Valley of California.

In dry hot rock deposits, the thermal energy is contained in impermeable rocks of very low porosity at relatively shallow depths, the heat being transferred by conduction rather than convection. The potential resources in dry hot rock are much greater than the hydrothermal potential given satisfactory methods of recovery.

Geopressured deposits result when formation waters, overlain by an insulation of 2 to 3 km of impermeable clay beds, become geopressured (high-pressured) and hotter as heat rising from the earth's interior is absorbed by the water. Geopressured zones are characterized by abnormally high pressures and low salinities. They occur worldwide. The waters are often saturated with recover-

able natural gas. Also, there may be a potential source of hydraulic energy in the abnormally high fluid pressures of these areas. There is a large geopressured zone in the northeastern Gulf of Mexico beneath an area of over 278,500 km<sup>2</sup>.

Magma or molten rock systems underlie all the earth's crust, sometimes coming near the surface, or surfacing in the form of volcanoes. This resource is essentially infinite, but no development is expected before 2000.

Normal thermal gradients are areas of heat produced by heat flows, radiogenic heat production, and the thermal conductivity of rocks. This is the only potential geothermal resource in most of the eastern two-thirds of the United States, but exploitation will occur only in the distant future, if then.

## U.S. GEOTHERMAL RESOURCES

The Energy Research and Development Administration (ERDA) has estimated the recoverable geothermal heat available using present or near-term technology without regard to cost. The total of 3,004 quads shown in Table XIV-1 is approximately equal to U.S. consumption of all forms of energy for 42 years (at the present rate of 71 quads per year). One quad is a quadrillion Btu or 10<sup>15</sup> Btu.

Exploration in the western United States increased rapidly from 1968 to 1976 encouraged by new public land leasing policies, increasing prices of energy, and by the successful development of geothermal energy at The Geysers. (See Figure XIV-3.) To quote from one authority:

"Extensive exploration and development are ongoing at The Geysers, and there have been significant discoveries made in the Imperial Valley, California, and at the Valles Caldera, New Mexico. Exploration is continuing at Beowawe and Brady's Hot Springs, Nevada, and Surprise Valley, California. In addition, exploration has been accelerated in portions of Utah, Idaho, Oregon, and Arizona. Discoveries have been sparse, but should increase as land becomes available and exploration is expanded."<sup>1</sup>

Several states have passed laws to permit leasing of state lands for geothermal exploration; however, the increased availability of land has coincided with increased legal requirements for environmental protection, resulting in conflicts and delays in the issuance of permits to drill.

particularly in California. The problem of defining surface rights, mineral rights, and water rights to allow for geothermal exploration and drilling activities has not been resolved in some areas. (See Legal and Institutional Problems in this chapter.) Increased interest in U.S. geothermal energy potential has encouraged both public and private sources to make financing more readily available for exploration and related activities.

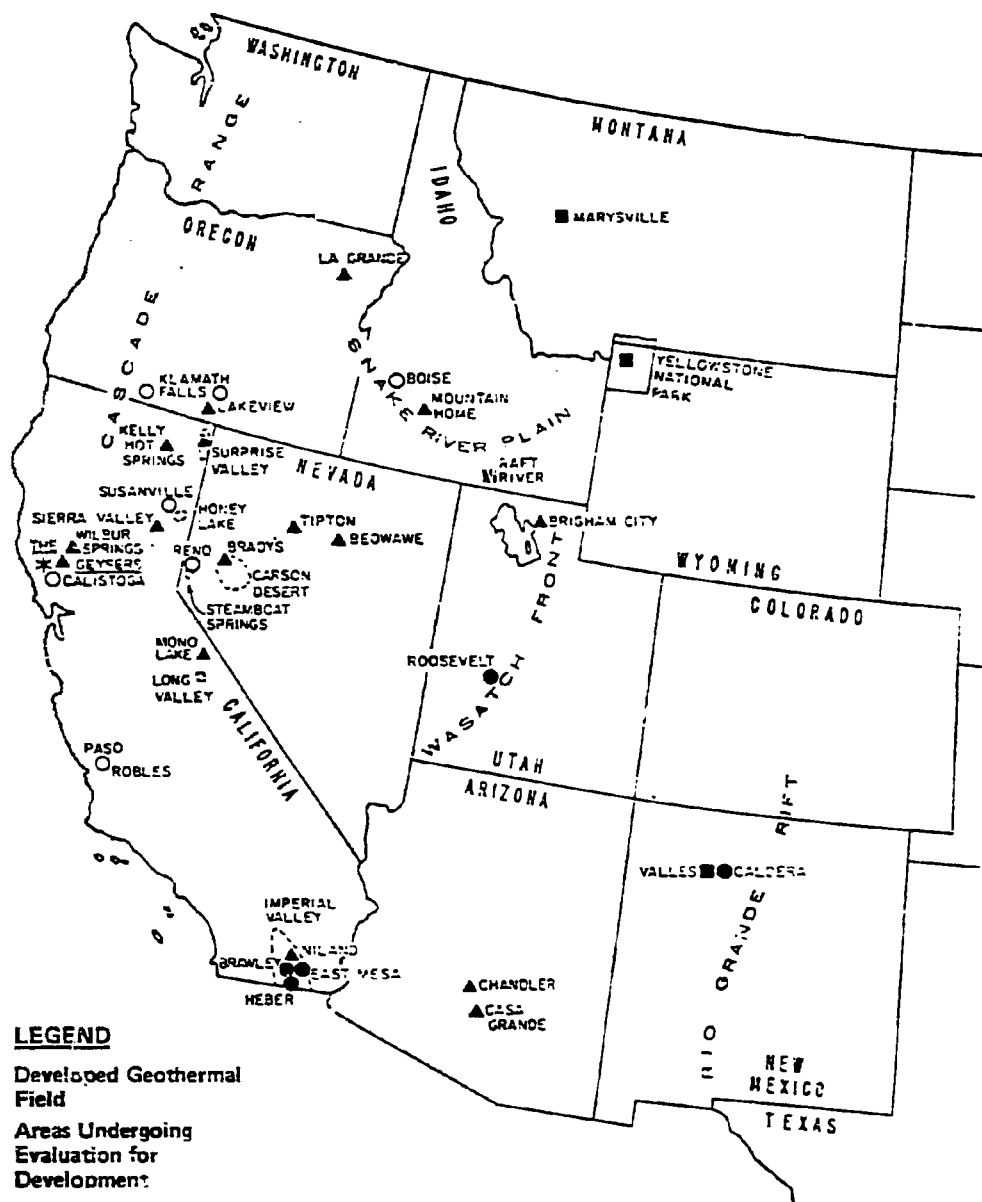
<sup>1</sup>James B. Koenig, *Exploration and Development of Geothermal Resources in the United States, 1968-1975*. Second United Nations Symposium for the Development and Utilization of Geothermal Resources, San Francisco, 1975.

Table XIV-1

### U.S. RECOVERABLE GEOTHERMAL HEAT

Type	From Known Resources (quads)	From Inferred Resources (quads)
Hydrothermal convective	102	262
Hot dry rock	80	230
Geopressured	782	1,730
	964	2,222

Source: ERDA Plan for Energy Research, Development, and Demonstration, ERDA 76-1.



Source: James B. Koenig, et al, "Exploration and Development of Geothermal Resources in the United States," Second United Nations Symposium for the Development and Utilization of Geothermal Resources, San Francisco, May 1975.

Figure XIV-3. GEOTHERMAL EXPLORATION IN THE UNITED STATES

## KNOWN GEOTHERMAL RESOURCE AREAS

The Geothermal Steam Act of 1970, which authorizes the Secretary of Interior to issue leases for development and utilization of geothermal steam and related resources, defines a known geothermal resource area (KGRA) as:

"an area in which the geology, nearby discoveries, competitive interests, or other indicia would, in the opinion of the Secretary (Interior), engender a belief in men who are experienced in the subject matter that the prospects for extraction of geothermal steam or associated geothermal resources are good enough to warrant expenditures of money for that purpose."

U.S. Geological Survey has four requirements before it establishes an area as having development potential:

- Temperatures above 150° to 400° F (65° to 204° C), depending on production and use technology.
- Depths under 10,000 feet to permit economical drilling.
- Sufficient rock permeability to allow the heat transfer agent—water, steam, or both—to flow continuously at a high rate.
- Sufficient water recharge to maintain production over many years.

"In general, the average heat content of rocks is considerably higher in the Western United States than in the east. This also helps to explain why the most favorable hydrothermal convection systems and the hot young

igneous systems also occur in the west."<sup>1</sup> (See Figures XIV-3, XIV-4, and Table XIV-2.)

<sup>1</sup> *Assessment of Geothermal Resources in the United States—1975*. Circular No. 726, U.S. Geological Survey, Washington.

Table XIV-2

### KNOWN GEOTHERMAL RESOURCE AREAS

State	Acres	
	KGRA	Potential Geothermal Resource Areas
California	1,051,533	15,737,000
Nevada	344,027	13,468,000
Oregon	84,279	15,048,000
Washington	17,622	5,759,000
Arizona	88,160	1,473,000
Colorado	—	1,014,000
Idaho	21,844	14,845,000
Montana	12,763	3,834,000
New Mexico	152,863	7,482,000
South Dakota	—	436,000
Utah	13,521	4,511,000
Wyoming	—	824,000
Alaska	88,160	11,277,000
Total	1,874,772	95,708,000

Source: Comptroller of the Currency, 1975.

## STATUS OF U.S. HYDROTHERMAL PHYSICAL DEVELOPMENT

### California

The already highly developed Geysers area produces more than 500 MW of electricity from hot dry steam and is projected to produce up to 2,000 MW.

In the Imperial Valley numerous wells yielding hot water have been drilled at several locations. Some of these locations produce water of excessive mineral content. ERDA and San Diego Gas and Electric Company have built a facility to test very salty brines in a heat exchanger; this facility is undergoing pre-start-up tests.

In Long Valley several promising holes have been drilled and drilling continues.

Calistoga has more than 60 wells producing hot water used for space heating.

In Modesto two wells are used for greenhouse opera-

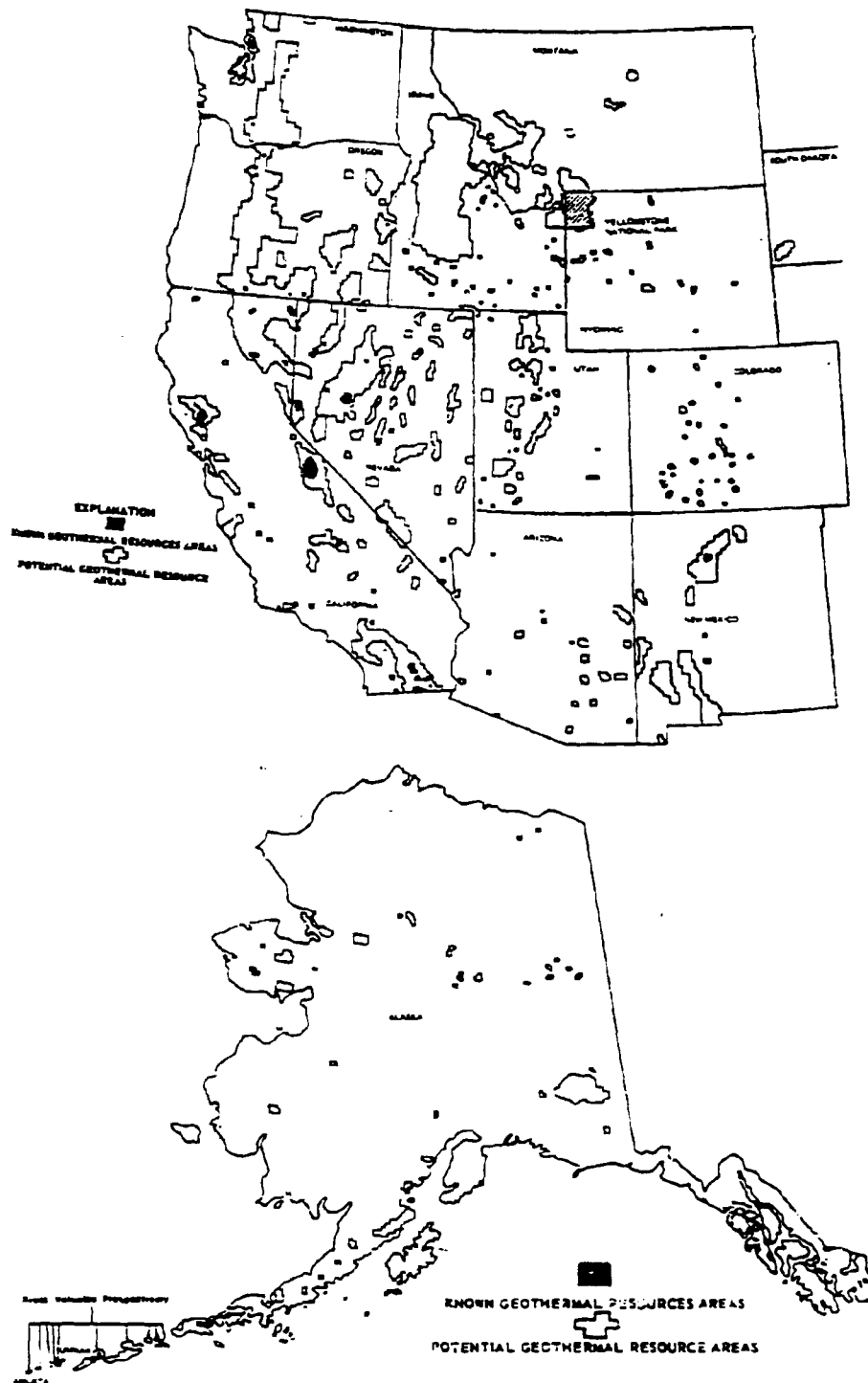
tions and further exploration is probable.

### New Mexico

At least 15 holes have been drilled and nine producible wells have been found in Valles Caldera. This water is hot enough to flash into steam at the surface. Further drilling is likely and negotiations may begin soon with a utility company to build a 50 MW power plant.

### Utah

Six wells have been drilled; three of them are good producers of hot liquids near Roosevelt Hot Springs. Further exploratory drilling is probable and power generation is under consideration.



Source: Comptroller General of the United States, "Problems in Identifying, Developing and Using Geothermal Resources," March 6, 1975.

Figure XIV-4. KGRA AND POTENTIAL GEOTHERMAL RESOURCE AREAS IN THE UNITED STATES

## Nevada

More than 17 holes have been drilled in four areas of Carson Desert. Further drilling and testing are expected in two of these areas along with wildcat drilling in adjoining areas. Twelve or more holes have been drilled in the Beoware area; continued drilling is expected. Dozens of shallow wells have been drilled in the Steamboat Springs area, and some are being used for space heating. Deeper holes to seek hotter water may be drilled.

## Oregon

Some 400 wells have been drilled at Klamath Falls.

Most of these are used for space heating. Further development and search for hotter water are expected.

## Idaho

Two wells have been drilled at Raft River, yielding low temperature water. ERDA probably will decide within a few months whether or not to build a test facility to evaluate these wells for power generation. Two wells at Boise supply water for space heating, and expansion of this use is underway.

## PRIMARY GEOTHERMAL POWER GENERATION CRITERIA

Six reservoir and fluid characteristics may be considered the primary criteria<sup>1</sup> that determine the potential of power generation from a geothermal reservoir: depth and lithology, reservoir temperature, tested flow rate per well, fluid chemistry, magnitude of the reserve, and reinjection potential. Economic and environmental criteria that are not directly related to reservoir or fluid characteristics have been omitted.

**Depth and Lithology.** The depth of the reservoir from the surface and the lithology of the area determine the drilling rate and cost. If there were no economic depth limit for drilling or production, hot water could be recovered from great depths in practically any sedimentary basin. However, cost and the technical problems of drilling and production from great depths prevent exploitation of such heat sources. Thus, the essential difference between a geothermal prospect and any ordinary sedimentary basin lies primarily in the depth to which one has to drill to recover water at a desired temperature. In general, the harder the rock formations to be penetrated, the slower is the drilling rate and the higher the cost. Hence, depth and lithology may be considered the most important criteria that determine reservoir development cost. Existing geothermal wells in the United States range in depth from 4,000 to 8,000 feet (1,200 to 2,400 meters).

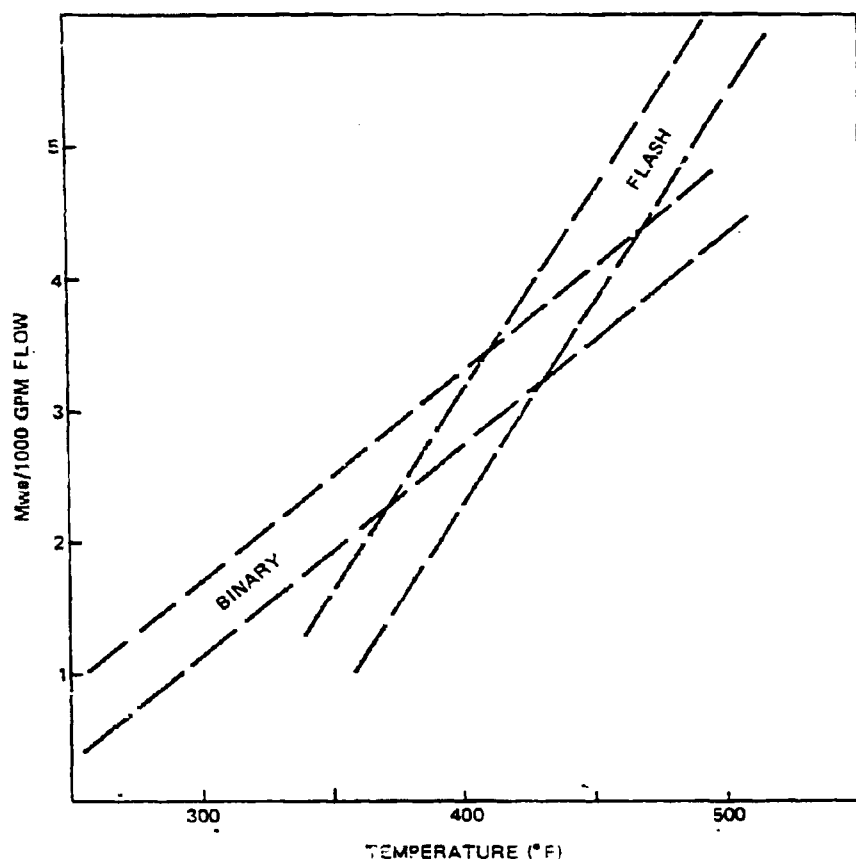
**Reservoir Temperature.** Reservoir temperature indicates the specific enthalpy and consequently the gross power conversion potential per unit mass of water or steam. The hot water reservoirs under development in the United States range from 300° to 700° F (150°-370° C), but reservoirs with temperatures near the upper limit of this range may contain extremely saline brine. The temperature of the dry steam at The Geysers is about 465° F (240° C).

**Flow Rate Per Well.** By knowing the temperature and fluid production rate per well, one can estimate the gross power generation potential per well. Then, for any desired power conversion process and power plant size, the number of wells required can be estimated. An accurate estimate of the flow rate required per megawatt net electricity depends on the temperature and pressure of the water or steam at the bottom conditions in the well bore (which determine the well-head conditions of the water or steam), the amount and chemical composition of the dissolved solids and gases at the well head, the design of the fluid handling facilities at the surface, and the design of the power conversion system. However, some broad generalizations can be made. Figure XIV-5 shows average values of MWe generated per 1,000 gallons per minute flow rate (5,450 cubic meters per day) under both binary and flash processes. The figure shows that the higher the temperature, the lower the flow rate needed to obtain a certain amount of power. For a geothermal fluid with a specific temperature, the lower the flow rate the higher will be the number of wells required for a particular conversion process and a specific power plant size. The cost of development and operation of a reservoir will then be approximately proportional to the number of wells required. Thus, the flow rate per well is a criterion that determines the development as well as the operation costs of a reservoir. Existing hot water wells in the United States show flow rates in the range of 500 to 3,000 gallons per minute (2,725-16,350 cubic meters per day).

**Fluid Chemistry.** Geothermal water normally contains dissolved solids and gases as well as suspended particles.

<sup>1</sup> S. K. Sanyal, *Geothermal Reservoir, Exploration, Assessment and Development*, Geonomics, Inc., September 1976.





Source: TRW Systems and Energy, 1975

Figure XIV-5. ENERGY FROM GIVEN WELL FLOW

During its travel from the reservoir to the power plant the hot water may undergo loss of temperature and pressure. In response to this change in its thermodynamic state, a part of the dissolved and suspended solid content may precipitate, while a part of the dissolved gases may evolve from solution. Precipitation of solids may cause plugging of the formation around the well bore and reduce well productivity. Precipitation of solids in the pipes causes scaling which reduces flow rates and damages equipment. Noncondensable gases evolved from brine may cause problems in the power conversion process. Some of the dissolved solids and gases cause corrosion in the well bore, flow lines, and equipment, sharply reducing the life of expensive hardware. Highly corrosive geothermal fluids are rather uncommon. Wherever they do occur, for example, in some parts of the Niland, California, field they have created severe problems.

The waste brine from the power plant is reinjected into the formation. The injection rate in a well may decrease with time (or injection pressure required to

maintain a steady injection rate may increase with time) due to formation plugging around the well bore. Hydrogen sulfide gas and dissolved boron, fluoride, and arsenic in a geothermal fluid can be hazardous to plants and human health if present in sufficient concentration. Knowledge of the chemistry of the fluid is required to assess potential technical and economic problems caused by corrosion and scaling of equipment, plugging of formation, and adverse environmental impact.

Total dissolved solids in geothermal water can vary from a few hundred ppm to several hundred thousand ppm. Usually, the degree of salinity increases with temperature, although not in a linear fashion. The typical salinity of some well known hot water geothermal systems is 1 to 2 percent. Some exceptions occur, such as the Niland Field in the Imperial Valley, where salinities as high as 30 percent solid content occur in the fluid.

*Magnitude of the Reserve.* Even if a reservoir satisfies depth, temperature, flow rate, and fluid chemistry criteria, reservoir development will not be economically feasible

ble unless it is proven to have sufficient heat and fluid reserves. The gross heat reserve of a reservoir consists of the heat stored in the fluid, the rock matrix that houses the fluid, and the impermeable layers within the rock.

While a large part of the heat in the fluid can be recovered, only a small fraction of the heat stored in the impermeable layers is recoverable with present technology. This is the result of the slow heat transport rate from rock to water. A part of the stored heat in the rock can be scavenged by reinjecting low temperature waste brine into the cooler parts of the reservoir. This reinjected water will gain heat from the surrounding rock matrix while slowly traveling to the producing wells.

**Reinjection Potential.** It is desirable, and even essential in some cases, to reinject waste geothermal brine from the power plant into the reservoir for several reasons. Waste geothermal water not reinjected into the reservoir has to be disposed into shallower ground water aquifers or surface water bodies, causing adverse chemical and thermal pollution of the local ground water resource. Failure to replace reservoir voidage by reinjection of fluid may cause ground subsidence. Geothermal fields at Cerro Prieto, Mexico, and Wairakei, New Zealand, where fluid reinjection is not practiced, have settled. If reservoir voidage is not replaced by reinjection, reservoir pressure will decline causing a decline in well productivity. If the reservoir pressure is allowed to decline, eventually steam will form in the reservoir. Although formation of steam in the reservoir extracts energy from the rock matrix, this is not an efficient method.

The main considerations in reinjection are the selection of optimum sites for injection wells, the pressure required to inject at a certain rate, and the eventual plugging of injection wells. In the optimum reinjection scheme, injection sites and rates are selected so that the travel path and time for the flow of water from injectors to producers is maximized. This prevents rapid cooling of the produced water. At the same time, injected water should be close enough to the producing reservoir to minimize the decline in reservoir pressure with time. The key factor which determines the optimum injection plan is the variation, both in area and depth, of water temperature and permeability in the reservoir. Cooling and pressure decline around the injection wellbore causes formation plugging from the dissolved and suspended solids present in the water. This reduces injection. In order to maintain the injection rate, pressure must be increased. This increases operating cost and technical difficulties. If the injection system reaches its maximum pressure capacity, more injection wells may have to be drilled or the old wells stimulated to maintain the total injection rate. This escalates the field development cost. As yet there is no simple way to estimate such gradual loss of injection with time.

It is possible to reduce plugging of formation pore space by a partial cleaning of the injection fluid by passing it through settlement ponds. However, accumulation of salt at the settlement ponds creates disposal problems. In some special cases, it is conceivable that the process of purification of the waste geothermal fluid might be linked with commercial mineral extraction.

## EXPLORATION AND ASSESSMENT

Many of the exploration methods used in the petroleum and mining industries are also used for finding and assessing geothermal deposits. There has been more experience in exploration for hydrothermal systems than for other types, partially because many of these systems have surface fluid manifestations and because they are more economical energy sources. Normally, exploration and assessment include geologic examinations, fluid geochemistry, and geophysics.

Exploration for geothermal resources begins with the selection of prospective areas by geological mapping and data analysis. This is often followed by geochemical analyses of water from hot springs, fumaroles, and other surface manifestations of geothermal energy. Such geochemical analyses provide estimates of the temperature of water in the subsurface reservoir. Usually, if geological and geochemical tests indicate reasonable prospect in an area, geophysical surveys are made. A geophysical survey

estimates the properties and structures of subsurface rocks by gathering physical data from instruments placed at the surface. Several types of geophysical surveys are used in geothermal exploration.

**Airborne Survey**—Includes aerial photography, aeromagnetic surveys, and airborne infrared surveys, although the latter two methods are being used less.

**Gravity Survey**—This is a measurement of the gravitational attraction of the earth at any location. The results of gravity surveys yield, among other things, the depth and profile of the basement rock underlying a sedimentary basin and the location of faults.

**Magnetic Survey**—This is a measurement of the intensity of the earth's magnetic field at any location. This survey provides results similar to the gravity survey.

**Passive Seismic Surveys**—Such surveys record naturally occurring microearthquakes or seismic ground noise. Microearthquakes are recurring low intensity earthquakes,

usually not felt by humans, caused by fracturing and displacement of subsurface rock along an active fault. Such active faults are often considered to be the flow conduits of geothermal water from depth. Seismic ground noise implies continuous low intensity vibrations in the subsurface and may be associated with geothermal areas.

**Geologic and Hydrologic Survey**—Includes structural and stratigraphic mapping to detect recent faulting, to determine the distribution and age of young volcanic rocks, and the location and character of surface thermal manifestations. Hydrologic analysis includes temperature and discharge measurements of hot and cold springs, evaluation of surface and subsurface water movements, and collection of basic meteorologic data.

**Geochemical Survey**—Data obtained from chemical analysis of water and gas samples are used to determine whether the system is vapor or hot-water dominated, to estimate temperatures and chemistry of the waters at depth, and to determine the source of recharge water. Analysis of the isotopic content can be used to specify the origin of the water in hydrothermal systems.

**Heat Flow Studies**—Vertical temperature gradients are

measured in shallow boreholes (100 to 500 feet) drilled in an area considered prospective from other surveys. Knowing the thermal conductivity ( $K$ ) of the subsurface rock, which is either measured from samples of the rock or assumed from experience, the rate of vertical conduct heat flow ( $q$ ) can be calculated from Fourier's Law:

$$q = -K \frac{dT}{dz}$$

where  $dT/dz$  is the vertical temperature gradient. Geothermal areas exhibit heat flow rates of several times the worldwide average of 1.5 microcalories/cm<sup>2</sup>/sec.

A judicious selection of these geophysical surveys can locate a geothermal reservoir and define its limits. However, the resource is not proven until exploratory boreholes have been drilled. Subsurface rock samples are collected from these boreholes either as drill cuttings or core samples. Various well logs are run in the borehole. The well is allowed to produce fluids and various well tests are run. Based on the results of these tests on the exploratory borehole, a preliminary assessment can be made of the power generation potential of the reservoir.

## DRILLING

Techniques used for drilling geothermal wells are similar to those used for conventional drilling for petroleum: rotary rigs efficient to 7.5 km and up to 250° C. As Koenig points out, the average well depth at The Geysers is 2.3 km and wildcat wells elsewhere have gone as deep as 3.3 km. Few significant holes are drilled to less than 1.2 km.<sup>1</sup> However there are some specific problems encountered in drilling geothermal reservoirs that differ from petroleum drilling:

- Higher temperatures are sometimes encountered; these can melt hard rubber fittings and valves on oil drill rigs and affect materials used for well casing.
- Many geothermal wells are drilled in harder rock than encountered in oil well drilling; this results in shorter bit life and slower penetration rates.
- Hydrothermal reservoirs having a high brine content can cause corrosion and scaling on drilling equipment.

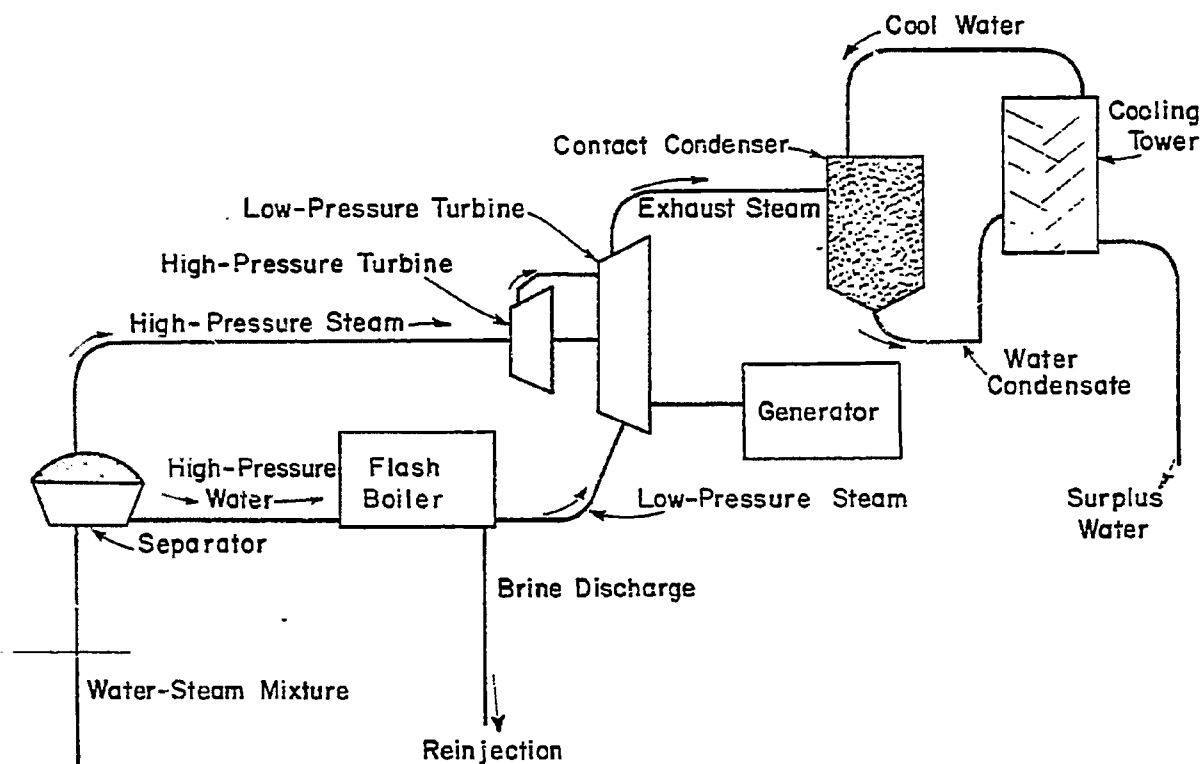
In May 1975, the United Nations Geothermal Symposium summarized some of the more recent research in geothermal drilling technology:

"Research is being done on over 30 novel drills ranging from lasers which melt rock to explosive drills which blast holes in the rock. Subterrenes (rock-melting drills) being developed by the U.S.

Alamos Scientific Laboratory utilize electric resistance heaters to melt holes in rocks. Subterrenes have potential for drilling into magma, lava beds, and other extremely hot rocks which exceed the temperature capabilities of conventional rotary drills. Sandia Laboratories is working on four novel drills which have potential for increasing drilling rate and bit life: spark drills, downhole changeable bits, continuous chain bits and Terra Drills which utilize projectiles to fracture the rock and roller bits to remove it. A new high-pressure erosion drill being developed jointly by Exxon and eight other oil companies utilizes fluid jets at 15,000 psi to disintegrate the rock. These high pressure bits drill two to three times faster than conventional bits and have potential for reducing the cost of drilling geothermal wells."<sup>2</sup>

<sup>1</sup>James B. Koenig, *Exploration and Development of Geothermal Resources in the United States, 1968-1975*. Second United Nations Symposium for the Development and Utilization of Geothermal Resources, San Francisco, 1975.

<sup>2</sup>William C. Maurer, *Geothermal Drilling*. Second United Nations Symposium for the Development and Utilization of Geothermal Resources, San Francisco, 1975.



Source: *Science and Public Policy Program, University of Oklahoma, Energy Alternative, A Comparative Analysis, May 1975.*

Figure XIV-6. GEOTHERMAL POWER PLANT

## PRODUCTION AND CONVERSION

### Liquid-Dominated Reservoirs

These reservoirs can be developed as energy sources for electrical power generation or space heating; minerals can be extracted from reservoirs having a high brine content. (See Table XIV-3 and Figure XIV-6.)

### Flashed-Steam Systems

When high-pressure hot water is brought to the earth's surface, the pressure reduction can cause 13 to 25 percent of the hot water to flash into steam. The water-steam mixture that flows to the wellhead is separated and the steam is piped to the steam turbines of a power plant. Additional steam can be produced from flashing again at a lower pressure, and the steam can then be introduced to a low-pressure section of the power turbine to increase total power output. The residual hot water can be rein-

jected into the reservoir, desalted, or used for process heating.

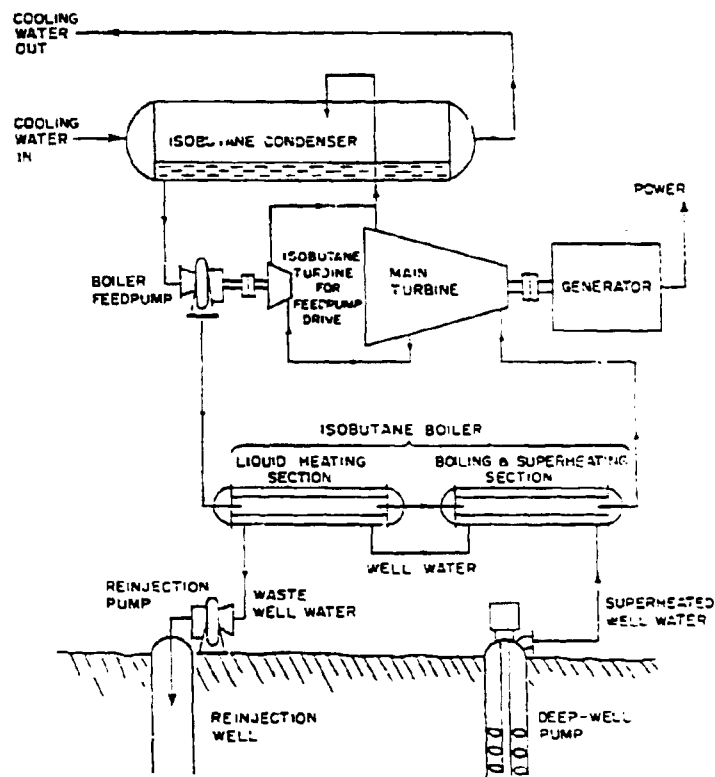
### Major Flashed-Steam Installations

Commercial flashed-steam systems began operating in New Zealand in 1950. About 180 Mw are being generated in the Wairakei-Broadlands field.

Two 37.5 Mw turbogenerators are operating in a geothermal field in Mexico near the volcano of Cerro Prieto. An ultimate capacity of 400 Mw is expected there.

Japan has numerous active geothermal regions. Two of these are producing electricity: Otake, Kyushu (13 Mw), and Matsukawa, Honshu (20 Mw). Other plants are in construction, one for 50 Mw near Otake and another for 50 Mw between Matsukawa and Onikobe.

A multipurpose, wet-steam geothermal facility is under development in Chile. Electricity will be produced, minerals extracted from brine, and fresh water produced by desalting the hot water.



Source: S. Hilbert Anderson, "The Vapor-Turbine Cycle for Geothermal Power Generation," *Geothermal Energy*, P. Kruger and C. Otte (ed), Stanford University Press, 1973.

Figure XIV-7. BINARY CYCLE SYSTEM

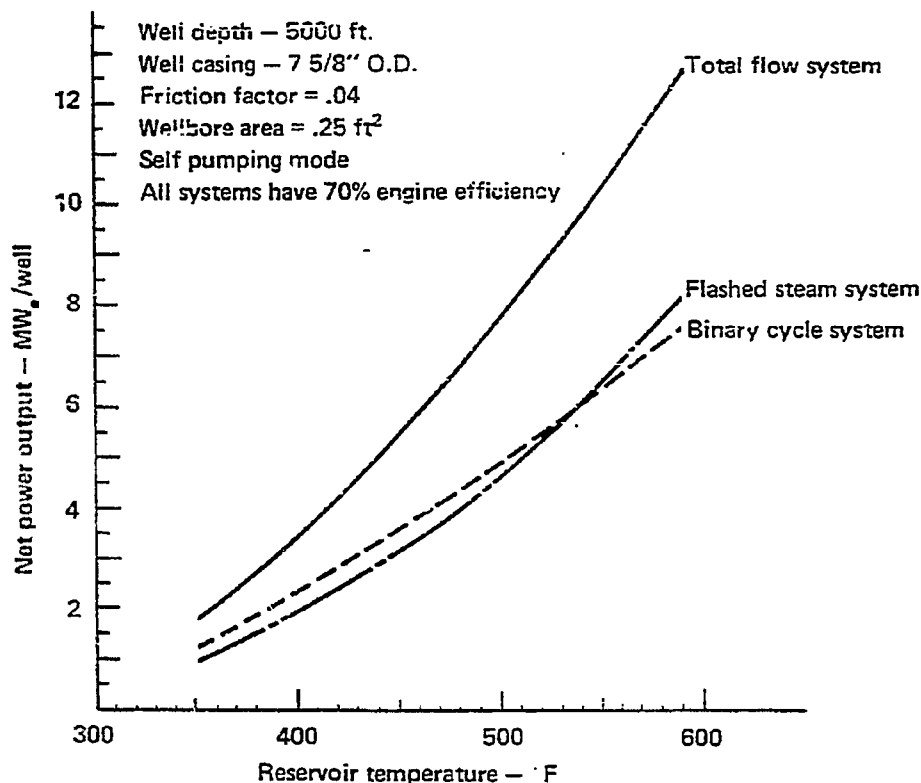
### Secondary Fluid Systems

Table XIV-3

#### TYPES OF GEOTHERMAL POWER PLANTS

Heat Source	Generation Mode
Dry steam	Steam turbine
Hot water ( $T > 180^{\circ}\text{C}$ )	Steam turbine
Hot water ( $T < 150^{\circ}\text{C}$ )	Binary cycle
Hot water (moderate salinity)	Hybrid cycle
Hot brine (pressurized)	Binary cycle
Hot brine (flashed)	Total flow concept: Impact turbine Helical screw expander Bladeless turbine

When the steam from a hot water reservoir is too corrosive to use directly in a turbine, the steam can be used to boil water in a heat exchanger; the clean steam can then be used in the turbine. The costs for this system are higher because of the heat-exchanger costs, and the overall efficiency is much lower than if the flashed steam were used directly. A slight variation of this system is called a binary cycle system. (See Figure XIV-7.) The hot water from the geothermal well is prevented from flashing to steam by maintaining its pressure, then pumped to a heat exchanger where it heats a liquid, boils it, and superheats it. The vapor from the secondary fluid (usually a low-boiling point liquid such as Freon or isobutane) drives the power turbine. The working fluid is then cooled, condensed, and recycled. The first geothermal power plant of this type was the Paratunka Station at Kamchatka, USSR, which operates on Freon.



Source: A. L. Austin, *The Lawrence Livermore Laboratory Geothermal Energy Development Status Report, January 1974-January 1975*, Lawrence Livermore Laboratory, University of California, February 1975.

Figure XIV-8. COMPARISON OF GEOTHERMAL POWER SYSTEMS

In the United States, the San Diego Gas and Electric Company, Magma Power Company, and Standard Oil Company of California are working jointly to design, install, and operate two prototype binary cycle plants in the Imperial Valley of California. The concentration of minerals in these waters is high: 200,000 to 300,000 parts per million, 10 times that of sea water. Pipes and heat exchangers were so severely affected by the brine that the plant has been redesigned to include a three-stage separator/scrubber system to produce clean steam.

#### Total Flow System

This is not a new concept for conversion of geothermal energy to electric power, but, until recently, there have been no practical applications. In one such system, a two-phase working fluid, hot water and steam, is expanded through a nozzle into a turbine, making use of the mechanical energy as well as the heat energy: theoreti-

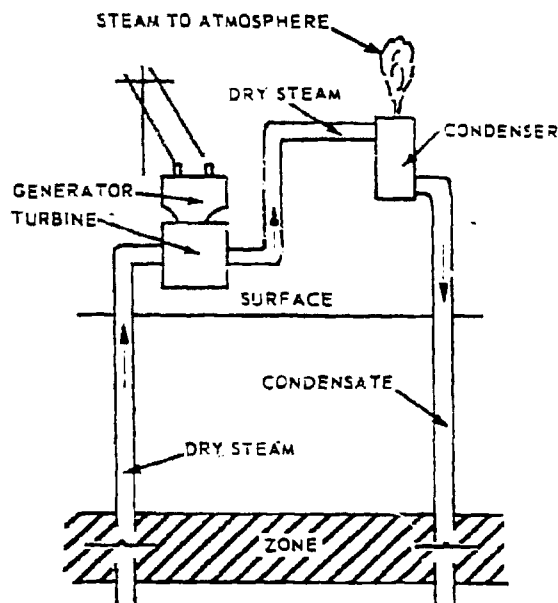
cally, it could produce 60 percent more power than other systems. (See Figure XIV-8.)

A Lawrence Livermore Laboratory (LLL) program funded by ERDA is developing the total flow concept. The program focuses on the development of systems for the recovery and conversion of energy stored in hot water deposits containing more than 3 percent total dissolved solids. These high-salinity brines pose formidable problems for the program because of precipitation, scaling, corrosion, erosion, and brine handling and disposal. The goal of LLL program is a full 10 MW experimental power plant system operational in FY 1980.<sup>1</sup>

#### Space Heating and Cooling System

Decades ago it was discovered that indigenous low-

<sup>1</sup> A. L. Austin, and others, *The Lawrence Livermore Laboratory Geothermal Energy Development Program Status Report, January 1975 through August 1975*. UCID-16954, September 1975.



Source: Comptroller General of the United States, "Problems in Identifying, Developing, and Using Geothermal Resources," March 6, 1975.

**Figure XIV-9. THE GEYSERS DRY STEAM SYSTEM**

temperature hot water could be piped to heat homes and greenhouses in the Scandinavian and middle European countries. In the 1930s, some of the first systems were installed in Budapest and Reykjavik. Today, it is recognized that geothermal space heating and cooling is preferable to burning highly-refined petroleum products at 1000° C in a power station boiler to produce air at 21° C as an end-product.

Geothermal energy now supplies about 2.2 GWh/year for space heating in Iceland at a savings of 2 million barrels of oil. As of 1972, the USSR was the world's largest user of geothermal energy for heating purposes.<sup>1</sup> Hungary and Japan utilize hot water heat extensively as well.

In the United States, a small geothermal district heating scheme has been in operation for many years at Klamath Falls, Oregon. At Boise, Idaho, a well has been successfully drilled and the feasibility of supplying geothermal heat to several large office buildings is being studied.

#### Desalination of Geothermal Brines Obtain Potable Water

The Bureau of Reclamation is in the first stage of a three-stage program for producing as much as 10,500 megawatts of power and 2.5 million acre-feet of fresh

**Table XIV-4**

#### THE GEYSERS GENERATING CAPACITY

Date	Unit	Capacity of Unit (megawatts)	Cumulative capacity (megawatts)
1960	1	11	11
1963	2	13	24
1967	3	27	51
1968	4	27	78
1971	5,6	106	184
1972	7,8	106	290
1973	9,10	106	396
1975	11	106	502
1977	12	106	608
1977	13	135	743
1977	14	110	853
1977	15	55	908
1979	*	110	1,018
1980	*	110	1,128
1981	*	110	1,238

\*Not yet identified.

Source: Comptroller General of the United States, "Problems in Identifying, Developing, and Using Geothermal Resources," March 6, 1975.

water a year from geothermal brines to augment the flow of the Colorado River.

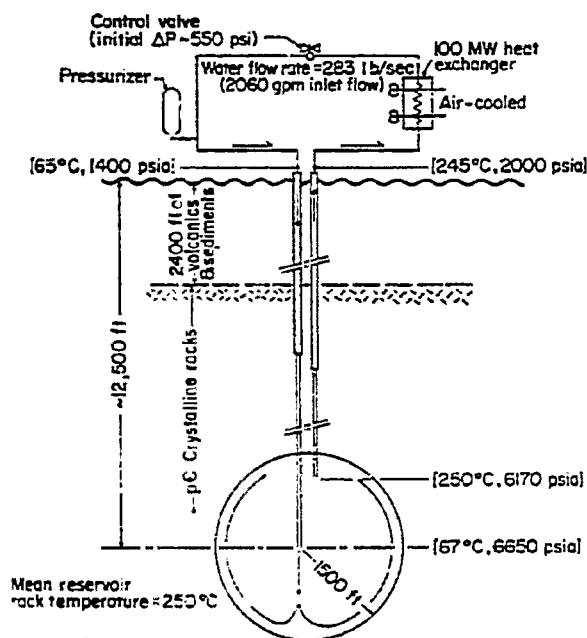
The program is being carried out on federally owned lands in Imperial Valley, California. Five deep geothermal wells have been drilled and two small test desalting units have been installed. These produce small amounts of high quality potable water. Data suggest that the Bureau might not obtain as much potable water as originally hoped for, and the potable water that will be obtained will cost at least four times more than the water now available for irrigation in the Imperial Valley area.<sup>2</sup> The results thus far would lead to the conclusion that the Imperial Valley geothermal resource cannot be attractively exploited for water without a significant change either in desalination technology or in cost of irrigation water. Nevertheless, valuable data and experience from this project could be used in other areas.

#### Vapor-Dominated Systems

The technology for this type of system is well-known largely because there are not as many technical di-

<sup>1</sup> ARPA Report AD-745 947, Report 2.

<sup>2</sup> Henry J. Vaux, Jr. and Benjamin Nakayama, *The Economics of Geothermal Resources in the Imperial Valley: A Preliminary Analysis*, University of California, Davis, November 1975.



Source: M. C. Smith, "Los Alamos Scientific Laboratory Dry Geothermal Source Demonstration Project," Los Alamos Scientific Laboratory, 1975.

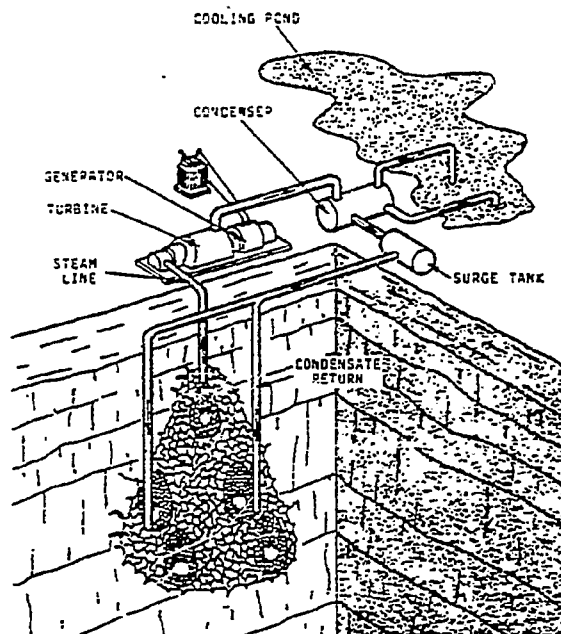
Figure XIV-10. LOS ALAMOS CONCEPT FOR EXTRACTION OF ENERGY FROM DRY HOT ROCK

culties: the steam can be used directly in a turbine generator. Most of the experience gained in the United States has been at The Geysers in California, the largest known geothermal field in the world. It is a KGRA consisting of 163,428 acres: 11,450 acres of which are federally owned. Total generating capacity is 300 Mw with an addition of 100 Mw planned for each year through 1983. This description of The Geysers was extracted from a recent General Accounting Office report.<sup>1</sup>

The first attempt to develop The Geysers' power potential was made in 1922. In 1956, the Magma Power Company and the Thermal Power Company, working jointly, found that geothermal steam could be produced economically. The Pacific Gas and Electric Company contracted to build a power plant and buy steam from the Magma-Thermal wells. In 1967, the Union Oil Company of California joined with Magma-Thermal in a project to drill for and produce steam. (See Figure XIV-9.)

The Pacific Gas and Electric Company has installed, contracted for, or planned the geothermal generating units at The Geysers shown in Table XIV-4.

About 20 to 24 wells are required to support a 110-megawatt generation plant, and each well has a life of 2 to 30 years; the average lifetime is about 15 years. As



Source: Edward R. Serman, *Geothermal Energy*, Noyes Data Corporation, 1975.

Figure XIV-11. PLCWSHARE CONCEPT OF GEOTHERMAL HEAT EXTRACTION

individual well pressures decrease, new wells must be drilled to maintain an adequate steam supply to the turbines.

The Pacific Gas and Electric Company states that the cost of electric power produced from dry steam at The Geysers varied from plant to plant. The company provided information showing that the cost of power produced from Units 9 and 10 average 5.325 mills<sup>2</sup> per kilowatt-hour at 80 percent capacity.<sup>3</sup> This figure can be broken down this way:

	Mills per kilowatt-hour
Annual cost of steam	2.599
Annual operating costs	0.223
Annual fixed costs	2.503
<b>Total</b>	<b>5.325</b>

<sup>1</sup> Comptroller General of the United States, "Problems in Identifying, Developing and Using Geothermal Resources," March 6, 1975.

<sup>2</sup> One mill equals one-tenth of one cent. In May 1975, Union Oil reported the price as 6.7 mills per kilowatt-hour.

<sup>3</sup> Capacity factor is the ratio of the average capacity required from a plant to the capacity of the plant.



In March 1974, however, the company estimated that the unescalated cost of power from Unit 13 will average about 10.36 mills per kilowatt-hour at 80 percent capacity. Although the cost of geothermal power appears to have risen significantly, it remains considerably lower than the cost of power produced from nuclear plants, which AEC estimated to be about 15.2 mills per kilowatt-hour. Union Oil officials stated that the charge for geothermal energy was comparable with the charges for fossil fuels.

Although dry steam represents a technically and economically acceptable energy source, its potential may be severely limited by its availability, since dry steam is not a replenishable resource and no commercial dry-steam fields have been identified in the United States, except The Geysers.<sup>1</sup>

### Dry Hot Rock

Since 1972, the Los Alamos Scientific Laboratory (LASL) of the University of California, under the auspices of ERDA, has been developing methods for the extraction of energy from dry, impermeable rocks such as the granite of the western and northern United States.

In the Los Alamos concept, a manmade geothermal reservoir would be formed by drilling into hot rock, then creating within the rock a very large surface area for heat transfer by use of large-scale hydraulic-fracturing techniques developed by the oil industry. After a circulation loop is formed by drilling a second hole into the top of the fractured region, the heat contained in this reservoir would be brought to the surface by the buoyant circulation of water, with no need for pumping. The water in the loop would be kept liquid by pressurization at the surface, thereby increasing the rate of heat transport up the withdrawal hole compared to the rate possible with steam. (See Figure XIV-10.)

Preliminary experiments and analyses indicate that thermal stresses created by cooling of the hot rock in

such a manmade reservoir may gradually enlarge the fracture system so that its useful lifetime will be extended far beyond the planned 10 to 15 years provided by the original reservoir. If these thermal-stress cracks grow preferentially downward and outward into hotter rock, seems probable, the quality of the geothermal source may actually improve as energy is withdrawn from it.<sup>2</sup>

The demonstration area is located about 20 miles due west of Los Alamos, New Mexico. Drilling of the first well began in February 1974. The well reached a depth of 9,619 feet, and a bottom-hole temperature of 386.6° F. A near vertical, 400-foot radius fracture was created with hydraulic pressure near the bottom of this hole. A second hole, located 252 feet from the first, intersected the fracture in October 1975 at a depth of 10,053 feet with a bottom-hole temperature of 402° F.<sup>3</sup> Circulation tests are now being conducted to determine the dimensions and characteristics of the down-hole reservoir system. LASL hopes to build a 10 Mw demonstration electrical generating plant by 1981.

Another method of fracturing dry hot rocks, using nuclear explosives followed by injection of water into a reservoir, is being studied by a team from Lawrence Livermore Laboratories, ERDA, Battelle Northwest, American Oil Shale Company, and Westinghouse. Called the Flowshare Concept, it might also be used to stimulate steam production enough in steam fields to permit more economical development. (See Figure XIV-11.)

<sup>1</sup>Comptroller General of the United States, "Problems in Identifying, Developing and Using Geothermal Resources," March 1975.

<sup>2</sup>Morton C. Smith, *Los Alamos Scientific Laboratory Dry Geothermal Source Demonstration Project*, Los Alamos Scientific Laboratory, 1975.

<sup>3</sup>Morton C. Smith, *Los Alamos Dry Geothermal Source Demonstration Project—Mini-Review 76-1*, LASL, USGPO, March 1976.

## FEDERAL GEOTHERMAL ACTIVITIES

Several federal agencies are conducting geothermal exploration and development, although the amount of money they spend in this area is small compared with federal spending on other energy programs.

The federal geothermal energy program has assigned the following priorities:

First, advance the development of hydrothermal sources, even though it is the smallest of the resources, because it is already well-advanced and further development can stimulate commercial interest in the other forms.

Second, develop geopressed resources in the gulf coast areas of Texas and Louisiana.

Third, develop hot dry rock resources.

The three phases of development actually will go on simultaneously, but ERDA and Congress propose to move more money toward geopressed than into hot dry rock.

The United States Geological Survey identifies, inventories, and characterizes geothermal resources available to the nation; it works on improvement of technology to exploit them and makes recommendations regarding environmental impacts of geothermal development. Cur-

rent activities include mapping the Gulf Coast geopressured zones and studying several geothermal areas in western states.

The U.S. Geological Survey has also initiated an International Geothermal Information Exchange Program (GEOTHERM). It will provide data on geothermal energy and resources, which will be entered into a computer file for prompt retrieval.

The Environmental Protection Agency has a statutory responsibility to assess and regulate the environmental impacts of geothermal development and is carrying on studies to determine the scope of environmental problems and methods of handling them.

The Bureau of Land Management and the Forest Service, the federal land management agencies, issue leases on public lands.

The Bureau of Mines conducts research to develop the corrosion-resistant materials needed to withstand scaling and corrosion by high-temperature, high-pressure saline fluids found in many U.S. geothermal areas. This research, conducted at the College Park, Maryland, Metallurgy Research Center. The Bureau develops technology to recover byproduct minerals and gases from geothermal fluids.

The Bureau of Reclamation provides environmental impact assessments and develops methods to produce fresh water from saline geothermal fluids after the generation of power.

The Energy Research and Development Administration (ERDA) is charged with the responsibility, under the Geothermal Energy Research, Development, and Demonstration Act of 1974, of carrying out a coordinated federal program of RD&D Development Administration.

The three main areas in the ERDA program<sup>1</sup> are:

- Resource Exploration and Assessment includes geosciences research to improve knowledge of the geo-

thermal processes in the earth's crust and their surface manifestations; improvement in the efficiency, reliability, and economics of assessment and exploration; identification and measurement of U.S. geothermal resources; and dissemination of research data on U.S. geothermal resources.

- Technology Development studies the major requirements for extraction and utilization of each resource type to ensure commercial development of geothermal energy sources. These projects include improved drilling technology, reservoir engineering, conversion equipment development, and pollution abatement technology development. Commercial scale demonstration plants will be planned to exhibit economic feasibility and environmental acceptability of a geothermal resource.
- Institutional Development incorporates the incentives, institutional relationships, and policies necessary to create industrial commitment. These incentives include a leasing program to make federal lands available for geothermal development, the Geothermal Loan Guaranty Program to reduce financial risk, and policy research to resolve the social, legal, economic, and environmental problems associated with development of these energy resources. Although the scope of this effort goes beyond the technology RD&D program, it is, however, an integral part of the total federal effort.

Detailed summaries of ERDA-funded geothermal projects can be found in the April 1976 edition of *Geothermal Project Summaries*, ERDA 76-53, available from ERDA Division of Geothermal Energy.

<sup>1</sup> *Definition Report*, Geothermal Energy Research, Development, and Demonstration Program, October 1975.

## ENVIRONMENTAL, LEGAL, INSTITUTIONAL, AND ECONOMIC CONSIDERATIONS

### Environmental Considerations

Although geothermal energy has been lauded as a "clean" energy source with few environmental problems associated with its development, there is only a small amount of environmental data available on the use of geothermal energy, and almost no field experience with many of the conversion technologies. However, the effects in most cases will be less than the impact of nuclear and fossil fuel systems.

In general, the environmental effects are site-dependent—that is, the drilling takes place in the immedi-

ate vicinity of the power plant or other facility. Transportation is limited to pipes and power lines; pipes would extend no more than a few miles, and power lines would be limited by the small capacity of most geothermal plants. Most negative impacts would occur because of drilling and construction during the development period.

This section summarizes some potential negative environmental impacts. Details can be found in the *Final Environmental Impact Statement for the Geothermal Leasing Program*, Department of Interior, in *Energy Alternatives: A Comparative Analysis*, prepared for CEQ, ERDA, EPA, FEA, FPC, DOI, and NSF, May 1975, and

in the *Proceedings of the NSF Workshop on Environmental Aspects of Geothermal Resources Development*, 1974.

**Air Pollution**—Noncondensable gases such as hydrogen sulfide, carbon dioxide, methane, ammonia, and nitrogen found in the vapor phase of a geothermal source, could cause serious air pollution if released. Hydrogen sulfide ranks as the most likely potential environmental hazard, occurring at 16 times the toxic level in undiluted geothermal steam at The Geysers, although normally the gas is dispersed in the atmosphere before it reaches a toxic level. Mercury is also a potential hazard in some geothermal fluids and would have to be monitored continuously.

**Water Pollution**—Introduction of highly saline or toxic geothermal fluids to surface waters, resulting from brine disposal, blowouts, or spills, could cause water and thermal pollution, although reinjection of spent fluids into the reservoir greatly mitigates the risk. Ground water contamination can result from interference with aquiferous fresh water during drilling and production.

**Land Subsidence**—Sinking of the earth's crust sometimes occurs when supporting fluids are removed from underground reservoirs. Subsidence has occurred in areas where very large amounts of water have been removed during geothermal development. There is a potential for this occurring in the Imperial Valley. Prevention of subsidence involves injecting replacement fluids, usually the spent geothermal fluids.

**Seismic Activity**—It is possible for changes in reservoir pressures to cause an increase in seismic activity. Although not well studied to date, either injection or withdrawal of large volumes of fluid may have a powerful enough effect on the stresses in a fault zone to cause a major earthquake. On the other hand, minor changes in seismic activity may relieve accumulated strain before a major earthquake occurs.

**Noise Pollution**—This can result during venting of geothermal steam through relief valves. Mufflers are being developed. Drilling and construction activities produce noise as well.

**Land Modification**—Most geothermal power plants would be in areas not now industrialized or urbanized, necessitating disruption of existing land use and possibly disturbing wildlife. However, it is also true that since such facilities would be smaller than most power plants, fossil or nuclear, and since the electricity or steam would usually not be transmitted great distances, the negative impacts on land use and wildlife would be minimal and restricted to the immediate area of the plant. Also, a developed geothermal field need not be incompatible with other land uses. For example, in Italy farms, orchards, and vineyards are interspersed among the pipelines and wells. At The Geysers, cattle graze and wildlife live in areas immediately adjacent to the power plant. Geo-

thermal developments would not be drilled normally in recreational areas, especially in federal and state parks.

Considerable attention has been given to the environmental impacts of geothermal energy development in Japan.

## Legal and Institutional Problems

In a recent workshop the National Science Foundation (NSF) has reviewed legal problems associated with the development of geothermal sources.<sup>1</sup> Some of the problems uncovered are:

**Resource definition** varies from state to state. In Hawaii, geothermal resources are defined as minerals, in Wyoming as water resources.

**Ownership rights.** Federal grants of public land retain mineral rights for the federal government, while some state grants include mineral rights.

**Control over use of water.** Some states such as Oregon, California, and Colorado have laws which prohibit transporting water out of state.

**Overlapping and conflicting regulations and jurisdiction** for permits, licenses, taxes, environmental control, etc., exist between federal, state, and local governments.

**Leasing complications.** Since almost 75 percent<sup>2</sup> of all KGRA's in the United States are located beneath federally owned land, most of the leasing contracts must be negotiated through the Department of Interior. Industry representatives have criticized DOI's land classification and leasing policies, maintaining that in many cases, they cause unwarranted delays in resource development.

**Environmental problems.** The lack of environmental impact data also tends to discourage or delay acceptance of geothermal technologies.<sup>2</sup>

## Economic Considerations

The only geothermal operation in the United States generating data on the economics of developing a geothermal steam resource has been from The Geysers development. However, many experts agree with S. D. Worthington that "the technology and economics of The Geysers development must never be used as a measure of other locations having even modestly different characteristics."<sup>2</sup> And since steam developers, like those who operate The Geysers, do not normally reveal their costs, mills/kw published are usually the cost of power to the utility,

<sup>1</sup> *Proceedings Conference on Geothermal Energy and the Law*, National Science Foundation Report No. NSF-RA-S-75-003, 1975.

<sup>2</sup> S. D. Worthington, "Geothermal Development," *Status Report—Energy Resources and Technology*, Atomic Industrial Forum, 1975.

not the actual cost of producing the power. Other uncertainties include:

- The extent and characteristics of the resources for most potential areas are not known with enough accuracy to predict the exploration and drilling required for development, both of which can add significantly to the total investment and discourage industry and financial institutions from committing capital for development.
- Conversion efficiencies have not been proven for most systems suggested; and these efficiencies will vary as the fluid temperatures vary from reservoir to reservoir.
- Costs for all forms of energy production are rising, making it difficult to compare geothermal costs with other energy sources.
- The geothermal industry does not have the same tax incentives as do other energy extraction industries.

Known factors that can contribute toward making geothermal energy economically competitive with other rms include:

- Continued and increased government support in R&D and federal loan guarantee programs.
- Willingness of industry to make the investments.
- Successful compliance with EPA without prohibitive expenditures on environmental control technologies.
- Continued high costs for more conventional energy sources.
- Integrated operation of geothermal power stations from exploration to production rather than purchase of steam or hot water by the utility companies from independent suppliers (the effect would be increased investment cost/kw of capacity but decreased production cost per kWh of energy).
- Improved technology for drilling and conversion methods.
- Expedition of leasing and regulatory procedures.

Many estimates of the potential contribution of geothermal electricity production to the national supply have been made under various growth scenarios. The estimates cited most recently range from 3,500 to 132,000 Mwe in 1985 (University of Oklahoma, 1975).

**CHAPTER XV**  
**HYDROGEN AND**  
**ALTERNATIVE FUELS**

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## INTRODUCTION

The alternative fuels discussed in this chapter include synthetically produced nonhydrocarbons. They all have the common properties of being synthesized from abundant materials and of having products of combustion that are not noxious and that can be assimilated into the environment at the point of use, without having to be recycled to the generating station. These alternative fuels are hydrogen, ammonia, hydrazine, methanol, and methylamines. The emphasis is on hydrogen, not because it is the simplest, cleanest and has the highest heating value per pound of any fuel, but because it is a basic ingredient for the other alternate fuels, as well as a necessary feedstock for production of synthetic hydrocarbons.

Production costs for the various alternative fuels are not treated directly; rather the energy required to produce the fuel—known as process energy—is given in kilowatt hours electric per pound (kWh<sub>e</sub>/lb) or kilowatt hours thermal per pound (kWh<sub>t</sub>/lb). The former is used for manufacturing processes that are basically electrochemical and the latter is used for processes that are thermochemical. Also the process energy used per Btu of fuel produced is given where appropriate in units of kWh<sub>e</sub>/Btu or kWh<sub>t</sub>/Btu. In all cases, the lower heating value of hydrogen is used. Production costs of the fuels can be compared from a knowledge of the cost of process energy. (Capital investment costs, financing costs, labor costs, etc., are not included.)

The source of the process energy is not discussed; it could be solar, nuclear or thermonuclear in most cases. The majority of papers on the production of alternative

Table XV-1

### ALTERNATIVE FUELS PRODUCTION

	Combustion Energy <sup>a</sup> (Btu/lb)	Manufacturing Energy (kWh <sub>e</sub> /lb)	Process Efficiency <sup>b</sup> (percent)
Hydrogen	51,536	62.5	24
Ammonia	7,986	9.2	25
Hydrazine	7,200	30.2	7
Methanol	8,600	4.35	58
Methylamines	15,085	11.2	40

<sup>a</sup> Lower heating value.

<sup>b</sup> Ratio of combustion energy to manufacturing energy.

Source: Adapted from B. Berkowitz, et. al., "Alternative, Synthetically Fueled, Navy Systems," TEMPO, General Electric Company, November 1974.

fuels assume the source of the process energy to be nuclear, but, with a few exceptions, no such restriction is necessary.

The production costs of alternative fuels are shown in Table XV-1. The manufacturing energy in each case is for the most likely production process. For all of the fuels, hydrogen is assumed to be produced electrolytically and the manufacturing energy is expressed in kWh<sub>e</sub>/lb using the optimistic figure of 40 percent thermal to electric conversion efficiency.

Some of the more important physical properties of these alternative fuels and methane are displayed in Table XV-2.

Table XV-2

### PROPERTIES OF ALTERNATIVE FUELS

	Hydrogen	Ammonia	Hydrazine	Methanol	Methylamines	Methane
Liquid density (lb/ft <sup>3</sup> )	4.43	42.6	63.1	49.7	41.7	25.9
Melting point (° C)	-259.02	-77.8	1.1	-97.8	—	-182.5
Boiling point (° C)	-252.77	-33.3	113.3	64.7	—	-161.5
Heat of vaporization (Btu/lb)	191.7	590.0	548.0	473.02	280.0	219.42
Critical temperature (° C)	-239.9	132.2	380.0	240.0	—	-82.1
Critical pressure (atm)	12.80	111.0	145.0	78.5	—	45.8
Autoignition temperature in air (° C)	585	651	270	464	—	538
Explosive limit in air						
lower (%)	4.0	15.0	4.7	6.0	2.0	5.0
upper (%)	75	28	100	37	21	15
Flame speed (ft/sec)	8.8	0.034	—	1.6	—	1.2

Adapted from B. Berkowitz, et. al., "Alternative, Synthetically Fueled, Navy Systems," TEMPO, General Electric Company, November 1974.

D. Mathis, *Hydrogen Technology for Energy*, Noyes Data Corporation, 1976.

## HYDROGEN PRODUCTION

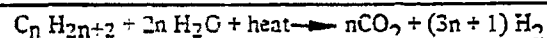
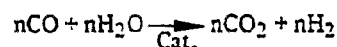
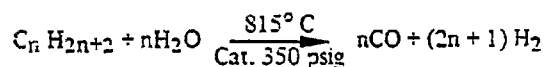
The most common method of producing hydrogen in large quantities today is by reforming of volatile hydrocarbons. This is not likely to be the method of production in the future because of the increased costs and reduced availability of these feedstocks. In the near term (1975 to 1985), hydrogen production will still depend on fossil fuels, but the feedstock for the chemical processes will shift to heavy petroleum fractions and coal.

Some hydrogen is produced by electrolytic decomposition of water. In the future, this may become the preferred method for obtaining bulk quantities of hydrogen. However, the electrolysis of water requires large quantities of electricity—quantities that may be available only from thermally inefficient nuclear power plants. Looking beyond electrolysis, the need for electricity for hydrogen production can be reduced by direct utilization of thermal energy through multistage thermochemical processes of high efficiency.

Other possibilities for hydrogen production include bioconversion, use of ultraviolet light from a fusion torch, and use of municipal rubbish and plants as feedstock for chemical reforming using existing technology.

### Steam Reforming of Volatile Hydrocarbons

The major process for hydrogen production today is by steam reforming of volatile hydrocarbons (particularly methane because of its traditional low cost).<sup>1</sup> Desulfurized hydrocarbon gas is combined with steam in a reformer over a nickel (Ni) catalyst bed to produce synthesis gas ( $H_2$  and CO). The CO is removed in a catalytic shift converter to form additional  $H_2$  and  $CO_2$ . The overall reaction is endothermic. The two reactions and the summary reaction are:



The catalysts are susceptible to feedstock poisoning.

### Partial Oxidation of Heavy Petroleum Fractions

This is a two-stage process in which the feedstock is partially oxidized to produce synthesis gas. The heat released in this process is used to aid in the subsequent shift reaction of CO with  $H_2O$  to increase the yield of hydrogen:

Table XV-3

ELECTROLYTIC COST OF HYDROGEN

	Cost of Electricity (mills/kWh)		
	10	15	20
Dollars per pound $H_2$	0.19	0.29	0.38
Dollars per million Btu <sup>a</sup>	3.69	5.53	7.37

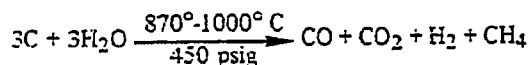
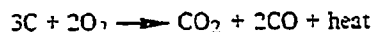
<sup>a</sup> Lower heating value.



In addition to requiring a hydrocarbon feedstock, this process depends on a supply of pure oxygen.<sup>1</sup>

### Coal Gasification

The inputs for the production of hydrogen from coal are pure oxygen, water, and coal. The coal is oxidized to produce heat to promote the endothermic gasification reaction. The result is synthesis gas, which is steam treated in a shift reactor to increase the hydrogen yield. For bituminous coal, the basic reactions are:



Trace materials in the coal feedstock can poison the catalysts. As a result, extensive preparation of the coal is necessary to remove contaminants. In addition, the need for pure oxygen makes this process expensive.<sup>1</sup>

### Electrolysis

Electrolysis is the only currently available method for large-scale production of hydrogen not requiring fossil

<sup>1</sup>Homer W. Carhart, *et. al.*, "Hydrogen as a Navy Fuel," *NRL Report 7754*, June 12, 1974.



Table XV-4

## OPERATING CHARACTERISTICS OF ELECTROLYZERS

	Teledyne	Lurgi	GE
Size of system compared, MW equivalent of H <sub>2</sub>	39.9	53.3	51.6
Million SCF H <sub>2</sub> /stream-day	10	13.44	13.0
D-c electric input (max) (kW)	58,400	69,000	65,300
Specific cell efficiency (%)	68-70	77	82.2
A-c to d-c converter efficiency (%)	97	97	97
Auxiliary system efficiency loss (%)	2	NA <sup>a</sup>	1
Overall efficiency (%)	64-66	74.7	78.9
Operating pressure	100 psig	440 psia	Pressure vessel designed for operating pressure up to 3000 psig
Cooling water	NA	184,940 gal/hr	Closed cycle dry cooling tower
Feedwater (gal/1000 SCF)	6.36	6.36	6.36
Nitrogen per start-up, SCF	Yes	74,640	No
Caustic potash initial charge (lb)	NA <sup>a</sup>	344,000	None
Labor	NA <sup>a</sup>	2 men/shift	NA <sup>a</sup>
Mode of operation	Fully automatic	Fully automatic	Fully automatic

<sup>a</sup>NA = not available.

Source: K. Darrow, et. al., "Commodity Hydrogen Off-Peak Electricity," Proceedings, First World Hydrogen Off-Peak Electricity," Proceedings, First World Hydrogen Energy Conference, 1976, pp 8C-32.

fuels.<sup>1</sup> Large-scale electrolysis plants are in operation in many parts of the world where cheap electric power is available, mainly supplying hydrogen to the ammonia and fertilizer industries. The existing plants are modular in design and could be scaled up without difficulty.

An electrolytic process is a decomposition reaction that occurs by passing a direct electric current between two electrodes immersed in an electrolyte. Each hydrogen molecule is formed by the addition of one electron to each of two hydrogen ions in solution. In the ideal case, a voltage of 1.47 volts applied at 25°C would generate hydrogen and oxygen isothermally with 100 percent of the heating value of the electrical energy converted into the fuel value of the hydrogen. However, a water electrolysis cell can be operated at a lower applied voltage if heat is supplied to maintain the cell temperature, with the result that the fuel value of the hydrogen produced can exceed the heating value of the electrical energy supplied. In practice, electrolysis cells have efficiencies of 60-70 percent. Cell efficiency can be increased by operating at higher temperatures, and advanced designs can be expected to have higher efficiencies than current cells. For the near term, a realistic figure for the energy cost of electrolytic hydrogen is 19 kWh<sub>e</sub>/lb hydrogen gas. The cost of hydrogen production is related to the cost of electrical power as shown in Table XV-3.

Three types of electrolyzers are suitable for large-scale hydrogen production: the bipolar alkaline cell (manufactured by Lurgi and Teledyne), the unipolar alkaline

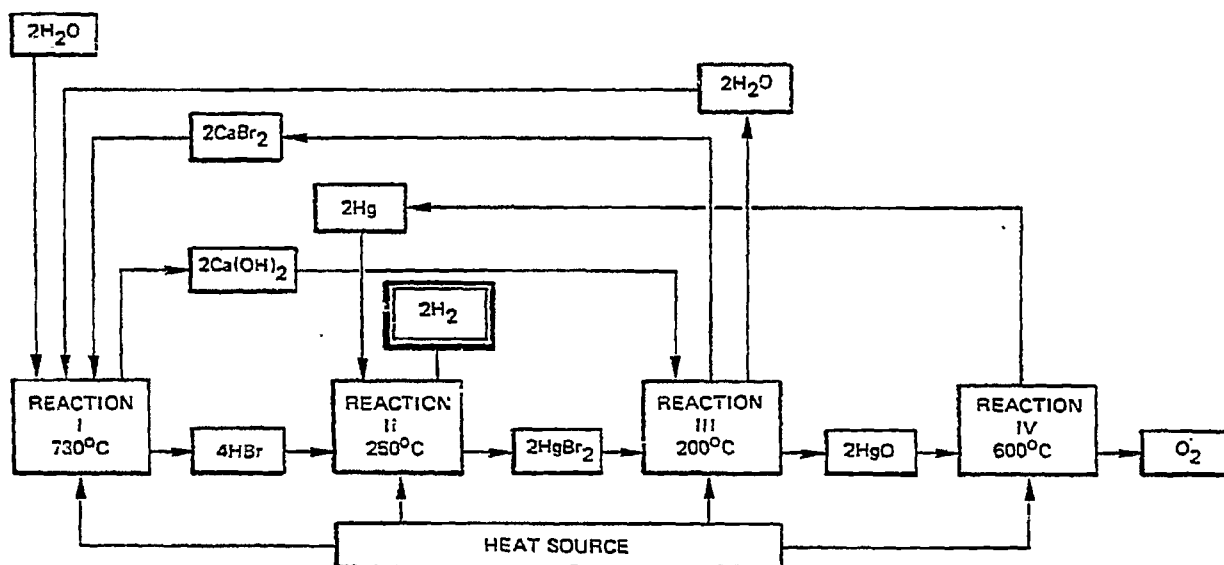
cell (manufactured by Electrolyzer Corp.), and the bipolar solid polymer cell (manufactured by General Electric). The Lurgi bipolar alkaline cells are the only large-scale electrolyzers in commercial service. However, the solid polymer electrolyzers can provide lower capital costs and improved efficiency in the near future. Table XV-4 displays the operating characteristics of the Lurgi, Teledyne, and GE electrolyzer cells. Because the cells require direct current, ac-to-dc rectification equipment will be necessary if dc power is not available. Although quite efficient, the capital cost of such equipment is high.

### Thermochemical

An alternative to the electrolytic method of generating hydrogen from water is thermochemical water splitting in which multistage reactions are used to dissociate water. Single-stage (pure thermal) dissociation occurs at 2500°C and is not considered feasible for hydrogen production. Two-stage processes have been eliminated because they too require extreme temperatures. Several multistage processes that appear technically feasible have been proposed.

The most widely discussed thermochemical process is the Marchetti process, which is based on the splitting of HBr (hydrogen bromide) produced by the hydrolysis of

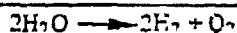
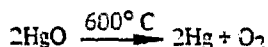
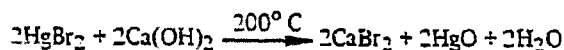
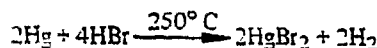
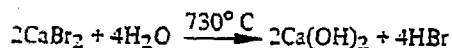
<sup>1</sup>D. P. Gregory, *A Hydrogen-Energy System*. American Gas Association. August 1972.



ADAPTED FROM G. DE BENI AND C. MARCHETTI, "MARK I, A CHEMICAL PROCESS TO DECOMPOSE WATER USING NUCLEAR HEAT," AM. CHEM. SOC. DIV. FUEL CHEMICAL PREPRINT 16, NO. 4, APRIL 1972, PP. 110-120.

Figure XV-1. THERMOCHEMICAL PRODUCTION OF HYDROGEN

$\text{CaBr}_2$  (calcium bromide).<sup>1</sup> The process is diagrammed in Figure XV-1. All steps in the sequence can be carried out at or below 730°C. The only inputs to the process are water and heat; the calcium bromide and mercury (Hg) are recycled. The sequence of reactions and the summation reaction are:



The process has a theoretical thermal efficiency of 59 percent and preliminary laboratory work indicates practical efficiencies of 40-50 percent can be expected. Here the efficiency is defined as the ratio of the higher heat value of the hydrogen produced to the thermal heat input. A serious drawback to the process is the highly corrosive nature of the compounds used (especially hydrobromic acid) and the large inventory of mercury involved.

The Marchetti process is compared with four other thermochemical hydrogen production processes in Table XV-5.

Another variation of the thermochemical process is the Von Fredersdorff process based on the conventional steam-iron-carbon monoxide process with the product  $\text{CO}_2$  being split to regenerate the carbon monoxide and produce oxygen.<sup>2</sup> The latter step is carried out at low temperatures (320°C) by use of ionizing radiation from a chemonuclear reactor. The technical feasibility of the process depends heavily on the development of chemonuclear reactors.

### Bioconversion

Several efforts are underway to develop a biophotolytic process for producing hydrogen. The basis for the procedure is to exploit the ability of anaerobic bacteria, which can be induced to form hydrogen during part of their metabolic cycle. In general, the bacteria do not use water directly, but reduce organic or inorganic substances to form hydrogen photosynthetically from these substrates.<sup>3</sup>

<sup>1</sup>G. De Beni and C. Marchetti, "Mark I. A Chemical Process to Decompose Water Using Nuclear Heat," American Chemical Society Division of Fuel Chemical Preparation, Vol. 16, No. 4, April 1972, pp. 110-120.

<sup>2</sup>D. P. Gregory, *A Hydrogen-Energy System*, American Gas Association, August 1972.

<sup>3</sup>Privileged communication from L. O. Krampitz, Case Western Reserve University.

Table XV-5

## THERMOCHEMICAL WATER DECOMPOSITION

	Marchetti Process	Cesium Oxide Process	Tin Oxide Process	Vanadium Chloride Process	Fe Chloride Oxide Process
Total Input Energy (Btu/lb H <sub>2</sub> )	103000	128060	145000	347000	117000
(kWh <sub>l</sub> /lb H <sub>2</sub> )	30.2	37.5	42.5	101.7	34.3
(kWh <sub>l</sub> /Btu) <sup>a</sup>	0.00059	0.00073	0.00082	0.00197	0.00067
Thermal Efficiency <sup>b</sup>					
Higher Heating Value	59%	48%	42%	18%	53%
Lower Heating Value	49%	41%	36%	15%	45%
Highest Endothermic Reaction Temperature (°C)	730	1050	1700	725	650
Fraction Process Heat at Highest Temperature	26%	70%	90%	30%	32%
Reactions in Closed Cycle	4	4	3	4	5

<sup>a</sup>Based on lower heating value of hydrogen.

<sup>b</sup>Full extent of reaction; 100% separation efficiency; no loss of intermediates; 100% internal heat recovery.

Source: Adapted from M. M. Eisenstadt and K. E. Cox, "Hydrogen Production from Solar Energy," *Solar Energy* 17, pp 59-65.

A process using algae rather than bacteria has been described for the photoproduction of hydrogen. Municipal sewage would be used as the growth medium with nitrates and phosphates as marketable by-products.<sup>1</sup>

<sup>1</sup>D. T. Blankenship, and G. D. Winget, "Hydrogen Fuel: Production by Bioconversion," *Proceedings, Eighth Inter-Society Energy Conversion Conference*, University of Pennsylvania, August 1973.

## HYDROGEN DISTRIBUTION

Since most the processes for hydrogen production require large heat sources, production plants will almost certainly be separated from the consumer by large distances. At the present time, hydrogen is transported from the source to the user by pipeline, truck, train and barge in both gaseous and liquid forms.

## Pipeline

The transmission of gaseous hydrogen by pipeline in moderate quantities is an established industrial practice, but is normally carried out over very small distances.<sup>1</sup> The longest hydrogen pipeline in the U.S. is an 8-inch line miles long operating at 200 psi. A comprehensive hydrogen pipeline network in the Ruhr Valley in Germany has a total length of 130 miles and has been in operation since 1940. Another hydrogen pipeline in Johannesburg, South Africa, is 50 miles long.

None of these networks is of such a length as to require in-line compressors to maintain transmission rates. Three types of compressors are applicable for service in hydrogen pipelines: piston or reciprocating compressors; radial or centrifugal turbocompressors; and screw compressors. All these can handle hydrogen without significant changes in design from those used for natural gas.

The existing network of natural gas pipelines will require extensive modification and expansion to adequately fill the needs of hydrogen transmission. Because the higher heating value of hydrogen is 325 Btu/SCF, to transmit the same energy, approximately three times the volume of hydrogen must be moved as natural gas. Higher pressures can be achieved by multi-stage compressors.

<sup>1</sup>D. P. Gregory, *A Hydrogen-Energy System*, American Gas Association, August 1972.

Table XV-S

## COSTS OF DELIVERING ENERGY

	Electricity	Natural Gas <sup>a</sup>	Hydrogen Gas <sup>b</sup>
Transmission (Dollars per million Btu)	0.61	0.20	0.52
Distribution (Dollars per million Btu)	1.61	0.27	0.34

<sup>a</sup>Natural gas optimized pipeline; natural gas cost \$0.25 per million Btu.

<sup>b</sup>Hydrogen gas optimized pipeline; hydrogen cost \$3.00 per million Btu.

Source: Adapted from D. P. Gregory, *A Hydrogen-Energy System*. American Gas Association, August 1972, p. 11-5.

Ultimately, to take advantage of the potentially low transmission costs of hydrogen pipelines, a new, specially designed system will be required. A comparison of the costs of energy transmission and distribution between electricity, natural gas pipelining, and an optimized hydrogen pipeline is shown in Table XV-6.

The pipeline transmission of liquid hydrogen presents greater problems than the pipeline transmission of liquid natural gas (LNG) because the temperature at which hydrogen enters the liquid phase is  $-253^{\circ}\text{C}$ . Thermal insulation and in-line refrigeration plants would greatly increase the capital costs of the pipeline. The minimum work required to cool hydrogen from  $21^{\circ}\text{C}$  and one atmosphere to a liquid at one atmosphere is 5198 Btu/pound. However, because of thermodynamic limitations, the energy consumed in liquefying hydrogen is 15,000 to 30,000 Btu/pound, depending on the process used. Because of the temperatures involved and the refrigeration costs, pipeline transmission of liquid hydrogen may be

desired only if the end use form requires liquid hydrogen.<sup>1</sup>

The pipeline transmission of cryogenic hydrogen has been limited to short runs at production plants and to somewhat longer lines at space program test and launch facilities.

The possibility of pipeline transmission of subcooled liquid hydrogen as a slush solid/liquid mixture has been suggested. The advantages of this scheme are an increased density of 15-20 percent over cryogenic hydrogen and the very significant additional heat sink capability, which minimizes the refrigeration required along the pipeline.

## Truck, Train and Barge

The transportation of small volumes of gaseous hydrogen in high pressure containers is common.<sup>2</sup> However, for large volumes, this form of transmission is not practical. Transportation of cryogenic hydrogen has been carried out by truck trailers with capacities of 16,000 gallons and by railroad tank cars with capacities of 34,000 gallons. The insulation problems and the boil-off losses are disadvantages for the long distance transmission of hydrogen by these means.

The Chicago Bridge and Iron Co. has built hydrogen transportation barges for NASA with tank capacities of 240,000 gallons. The tanks consist of concentric cylinders separated by 23 inches of evacuated perlite. The boil-off losses from these tanks is about 0.25 percent per day.<sup>2</sup>

<sup>1</sup>D. P. Gregory, *A Hydrogen-Energy System*, American Gas Association, August 1972.

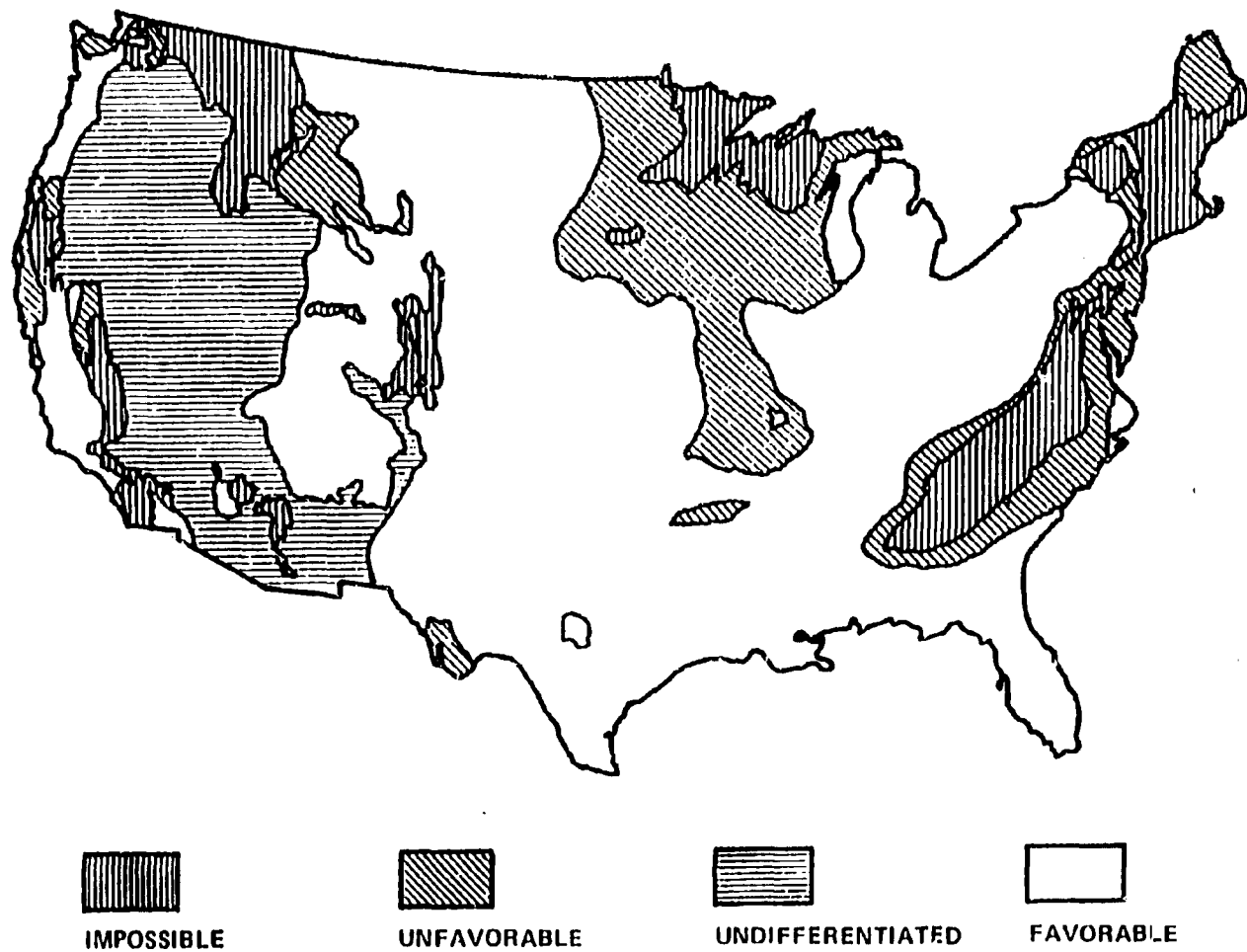
<sup>2</sup>Homer W. Carhart, et. al., "Hydrogen as a Navy Fuel," *NRL Report 7754*, June 12, 1974.

## HYDROGEN STORAGE

The need for hydrogen storage on a large scale is necessary because it allows production and transmission facilities to operate at a fairly even rate while the customers are supplied at a rate that fluctuates widely on 24-hour, weekly, and seasonal cycles. Storage close to the load center is desirable to reduce demands on the transmission system. (Seasonal variations in demand for natural gas vary by factors as large as 7.) Hydrogen can be stored both as a gas and as a liquid with the type of storage depending on end use. Table XV-7 provides a comparison of hydrogen storage requirements.

## Hydrogen Gas

The U.S. has developed extensive underground storage facilities for natural gas. At the end of 1970 there were 325 gas storage fields with a total storage capacity of 2.7 trillion CF. Storage fields are located in depleted oil and gas reservoirs and in sedimentary structures that have suitable caprock containment, and some storage is in abandoned salt caverns. The areas in the 48 contiguous states amenable to underground storage of gas in porous rock are shown in Figure XV-2.



Source: D. P. Gregory, "A Hydrogen Energy System." American Gas Association, August 1972, p. V-4.

Figure XV-2. REGIONAL AREAS AMENABLE TO UNDERGROUND STORAGE OF GAS IN POROUS ROCK

Table XV-7  
STORAGE OF HYDROGEN

	Weight of Carrier	Weight of Carrier and Fuel	Volume of Carrier and Fuel
45 pounds hydrogen			
Gas at 2000 psi	2205 lb	2250 lb	66 ft <sup>3</sup>
Cryogenic liquid	308 lb	353 lb	10.2 ft <sup>3</sup>
Metal hydride			
Mg <sub>2</sub> NiH <sub>4</sub>	1355 lb	1400 lb	8.5 ft <sup>3</sup>
FeTiH <sub>1.5</sub>	3305 lb	3350 lb	8.5 ft <sup>3</sup>
20,000 pounds hydrogen			
Gas at 3000 psi	1750 tons	1760 tons	40,000 ft <sup>3</sup>
Cryogenic liquid	3.3 tons	13.3 tons	8000 ft <sup>3</sup>
Metal hydride			
Mg <sub>2</sub> NiH <sub>4</sub>	320 tons	330 tons	4000 ft <sup>3</sup>
FeTiH <sub>1.5</sub>	740 tons	750 tons	4000 ft <sup>3</sup>

Adapted from D. P. Gregory, *A Hydrogen-Energy System*. American Gas Association, August 1972, p v-26.

B. Berkowitz, *et al.*, "Alternative, Synthetically Fueled, Navy Systems," TEMPO, General Electric Company, November 1974, p 29.

Natural gas may also be stored at pressures from 60 to 2040 psi in special vessels or lengths of transmission type-pipe.<sup>1</sup> The advantages of this type of storage are the ability to concentrate storage by design at the load center and the availability of the stored gas at above system pressure, which eliminates a send-out compressor.

Because the higher heating value of hydrogen is only a third that of natural gas on a volume basis, larger storage fields and tanks would be required for hydrogen. Tank storage for pressurized hydrogen gas has yet to be proven safe because of the unresolved question of metal fatigue resulting from hydrogen embrittlement of carbon steels.

### Liquid Hydrogen

Reducing the temperature of hydrogen from standard conditions to a temperature at which hydrogen enters the liquid phase results in a volume reduction by a factor of 850. NASA has been the pioneer agency in the storage of cryogenic hydrogen. As part of the Apollo complex, NASA operates two 900,000 gallon spherical vacuum-insulated tanks capable of storing liquid hydrogen with boil-off losses of 0.05 percent per day. This design with its expensive vacuum lining could be scaled up threefold. If the vacuum insulation were replaced with dry, gas-purged perlite, boil-off losses of 1.3 percent per day would be expected.<sup>2</sup>

At room temperature hydrogen is a two-phase gas composed of 75 percent orthohydrogen and 25 percent parahydrogen. Orthohydrogen is a form in which the two protons in the hydrogen molecule spin parallel; parahydrogen is a form in which their spins are anti-parallel.

At the boiling point of liquid hydrogen ( $-253^{\circ}\text{C}$ ), thermodynamic equilibrium is achieved when the hydrogen is 99.79 percent parahydrogen. Conversion from ortho to the para state is a second-order reaction with an initial rate of about 1 percent. (This rate can be greatly accelerated by catalysts). Conversion is important because the heat of conversion from the ortho to para state is 302 Btu/lb at the boiling point, while the heat of vaporization is 191 Btu/lb. If hydrogen is liquefied without conversion from the 25 percent para state, boil-off from the spontaneous conversion will amount to about 18 percent in 7 hours and 50 percent within one week. Thus, in addition to the removal of 5007 Btu/lb of hydrogen to cool it from  $21^{\circ}\text{C}$  to  $-253^{\circ}\text{C}$ , 191 Btu/lb must be removed to liquefy it and another 302 Btu/lb must be removed to accomplish the ortho to para phase change.

### Unconventional Storage Methods

Hydrogen can be stored as a metal hydride. Liquid hydrogen has a density of 4.42 lb/ft<sup>3</sup>. Metal hydrides can exceed this storage density. Two likely candidates for hydride storage are:

Mg<sub>2</sub>NiH<sub>4</sub> (density 160 lb/ft<sup>3</sup>; available H<sub>2</sub> 5.3 lb/ft<sup>3</sup>),

FeTiH<sub>1.5</sub> (density 375 lb/ft<sup>3</sup>; available H<sub>2</sub> 5.1 lb/ft<sup>3</sup>).

<sup>1</sup> D. P. Gregory, *A Hydrogen-Energy System*. American Gas Association, August 1972.

<sup>2</sup> Homer W. Carhart, *et al.*, "Hydrogen as a Navy Fuel," *NRL Report 7754*, June 12, 1974.

The formation of the hydride is exothermic. Consequently, to release hydrogen from the hydride requires heat. Typically, for each pound of hydrogen released, 15,000 Btu must be supplied to dissociate the hydrogen. This is 9 percent of the lower heating value of the hydrogen released. In addition to the thermal penalty paid to release the hydrogen, the storage medium is heavy and

costly and is not considered economically feasible. Use of lightweight metal hydrides, however, could significantly alter this.

<sup>1</sup>B. Berkowitz, *et. al.*, "Alternative, Synthetically-Fueled, Navy Systems," TEMPO, General Electric Co., November 1974.

## HYDROGEN UTILIZATION

### Heating

Two types of combustion are possible for hydrogen. The first is by conventional burners modified to account for the particular physical and chemical properties of hydrogen. The second is by catalytic or surface combustion, which can occur below the normal flame temperature and avoid the formation of nitrogen oxides. Catalytic burners eliminate the open flame (particularly serious for hydrogen since the flame is invisible) and produce only water vapor. This eliminates the necessity of venting the exhaust gases with the accompanying loss of heat. Catalytic space heating systems would be decentralized and resemble electrical appliances in flexibility.

### Electrical Power Generation

Hydrogen can be converted to electricity by fuel cells and by direct thermal-mechanical systems. Hydrogen is the ideal fuel for efficient production of electricity in fuel cells. (See Chapter XIII.)

Direct thermal-mechanical systems for electric power production include central steam plants, gas turbine generators and diesel generators. These systems can be converted to hydrogen without great difficulty. The efficiency of these systems can be increased by supplying pure oxygen for the combustion. For base-loading, hydrogen-oxygen fired plants could have efficiencies as high as 55 percent.

The expense of pipelining oxygen (a by-product of the electrolysis and thermochemical production of hydrogen) is prohibitive over distances greater than 30 miles. If liquid

hydrogen is the chosen method for transporting energy, the recovery of the hydrogen liquefaction energy can make it possible to separate stoichiometric amounts of oxygen from air on site with little additional energy.<sup>1</sup>

### Vehicles and Aircraft Propulsion

Considerable work, dating from the late 1920s, has been done on the use of hydrogen in internal combustion engines. The use of hydrogen in piston engines appears to be quite possible by the application of fuel injection and proper ignition timing.

In 1956, Pratt and Whitney converted a standard J57 aircraft engine to operate with hydrogen. At a later date, a B-57 was flown with one engine operating on hydrogen from a liquid hydrogen fuel tank. Engine conversions to hydrogen appear to present few problems.<sup>2</sup>

Although handling and on-board storage of hydrogen is a serious problem for any vehicle, liquid hydrogen as a fuel for transportation is technically possible. In fact, it may be the only fuel for long-range, high-performance hypersonic transports and might be adaptable for use by jumbo jets. Small, vacuum-insulated tanks have been constructed for use in automobiles which can contain boil-off for up to 18 hours.

<sup>1</sup>W. R. Parrish, *et. al.*, "Selected Topics on Hydrogen Fuel," NBS Special Publication 419, May 1975.

<sup>2</sup>R. J. Schoepfel, *Chemical Technology* Vol. 2, No. 476, 1972.

## AMMONIA

The standard U.S. method for ammonia production is the Haber process in which a hydrogen-nitrogen mixture of mole ratio 3:1 is compressed to 2500-4500 psi in contact with a catalyst between 370° and 540° C. A common catalyst used is ferric oxide with small amounts

of aluminum and potassium oxides. Because the reaction does not go to completion, a pressurization, depressurization, cooling, separation, and recompression cycle must be used. A typical energy requirement for this cycle is 0.25 kWh/lb ammonia produced.

To prevent poisoning of the catalyst, a feedstock of pure hydrogen and nitrogen must be used. Nitrogen may be separated from air at a cost of 0.10 kWh<sub>e</sub>/lb NH<sub>3</sub> with 93 percent of this requirement resulting from electrolytic hydrogen costs.<sup>1</sup> Most of the hydrogen used for ammonia production is obtained by the steam reforming of methane. In 1973, 15 million tons of ammonia were produced in the U.S. almost entirely using the Haber process with methane as the hydrogen source.

Ammonia can also be produced by coal gasification. Table XV-8 lists ammonia production facilities based on coal gasification. In 1973 these plants produced approximately 2 million tons of ammonia.

Ammonia is used extensively in the chemical and fertilizer industries, and it can also serve as a fuel. The research

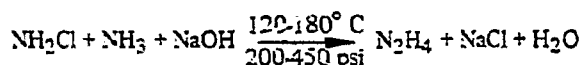
octane rating of ammonia is 130; it can either be burned directly (with only a minor nitrous oxide production problem) or be used as an input to a fuel cell. Ammonia has a heating value of 8080 Btu/lb, a density of 38 lb/cu. ft. and ammonia has a latent heat of vaporization of 6 Btu/lb, which makes it attractive as a coolant. It is toxic, but its characteristic odor is detectable well below the hazardous level.<sup>2</sup>

<sup>1</sup> B. Berkowitz, *et. al.*, "Alternative, Synthetically-Fueled, Navy Systems," TEMPO, General Electric Co., November 1974.

<sup>2</sup> J. W. Hodgson, "Alternate Fuels for Transportation," *Mechanical Engineering*, July 1974.

## HYDRAZINE

The Raschig process is the most widely used method for producing hydrazine. A concentrated brine solution is electrolyzed, and the chlorine evolved at the anode is conducted back into the electrolyte to produce sodium hypochlorite (NaOCl). The hydrogen evolved supplements the hydrogen required for ammonia preparation. The hypochlorite solution is diluted and treated with a 10- to 20-mole excess of saturated ammonia solution to produce chloramine (NH<sub>2</sub>Cl). In a second reactor, the solution is rapidly heated to 120-180° C at 200-450 psi while maintaining the high ratio of ammonia to hypochlorite to facilitate hydrazine formation. The series of reactions that produce hydrazine are:



Good yields of hydrazine depend on using dilute solution (1 to 2 percent hydrazine). The reaction solution must be distilled and the sodium chloride removed in a crystallizing evaporator. The product at this stage is hydrazine hydrate N<sub>2</sub>H<sub>4</sub> · H<sub>2</sub>O. To obtain anhydrous hydrazine, the hydrate is subjected to extractive distillation using ethylene glycol as the entraining solvent. The energy requirement of the process is extremely unfavorable because of the electrical demand for the brine electrolysis, the use of excess ammonia, and multiple distillation of the product solution.

Other methods of hydrazine production exist, but all are even less efficient than the Raschig process.<sup>1</sup>

Hydrazine is a clear, hygroscopic, toxic liquid that is thermodynamically unstable with respect to ammonia, hydrogen, and nitrogen. It can be used directly as a fuel or as a feedstock for a fuel cell.

<sup>1</sup> B. Berkowitz, *et. al.*, "Alternative, Synthetically-Fueled, Navy Systems," TEMPO, General Electric Co., November 1974.

## METHANOL

Most of the 10 million tons of methanol produced annually are manufactured from synthesis gas (CO-H<sub>2</sub> mixture) obtained from coke, coal or natural hydrocarbons. The basic reaction is



which is carried out in a low pressure (50 atm) process employing a high activity copper catalyst at 260° C. The

exothermic synthesis evolves 1570 Btu/lb CH<sub>3</sub>OH and the excess heat is removed by heat exchange with the incoming synthesis gas. The reaction does not go to completion in a single pass and depressurization, condensation of the methanol, separation and recompression reduce the process efficiency. The process is similar to coal gasification except that supplemental hydrogen must be supplied at a cost of 0.72 kWh<sub>e</sub>/lb methanol produced.



Table XV-8  
COAL-BASED SYNTHETIC AMMONIA PLANTS

Customer and Location	Gasification Process and Ammonia Production (tons per day)		
	Winkler	Lurgi	Koppers Totzek
Azot Gorazde, Yugoslavia	50		
Empreso Nacional, Calvo Sotelo, Puertolano, Spain	140		
Azot Sanayii, Kutahya, Turkey	120		
Typpi Oy, Oulu, Finland			60
Nippon Suiso, Onahama, Japan			100
Empreso Nacional Calvo Sotelo, Puentes, Spain			100
Typpi Oy, Oulu, Finland Extension			60
Daudhkel, Pakistan		60 <sup>a</sup>	
Nitrogenous Fertilizer, Ptolemais, Greece			300
Neyveli, South Arcot, India	300		
Naju Fertilizer, Korea		150 <sup>a</sup>	
Chemical Fertilizer, Mae Moh, Lampang, Thailand			100
Azot Sanayii, Kutahya, Turkey			250
Industrial Development Corp., Kafue/Lusaka, Zambia			100
Nitrogenous Fertilizer, Ptolemais, Greece			75 <sup>b</sup>
Fertilizer Corp. of India Ramagundam, India			900
Fertilizer Corp. of India, Talcher Plant, India			900
Nitrogenous Fertilizer, Ptolemais, Greece			150
Fertilizer Corp. of India, Korba Plant, India			900
AE & CI Ltd., Modderfontein, Republic of South Africa			1000
Industrial Development Corp., Kafue/Lusaka, Zambia			100 <sup>b</sup>
Total	610	210	5195 = 5015

<sup>a</sup>Exact production rate unknown

<sup>b</sup>Ammonia production calculated from the increased synthesis gas production

Source: *Proceedings, First World Hydrogen Energy Conference*, 1976, pp 98-39.

Because the synthesis gas feedstock usually contains CO<sub>2</sub> and hydrocarbon impurities, other products are produced, and distillation of the reaction products is necessary. The total energy demand for the process is 1.74 kWh<sub>e</sub>/lb CH<sub>3</sub>OH.<sup>1</sup>

Methanol can also be produced by the destructive distillation of wood or municipal solid waste. The wood

or wastes are partially oxidized to produce synthesis gas, which is then converted to methanol by a shift reaction.

<sup>1</sup> B. Berkowitz, et. al., "Alternative, Synthetically-Fueled, Navy Systems," TEMPO, General Electric Co., November 1974.

## METHYLAMINES

The three methylamines are ammonia derivatives in which one, two or all three of the ammonia hydrogen atoms are replaced by methyl groups. These amines [ $\text{CH}_3\text{NH}_2$ ,  $(\text{CH}_3)_2\text{NH}$ , and  $(\text{CH}_3)_3\text{N}$ ] are gases formed by gas phase condensation of methanol and ammonia over a dehydration catalyst of aluminum oxide gel. The synthesis of the methanol and ammonia is carried out at 100-200 psi

and 320-370° C. The overall reaction is mildly exothermic, evolving 445 Btu/lb mixed methylamines. The total ene. demand is 4.5 kWh<sub>e</sub>/lb mixed methylamines.<sup>1</sup>

<sup>1</sup> B. Berkowitz, *et. al.*, "Alternative, Synthetically-Fueled, Navy Systems," TEMPO, General Electric Co., November 1974.

**CHAPTER XVI**

**MAGNETOHYDRODYNAMICS  
(MHD)**

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## INTRODUCTION

Magnetohydrodynamic (MHD) generation is a method of directly converting heat energy to electrical energy by passing electrically conductive fluids through a magnetic field. Michael Faraday pioneered electromagnetic induction in fluids in the early nineteenth century. In the generalized MHD generator of Figure XVI-1, high-temperature, high-speed gases move through the MHD duct at right angles to a magnetic field. The gases are

weakly ionized at the high temperatures and further ionized by seeding with cesium or potassium. As the ionized gases cross the magnetic flux, an electric current is induced across the plasma normal to both the flow and the magnetic field directions. Electrodes on the duct walls collect the electrical energy in the form of direct current.<sup>1</sup>

<sup>1</sup>G. J. Womack, *MHD Power Generation: Engineering Aspects*, London, Chapman and Hall, 1969.

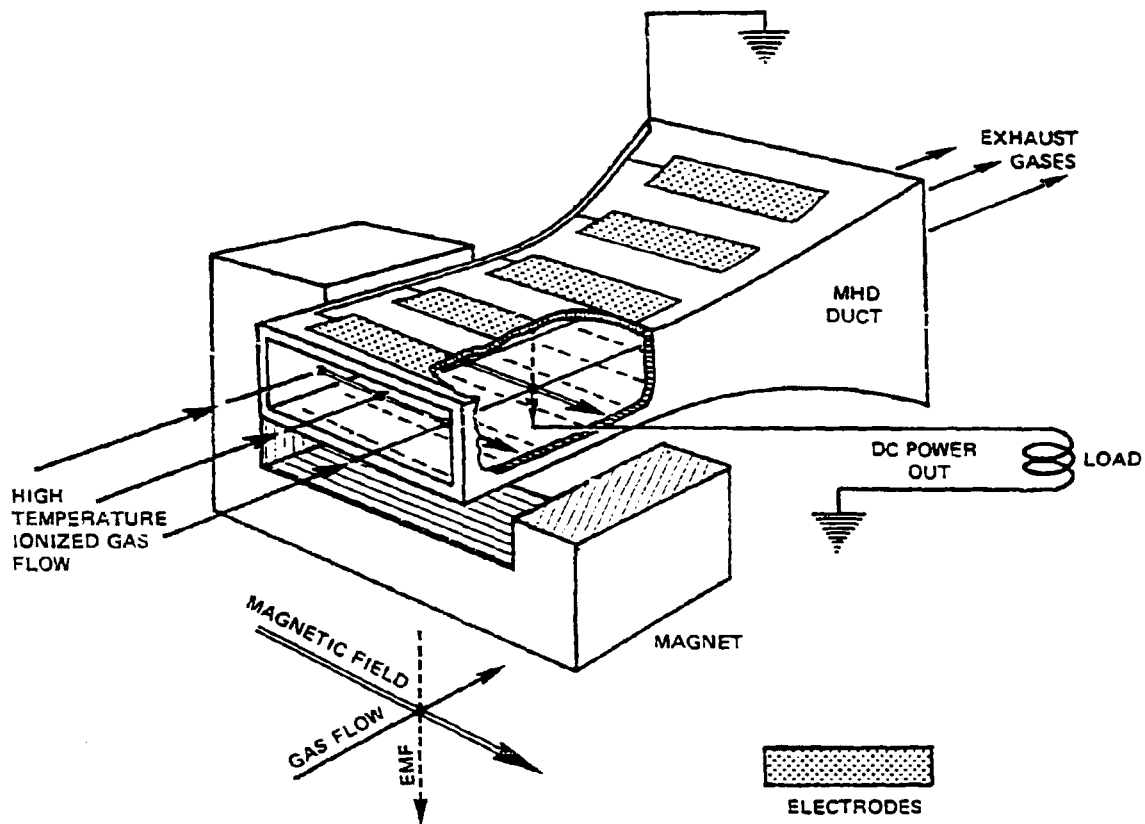


Figure XVI-1. SIMPLIFIED MHD GENERATOR CONFIGURATION

## MHD TOPPING CYCLES

In general, MHD cycles extract the energy of combustion (or potentially the energy of nuclear reaction) at the highest temperatures that state-of-the-art materials will allow because the MHD channel has no moving parts. Exhaust gases may have a considerable amount of remaining high-temperature energy that can be further converted through conventional steam or gas turbine power

systems. Consequently, MHD generators are most attractive as "topping cycles" to conventional plants: the two systems together form a binary cycle to take advantage of the widest possible temperature difference and therefore the maximum possible thermal efficiency that can result from the heat of combustion or nuclear reaction.

Table XVI-1

## POWER PLANT EFFICIENCIES

	Conventional Steam Plant	Conventional Gas Turbine Plant	Advanced Gas Turbine Plant	MHD Topping Cycle	MHD High- Temperature Topping Cycle
Maximum cycle temperature, °F	1000	2000	2500	3000	4000
Carnot efficiency <sup>a</sup>	63%	78%	82%	84%	88%
Actual efficiency	39.5%	27% <sup>b</sup>	35% <sup>b</sup>	50% <sup>c</sup>	60% <sup>c</sup>

<sup>a</sup>All Carnot efficiencies calculated with an assumed heat sink temperature of 85° F.<sup>b</sup>Simple cycle gas turbine.<sup>c</sup>From published calculated estimates.

## IDEAL AND ACTUAL CYCLE EFFICIENCIES

The efficiency of any heat engine is limited by the maximum temperatures and the heat sink temperatures available to the engine's power cycle. The Carnot efficiency is the ideal conversion efficiency that could potentially be achieved in any given power cycle. In its simplest form, Carnot efficiency is:

$$\eta_i = 1 - T_A/T_H$$

The maximum cycle temperature ( $T_H$ ) and the heat sink or ambient temperature ( $T_A$ ) are both absolute temperatures in degrees Rankine (or Kelvin). Ambient temperatures are generally considered to be between 60° F and 100° F for temperate regions. The actual efficiency of a thermal power plant is:

$$\eta_a = \frac{\text{Power produced}}{\text{Heat rate supplied}}$$

Actual thermal power plant efficiencies are much lower than their theoretical Carnot efficiencies. However, as usable cycle temperatures increase, Carnot efficiency and actual cycle efficiency increase. Gas turbine efficiencies are expected to increase as material improvements increase cycle temperatures from 2000° F (with existing technology) to 2500° F. To further improve cycle efficiencies, high temperatures could be used in an MHD generator. An open-cycle MHD generator may be able to use temperatures up to 4000° F. The potential increase in cycle efficiency is indicated in Table XVI-1.

## COMBINED PLANT EFFICIENCY

The generalized efficiency equation for binary MHD/conventional power plants<sup>1</sup> can be expressed as:

$$\eta_T = \eta_c + \eta_m (1 - \eta_c)$$

where  $\eta_T$  = total plant efficiency

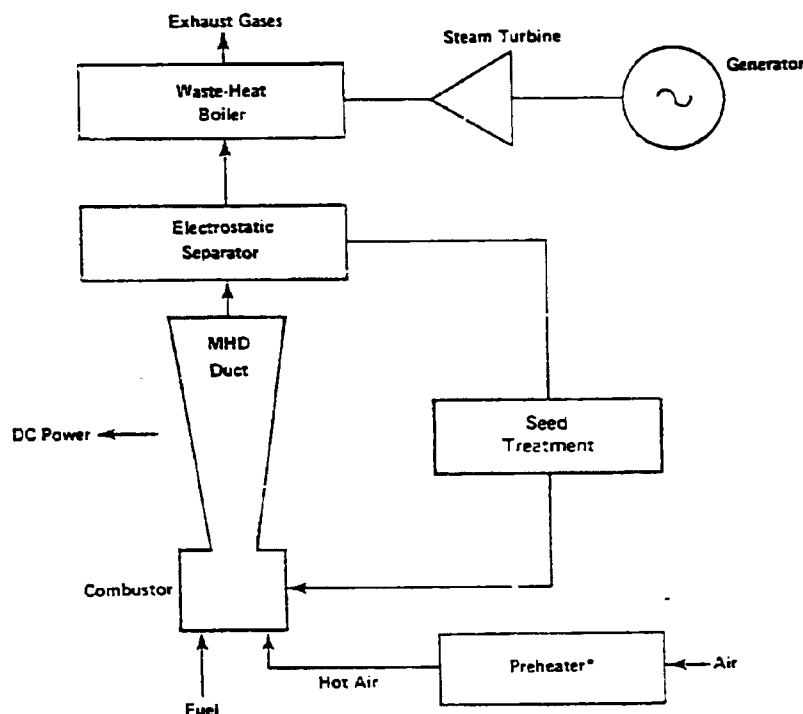
$\eta_c$  = conventional steam or gas turbine plant efficiency

$\eta_m$  = overall MHD generator efficiency

achieve overall efficiencies of 20 percent. If an MHD channel were used as a "topping cycle" to a conventional plant having a potential efficiency of 40 percent, the combined plant efficiency would be 52 percent: ( $\eta_T = 0.40 + 0.20 \cdot (1 - 0.40) = 0.52$ ). This 30 percent increase in overall plant efficiency would essentially result in comparable decrease in fuel consumption for any given power requirement. This calculated potential for fuel conservation is the attractive net attribute of MHD generators.

Advanced open-cycle MHD generators may be able to

<sup>1</sup>G. J. Womack, *MHD Power Generation: Engineering Aspects*, London: Chapman and Hall, 1969.



\*Air can be preheated by exhaust gases or heated separately.

Figure XVI-2. OPEN-CYCLE MHD GENERATOR

### OPEN-CYCLE MHD GENERATOR

In the open-cycle MHD system shown schematically in Figure XVI-2, the working fluid is eventually rejected to the atmosphere. Combustion air would have to be preheated so that gases from combustion of fossil fuel could reach temperatures above  $4000^{\circ}\text{F}$ . The combustion gases would then be seeded and used directly as the working fluid for the MHD generator. Seed material must then be separated from the exhaust gases and recycled to the incoming combustion flow. After MHD topping, exhaust gases can be used to generate steam via waste heat boilers. Some waste heat can be used to preheat combustion air in a "direct open cycle." An alternative is to preheat the combustion air through a "separately fired open cycle," which does not use waste heat from the MHD duct.<sup>1</sup>

A high flame temperature is necessary to maintain a high electrical conductivity and a high conversion effi-

ciency in open-cycle MHD generators. As gas temperatures drop below  $3600^{\circ}\text{F}$ , conductivity falls to the point that MHD electric power generation is uneconomical. Combustion of coal or residual oil with air preheated to  $2200^{\circ}\text{F}$  produces a flame temperature of approximately  $4500^{\circ}\text{F}$  at design operating pressures of 5 to 10 atmospheres. A conventional power steam power plant that uses MHD topping over a temperature difference of  $4500^{\circ}\text{F}$  to  $3400^{\circ}\text{F}$  could, in practical design, produce binary cycle efficiencies of 44 to 46.5 percent.<sup>1</sup> These combined plant efficiencies are potentially 10 to 16 percent more efficient than conventional steam plants.

<sup>1</sup>J. B. Heywood and G. J. Womack, *Open Cycle MHD Power Generation*, London: Pergamon Press, 1969.

The high operating gas temperatures present a materials reliability problem for open-cycle MHD generators. However, assuming that materials can be developed to provide relatively reliable and economical components for the generator, open-cycle MHD generators may be used in large combined plants. Below 2000 Mw (thermal), the ratio of

MHD power to combustion chamber and duct-wall heat loss decreases to the point that the actual payoff in MHD combined plant efficiencies is considered to be insufficient.<sup>1</sup>

<sup>1</sup>J. B. Heywood and G. J. Womack, *Open Cycle MHD Power Generation*, London: Pergamon Press, 1969.

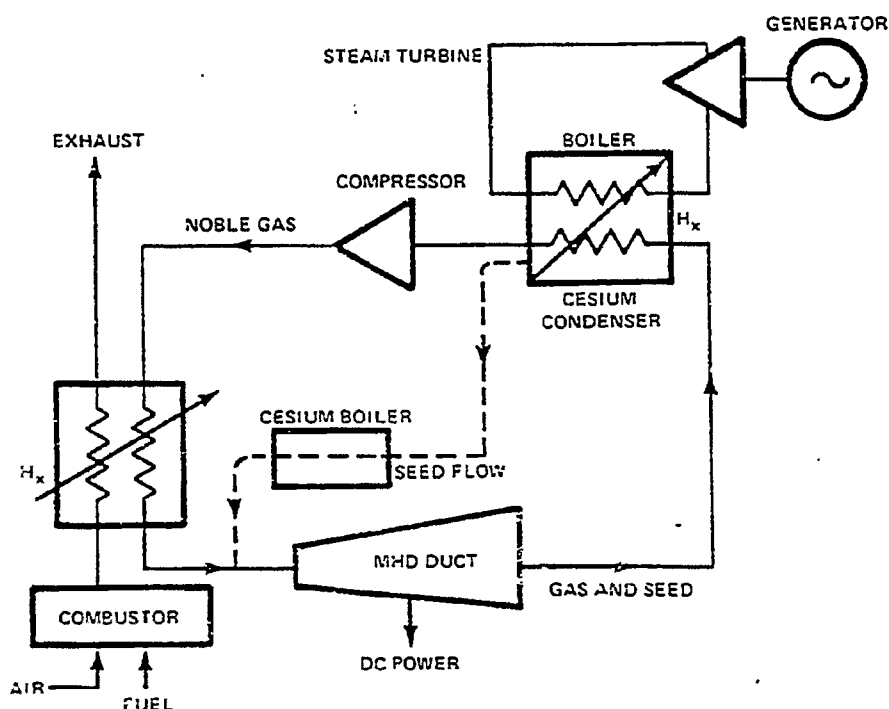


Figure XVI-3. CLOSED-CYCLE MHD GENERATOR

### CLOSED-CYCLE MHD GENERATOR

The closed-cycle MHD generator illustrated in Figure XVI-3, recycles the working fluid which is normally a noble gas. Heat is added to and rejected from the cycle through heat exchangers. The noble gases with their low electron affinity are used as working fluids in closed cycles because their nonequilibrium ionization enhances their electrical conductivity. The enhanced conductivity effect allows the generator to operate at stagnation temperatures of 3000° F and power extraction from the fluid can be maintained to gas temperatures as low as 1100° F. The high conductivity also results in high power densities.

In closed-cycle MHD generators, thermal efficiencies are

limited only by the dynamic stability of the gas. Extraction efficiencies as high as 45 percent are attainable with proper gas flow control. A small 15 Mw(e) closed-cycle MHD power plant can reach efficiencies of 45 to 50 percent in a regenerative Brayton cycle configuration.<sup>1</sup>

General Electric Space Science Laboratory has been developing closed-cycle MHD generator technology with

<sup>1</sup>*Closed Cycle MHD for Central Station Power with Fossil or Nuclear Fuels*. Prepared by Space Sciences Laboratory-Space Division, the General Electric Company, for the Office of Naval Research, August 1973 (AD-766500).



significant progress. Research has led GE to conclude that a 50 Mw(t) closed-cycle MHD topping generator operating at 3000° F and 10 atmospheres stagnation can electrically extract 20 percent of the incoming heat energy to yield a potential 50 percent combined power plant efficiency. GE estimates that this power plant may be only one-fifth the size of an equivalent open-cycle MHD power plant.

The major technical problem with the closed-cycle MHD is prevention of contamination of the working fluid. GE is developing a special ceramic matrix heat exchanger to transfer fossil fuel combustion heat to the closed MHD cycle. The entrainment of combustion gas products into the noble gas working fluid in the heat exchanger reduces conductivity. Molecular contamination levels must be limited to less than 0.10 percent, which has been maintained experimentally.<sup>1</sup> However, a noble gas purification stage may have to be designed into the closed MHD generator loop to

prevent the eventual build-up of contaminants. Fossil fuel combustion ash may tend to foul passages in the heat exchanger. Slag and sulfuric acid combustion products could also attack the ceramic matrix. Cleaning the combustion products before they enter the heat exchanger can alleviate these fouling problems to a great extent.

Possibly the most promising application for closed-cycle MHD is in conjunction with nuclear heat sources. The high-temperature, gas-cooled reactor operating at about 2400° F is a very attractive heat source for the closed-cycle MHD.<sup>1</sup> Since the MHD generator has no moving parts, sealing in the MHD generator with the reactor is a self-contained "direct conversion" system may be technically feasible.

<sup>1</sup> *Closed Cycle MHD for Central Station Power with Fossil or Nuclear Fuels*. Prepared by Space Sciences Laboratory-Space Division, the General Electric Company, for the Office of Naval Research, August 1973 (AD-766500).

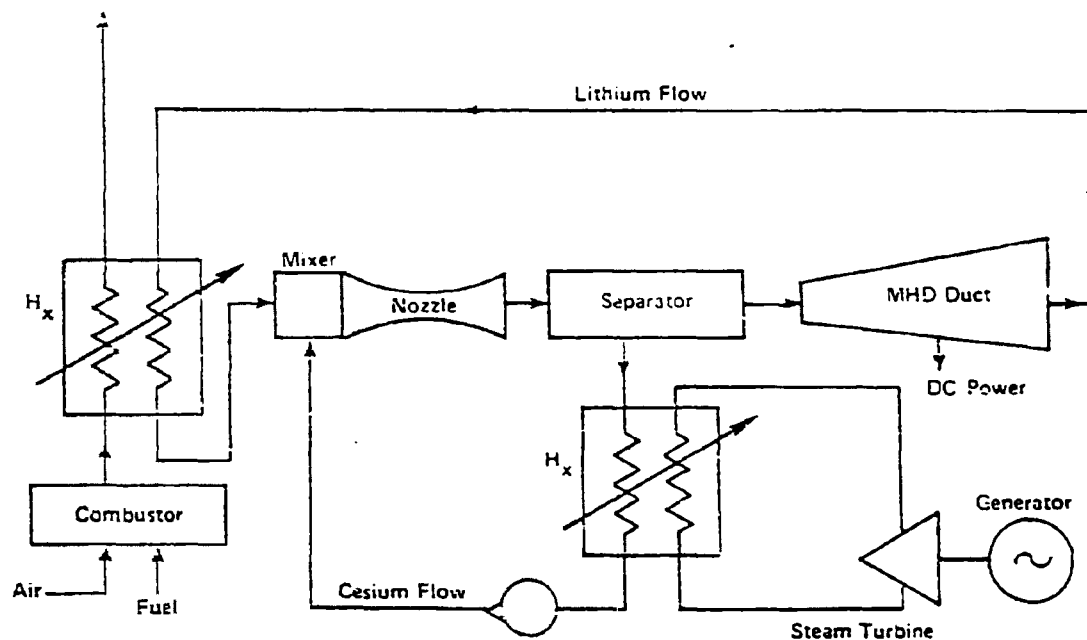


Figure XVI-4. THE JPL LIQUID-METAL MHD GENERATOR

## LIQUID-METAL MHD GENERATOR

The liquid-metal MHD cycle under development by the Propulsion Laboratory (JPL) of the California Institute of Technology is shown in Figure XVI-4. A liquid metal with a low vapor pressure, such as lithium, is heated and mixed with a liquid metal with a high vapor pressure, such as cesium, resulting in a two-phase mixture. The vapor accelerates the liquid to velocities of 200 to

500 ft/sec in a nozzle. The vapor phase is separated from the liquid metal, which flows through the MHD duct producing electric power. The liquid metal then circulates back to the heat source where the process is repeated. The separated metal vapor flows to a heat exchanger where it is condensed. This rejected heat is used to generate steam. The condensed liquid is then pumped

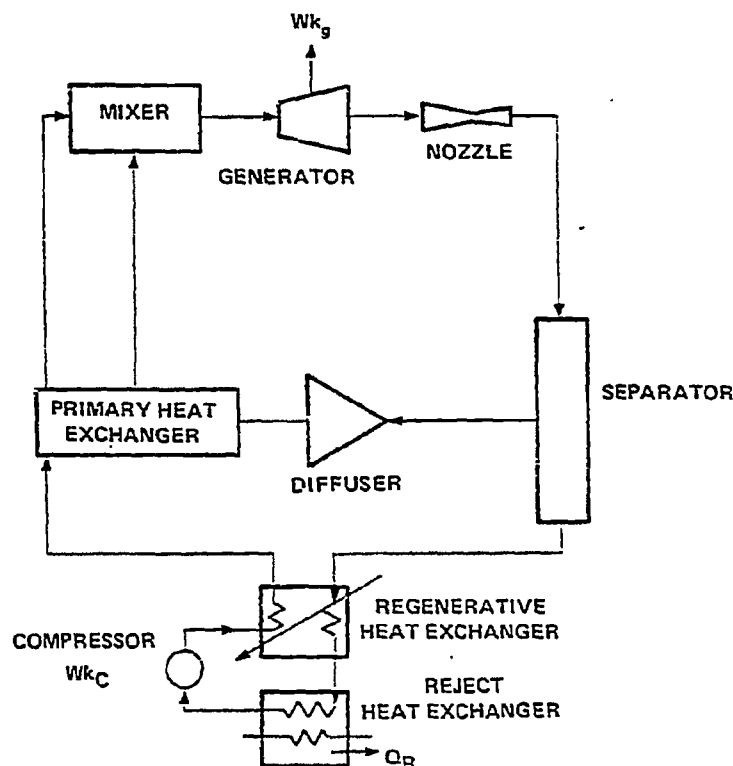


Figure XVI-5. SCHEMATIC OF THE ANL BASIC TWO-PHASE FLOW LIQUID-METAL AND GENERATOR CYCLE

back to be mixed with the lithium to repeat the process.<sup>1</sup>

The liquid-metal MHD cycle is limited in maximum operating temperatures by material limits. Design operating conditions may be limited to 1800° F at 137 psia. Maximum flow velocities are in the order of 400 to 550 feet per second. Maximum energy conversion efficiencies can approach 14 percent. JPL has conducted studies indicating that, in topping cycles, liquid MHD generators can contribute to central power system efficiencies approaching 46 percent.<sup>1</sup> Although the relation of efficiency versus power capacity is unknown, JPL implies that the high efficiencies will be limited to plants in the 1000 Mw category and up. JPL refers to a 200 Kw(e) space power system with an enthalpy extraction efficiency of 5.8 percent. A preliminary design is provided for a 1637 Mw(e) electric utility plant, which includes a 337 Mw(e) MHD topping generator at 13.5 percent efficiency.

A two-phase flow liquid-metal MHD generator is being developed by the Argonne National Laboratory (ANL) in Argonne, Illinois. Early ANL Work had been related to developing a cycle that used sodium-potassium liquid metal to enhance the conductivity of a nitrogen working fluid.<sup>2</sup>

The ANL liquid-metal cycle is significantly different arrangement from the JPL liquid-metal cycle. In the A. cycle, the two-phase medium is directed through the MHD generator, as illustrated in Figure XVI-5. After the electric conversion process, the liquid metal is separated from the working fluid. ANL has studied alternative electrodynamic fluids such as lithium or sodium to be used with thermodynamic working fluids such as helium or argon in the basic cycle of Figure XVI-5.

Most of ANL's testing apparently has been limited to maximum cycle temperatures of less than 1000° F and cycle pressures of about 1100 psi. Working fluid flow speeds have been about 45 feet per second, much slower than the speeds used in the JPL liquid-metal MHD cycles.

<sup>1</sup> *Liquid Metal Magnetohydrodynamics (LMMHD) Technology Transfer Feasibility Study*. Vol. I and II, prepared by Jet Propulsion Laboratory, California Institute of Technology, 13 May 1973.

<sup>2</sup> L. C. Pirtenger, W. E. Amend, R. Cole and E. S. Pierson, *Experimental Studies of Constant Velocity Two-Phase Liquid Metal MHD Generator*, Argonne National Laboratory, Argonne, Illinois; paper presented at "World Energy Conference-IX," Detroit, Michigan, 1974.

## STATUS OF DEVELOPMENT

Initial development of open-cycle MHD generators began during the late 1950's. There were programs both in this country and abroad, notably in the USSR and Japan. The USSR has used natural gas, and Japan has used oil. Since 1969, the United States has emphasized coal as the primary fuel. Coal with its sulfur and ash content poses an emissions problem. MHD generators have been tested for short periods with both clean and dirty gas streams. This experience and supporting analytical work provide a solid base for effective, first-phase electrode and channel design and engineering development. Simultaneous performance and endurance of large generators have not yet been demonstrated. Commercial applications typically require 15 to 20 percent recovery of the thermal energy input to the generator as electric power output. The best performance to date has been about 8 percent.

The University of Tennessee Space Institute (UTSI) recently demonstrated that an MHD generator would perform successfully on coal-combustion products and utilize coal slag as an effective duct lining material. Confirmation of this result by the AVCO Everett Research Laboratory, together with promising results in the control of oxides of nitrogen and the removal of sulfur dioxide obtained earlier by the Bruceton Energy Research Center (BERC), has provided a preliminary engineering demonstration of feasibility of coal-fueled MHD. Work has now progressed to the point where it is profitable to move on to larger-scale facilities.

Another important recent event was the start of modifications to an existing MHD facility at the Arnold Engineering Development Center (AEDC), Tullahoma, Tennessee, to provide a national test facility for MHD channel performance. This facility, which is designed to test MHD generator channels at a peak power rating of about 50 megawatts electrical output, will provide testing of channels under conditions appropriate to central station power conditions.

The U.S. Energy Research and Development Administration (ERDA) has coordinated the cooperative program in MHD power generation being undertaken with the USSR under the science and technology agreement reached in May 1972. Activities during the past year have included the development of a materials test program to be carried out in the Soviet's U-25 installation, arrangements for the USSR to supply diagnostic equipment for use on the AVCO Mark VI facility, development of a specification and preliminary design for the U.S. channel to be tested in the Soviet U-25 pilot plant, and specification of the design parameters for a U.S. magnet to be installed for joint experimental work on a bypass loop in the Soviet U-25 installation. A U.S. channel design is being proposed for installation

within the U-25 magnet for tests in 1977. Agreement was also reached on the joint study of technical and economic problems involved in the introduction of MHD power plants into commercial service. Technical areas of mutual interest were featured in the first joint U.S.-USSR Colloquium held in Moscow, October 1974.

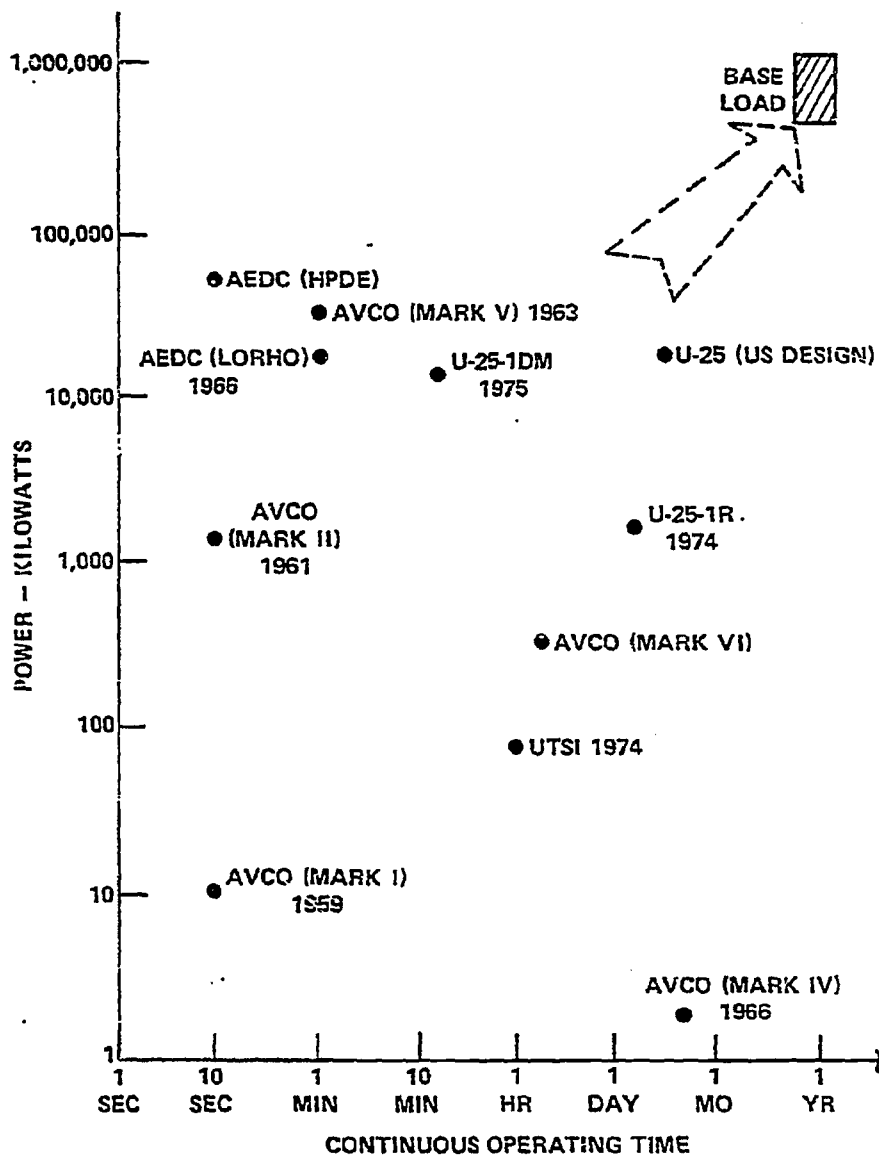
Recently the Soviets achieved 12.4 Mw(e) performance in their MHD facility and supplied power to the Moscow electric power grid for 30 minutes. This facility uses natural gas as a fuel, with a separate gas-fired air preheater and oxygen enrichment. In a previous operation, the U-25 supplied electric power for 100 hours at the 1.4 Mw(e) power level.

In Japan, notable progress has been made in the design and construction of MHD generators and superconducting magnets. The Electro-Technical Laboratory's Mark V generator has achieved a power output level of 800 Kw(e) for several minutes with a conventional magnet and has also been operated with a superconducting magnet. A model power plant, called the Mark VI, is to provide tests of a long duration channel, three types of air preheaters, and a seed handling system.

Smaller programs are under way in several other countries. For instance, a program concentrating on air preheaters and auxiliary components for coal-fired open cycle MHD systems is being pursued in Poland. Other nations, such as France, the United Kingdom, and the Federal Republic of Germany, have been involved in MHD research, but have sharply curtailed or abandoned these efforts because of other national considerations.

ERDA and the Electric Power Research Institute are cosponsoring a national program for full-scale commercial MHD power generation. The joint government-industry program will include the construction of an engineering test facility in Montana to test an experimental 20 Mw(e) MHD generator. The test facility is the result of a shift in emphasis from past exploratory and scientific approaches to an engineering-oriented program of component and system testing. A facility of this size is believed to represent a threshold from which it should be possible to scale up the MHD system and its components to a commercial size with reasonably acceptable risk.

Figure XVI-6 summarizes the most significant generator performance data obtained to date. Results indicate that both the desired power output and continuous operating times required to justify commercial development have been achieved, but not simultaneously. As evidenced in the chart, progress is being made toward reaching base load operation criteria, which are represented by the cross-hatched block at the upper right (power output of 500 Mw(e) and above for continuous times of about a year).



Source: W. D. Jackson, *MHD Power Generation-Technology Status and Development Plan*, MHD Project Office, ERDA, from 1975 symposium "Clean Fuels from Coal-II," sponsored by Institute of Gas Technology (IGT).

Figure XVI-6. SELECTED DATA ON MHD GENERATOR PERFORMANCE

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## INTRODUCTION

Solar energy is an ideal energy source in many ways. Solar energy conversion systems generate neither air nor water pollution and negligible thermal pollution. Solar energy is abundant and perpetually renewable. Approximately 1,390 watts of energy arrive on each square meter of surface just outside the earth's atmosphere, and solar energy is equivalent to about 1,000 watts per square meter, directly facing the sun at the earth's surface on a clear day.

The annual U.S. energy demand for the early 1970s has been estimated at between  $12$  to  $15 \times 10^{12}$  kwh (after process losses).<sup>1</sup> Theoretically, a desert area of 50 miles by 50 miles would receive this equivalent energy each year. A desert area of 30 miles by 30 miles (equal to 85 percent of Rhode Island) would receive enough solar energy to meet U.S. conventional energy demands in the early 1970s. While these hypothetical examples provide a perspective of the intensity of solar energy available compared to total national energy requirements, they are misleading. Available solar energy conversion devices have nominal conversion efficiencies of 10 percent for photo-

voltic solar cells or thermionic devices and less than 70 percent for water and air heating panels.

Thermal electric systems require high operating temperatures (about  $1,000^{\circ}\text{F}$ ) relative to ambient temperatures. Concentrator collectors can produce these temperatures, but collector heat losses increase as mean collector temperatures exceed ambient temperatures. Overall solar-thermal electric system efficiencies may be, at best, about like those of photovoltaic conversion efficiencies; that is the overall collector area requirements for a solar-thermal electric plant will be nominally the same as those for a photovoltaic system to produce the same power.<sup>1</sup>

The most important near-term applications of solar energy include:

- Direct solar heating and cooling.
- Thermal generation of electricity.
- Photovoltaic generation of electricity.

<sup>1</sup> B. J. Brinkworth, *Solar Energy for Man*, 1972, Sections 1.5 to 1.6 and p. 240.

## TERRESTRIAL SOLAR ENERGY CHARACTERISTICS

The sun is neither a continuous nor a constant source of energy. Relative to any point on earth, the sun rises in the east, crosses the sky at  $15^{\circ}$  per hour, and sets in the west. On any day, the sun reaches a maximum altitude at mid-day, depending on the season of the year. Because of the earth's  $23\frac{1}{2}^{\circ}$  tilt, the solar altitude in the northern hemisphere is at its highest on June 21 and its lowest (at mid-day) on December 21. Correspondingly, the number of daylight hours available at the peak of summer are proportionally greater than the number of daylight hours at the peak of winter.

Solar radiation is usually measured in Langleys per minute or Langleys per day. A Langley of radiation energy is equivalent to one calorie of heat per square centimeter.

Approximately 700 stations in the world continuously record solar radiation intensity. These stations measure direct and scattered radiation on a horizontal surface. About 100 stations record radiation received on a surface maintained normal to the sun. However, most available solar radiation charts indicate the diffuse and normal intensity incident on a stationary, horizontal surface. A typical average solar radiation level for temperate regions is one Langley per minute for a surface tilted toward the sun on a clear day. This level of solar intensity can result in an accumulation of 500 Langleys for a

Table XVII-1  
COMMON SOLAR ENERGY INTENSITY  
CONVERSION FACTORS

1 Langley/min	=	1 cal/(cm <sup>2</sup> · min)
	=	221 Btu/(ft <sup>2</sup> · hr)
	=	0.700 kw/m <sup>2</sup>
Assuming 500 min/day of solar radiation,		
1 Langley/min	=	500 Langleys/day
	=	500 cal/(cm <sup>2</sup> · day)
	=	1841.7 Btu/ft <sup>2</sup> · day)

500-minute day (approximately eight hours). Table XVII-1 shows some useful energy conversions.

Regions between  $15^{\circ}$  and  $35^{\circ}$  latitude either side of the equator receive the greatest amount of solar energy with a minimum mean radiation of 500 Langleys per day. The southern United States, Mexico, Hawaii, India, Saudi Arabia, southern China and northern Africa all fall in the maximum solar energy band in the northern hemisphere. Australia, southern Brazil and southern Africa fall in the

corresponding maximum solar energy band in the southern hemisphere.

The equatorial belt between  $15^{\circ}$  N and  $15^{\circ}$  S receives between 300 to 500 Langleys per day throughout the year, which is somewhat less than the tropical regions receive. This equatorial belt includes the East Indies, southeast Asia, Central America, northern Brazil and central Africa.

Between  $35^{\circ}$  and  $45^{\circ}$  latitudes, radiation can average 400 to 500 Langleys per day during the summer; however there is a significant seasonal drop in solar intensity during the winter. The seasonal variation can be reduced by utilizing collectors that are maintained normal to the sun. Falling in this moderate solar energy band is most of the continental United States, southern Europe, the Mediterranean Sea, Japan and most of the People's Republic of China.

Regions north of  $45^{\circ}$  N receive a limited amount of annual solar energy, which is particularly low in winter months. This region of limited solar energy includes northern Europe, Scandinavia, Alaska, most of Canada and most of the Soviet Union. In those latitudes, half the total annual solar radiation may be diffuse with a higher proportion of diffuse energy in the winter than in the summer. Also, at those high latitudes, the maximum solar altitudes are low, particularly in winter; consequently, vertical surfaces facing the equator can receive greater amounts of solar energy than can horizontal surfaces. In Hamburg, West Germany, for example, solar radiation falling on a southfacing vertical surface can be over two and one-half times that falling on a horizontal surface.

Another form of solar radiation is that which is reflected from the ground, particularly from snow or water, and long wavelength infrared radiation released by warm ground temperatures to a cooler atmosphere. The reflected sunlight, known as albedo, may be an important factor in using solar heating in certain locations.

Many environmental factors affect the average solar energy that the earth receives in any given location. Cloud cover interferes with solar radiation; the solar intensity on mountaintops above the clouds normally would be greater than that in a neighboring valley, and a foggy location near the sea would receive diminished solar energy. Air pollution also severely limits the amount of solar radiation received.

Long-range weather characteristics, such as cloudy day sequences in northern regions, constitute important statistical information that can affect the design of solar energy systems. In locations such as New England, where up to 10 successive days of cloud cover may occur, large-capacity thermal storage systems may be required if solar energy is to be used as a primary heating system.<sup>1</sup>

Figure XVII-1 shows the annual or seasonal solar

energy intensity characteristics of specific regions. Other more specific insolation data has been published in *Solar Energy*.<sup>2</sup> These maps indicate the amount of energy that falls on a horizontal surface, a common measurement of solar energy intensity. However, this kind of statistic information is only a very preliminary indicator of available solar energy.

Figure XVII-2 indicates the variation in solar energy that occurs through the seasons based on measurements of various directional orientations at a New England latitude. The measured solar intensities for various months of the year as shown in Figure XVII-2 indicate that orientation of the collector panels critically affects the amount of convertible solar energy available during a given season. This figure indicates that a horizontally oriented collector receives less than one-half the solar energy that a southfacing vertical collector receives in December. Either orientation is similar in performance in March and September; consequently, if the primary function of a solar collector is to provide heat for late fall, winter and early spring months, then vertically oriented collectors would be more useful for New England latitudes.

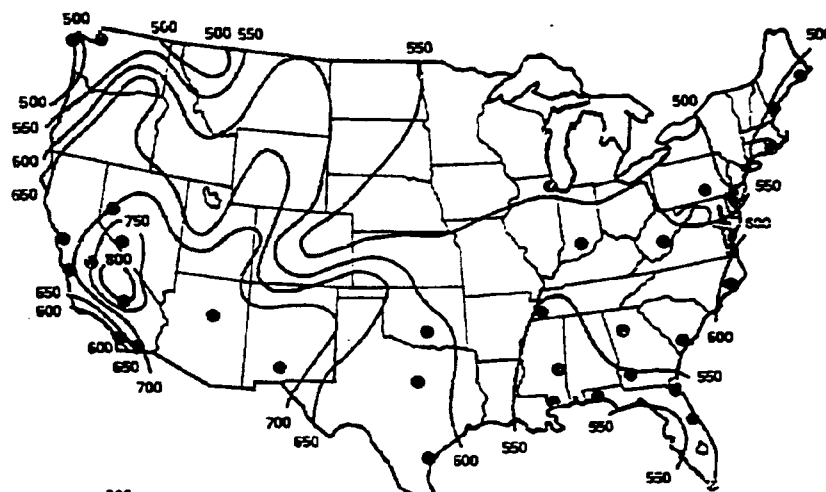
Empirical data indicating solar intensity on vertical surfaces or other selected orientations is limited. However, the solar intensity on a vertical or inclined surface can be derived from horizontal surface intensities through trigonometric relationships between the receiving surface and the sun's rays. The inclined surface intensities calculated by geometric relationships have been developed to compensate, to some extent, for clouding, albedo, and diffusion effects. Empirical performance has been correlated with the mathematical models developed resulting in a firm basis for estimating the solar intensity on any southfacing inclined surface. The hourly intensities derived from these models can be summed to result in expected daily insolation levels. The mean daily insolation can then be estimated for any month. The characteristic solar intensity levels of a given region directly affect the collector size required to generate the desired heat or electrical energy. The physical practicality and the economic justification for purchasing a collector are closely related to minimizing collector size and optimizing orientation for a maximum of energy conversion.<sup>3</sup>

<sup>1</sup>Farrington Daniels, *Direct Use of the Sun's Energy*, Chapter 3, 1974.

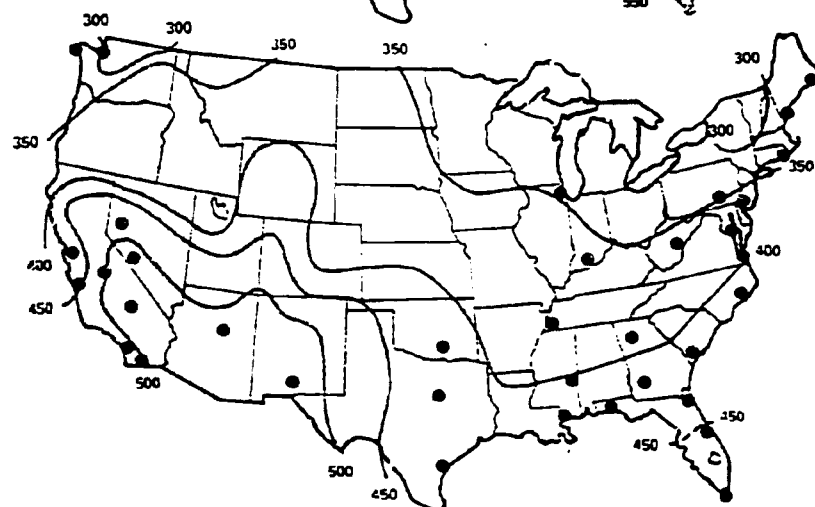
<sup>2</sup>Ivan Bennett, "Monthly Maps of Mean Daily Insolation for the United States," *Solar Energy*, IX, 3, 1965.

<sup>3</sup>B. Y. H. Liva and R. C. Jordan, "A Rational Procedure for Predicting the Long-Term Average Performance of Flat-Plate Solar Energy Collectors," *Solar Energy*, VII, 2, 1963.

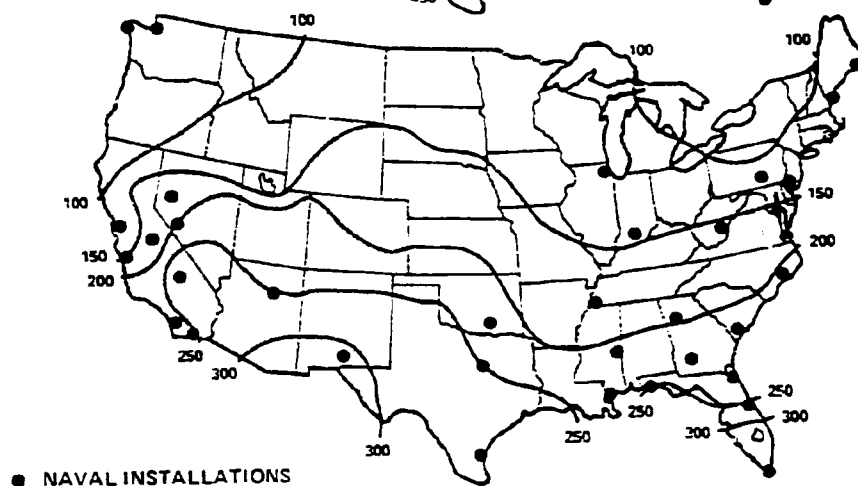
MEAN DAILY  
SOLAR RADIATION  
(LANGLEY/DAY)  
JUNE



MEAN DAILY  
SOLAR RADIATION  
(LANGLEY/DAYS)  
ANNUAL



MEAN DAILY  
SOLAR RADIATION  
(LANGLEY/DAY)  
DECEMBER

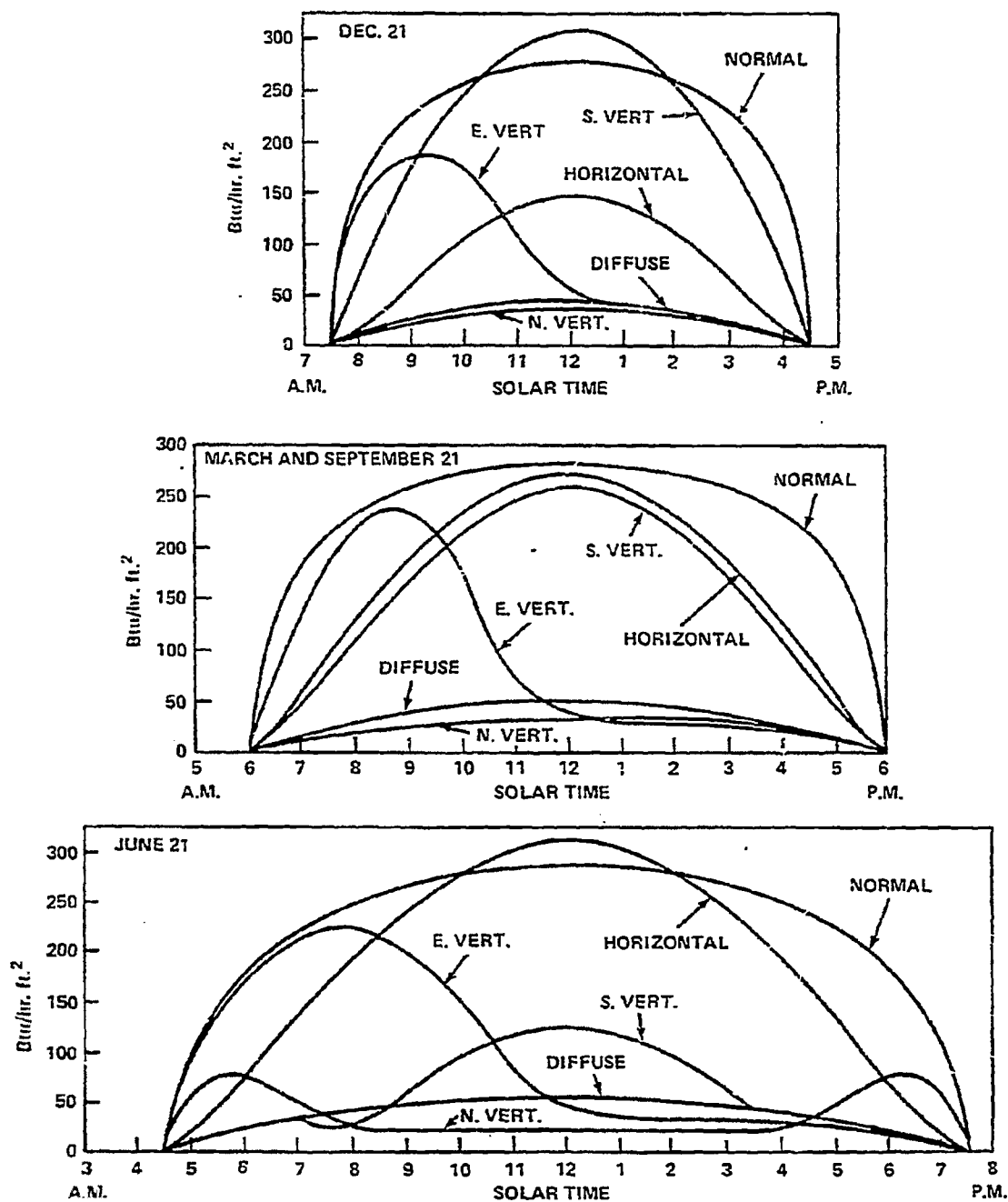


● NAVAL INSTALLATIONS

Source: *Solar Power*, IX, 3, 1963.

Figure XVII-1. SOLAR ENERGY DISTRIBUTION IN THE U.S.

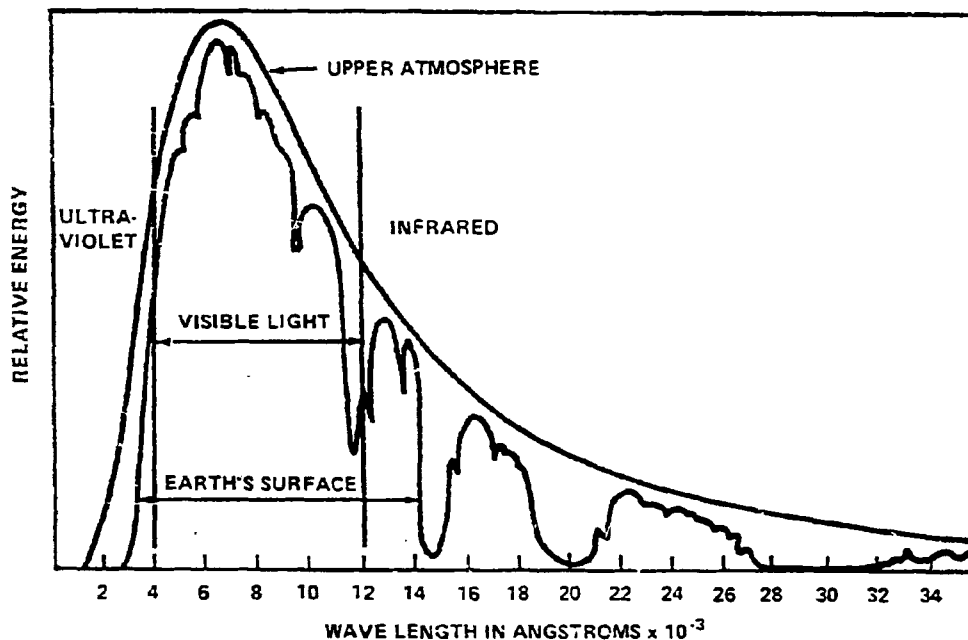




Incident solar energy on clear days, latitude 42° N. (Reported by I. F. Hand, U.S. Weather Bureau, Milton, Mass., January, 1950.)

Source: I. F. Hand, U.S. Weather Bureau, Milton, Mass.

Figure XVII-2. INCIDENT SOLAR ENERGY ON CLEAR DAYS  
IN NEW ENGLAND, LATITUDE 42° N



Source: Eppler Laboratory, Inc., Newport, R. I.

Figure XVII-3. SOLAR ENERGY SPECTRUM

### SOLAR ENERGY MEASURING DEVICES

Several types of instruments are available for measuring and recording the characteristics of solar energy. To measure solar intensity as a function of wavelength, as shown in Figure XVII-3, requires the use of fairly sophisticated equipment. A few of the less complex devices used to measure broadband intensity are listed in Table XVII-2. In addition, photovoltaic cell instruments can also measure solar intensity, but some care must be taken in using these instruments because they do not respond to the entire solar spectrum.

**Actinometer.** An actinometer is a solar radiation measuring instrument. The term is applied to certain designs of both pyranometers and pyrliometers.

**Pyranometer.** The pyranometer is an instrument intended mainly for measurement of total solar radiation received on a horizontal surface—direct and diffuse solar radiation. Diffuse solar radiation can best be understood by considering what a light coating of frost does to an automobile windshield. Without the frost, sunlight comes in from one direction; with frost, however, the entire windshield lights up, blocking vision in other directions. Sunlight has been reflected and scattered all across the windshield. If we were trying to collect sunlight through

the clear windshield, we would need only concern ourselves with the direct path; if, however, the sunlight were passing through the frosted windshield, we would collect only a small portion of the sunlight by focusing directly toward the sun, and much more could be collected if we were to gather in the diffuse light from the entire windshield.

Clouds and haze in the atmosphere have similar effects on sunlight. In southwestern United States, where clear days are numerous, solar collectors that focus light from a point source (the sun) work best. However, in areas of the country where the sun is not seen so often, most of the solar energy is diffuse.

A pyranometer consists of a thermopile<sup>1</sup> detector, a case in which this unit is mounted, and a pair of concentric glass hemispheres. It compares the heating produced by radiation on blackened metal strips with that produced by an electric current. The unit is also sometimes called a solarimeter.

<sup>1</sup>A thermopile is an array of thermocouples connected either in series to produce a higher voltage or in parallel to produce a higher current output.

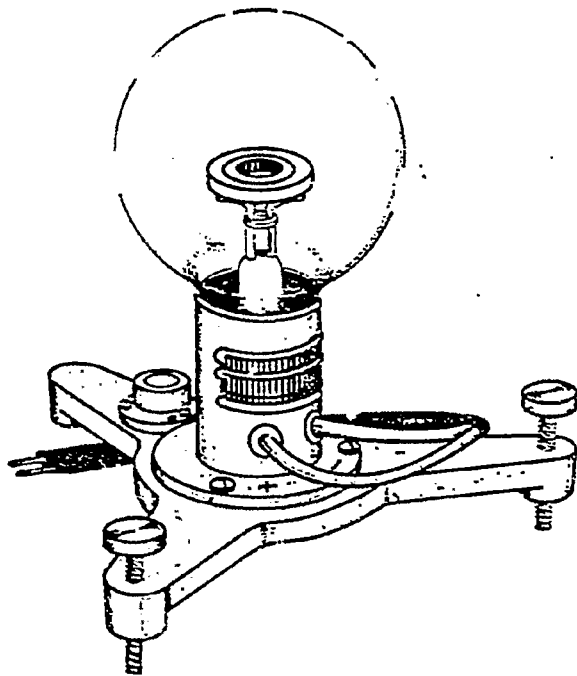


Figure XVII-4. PYRHOLIOMETER

*Pyrliometer.* The instrument that measures the direct solar radiation on a surface normal to the solar beam is called a pyrliometer. This name is sometimes loosely used by instrument manufacturers to describe instruments that measure total solar radiation but that are actually pyranometers. Absolute pyrliometers are calorimeters, and secondary pyrliometers are thermometers. Several different designs have evolved since pyrliometers were first introduced. A typical construction for a contemporary design is shown in Figure XVII-4. The activated unit consists of two rings of equal area, one black and the other white, connected by a thermocouple to produce an electromotive force proportional to the intensity of solar radiation. A true or normal incident pyrliometer would use this instrument with a tube to block all light except that coming straight in, as shown in Figure XVII-5.

Table XVII-2  
SOLAR MEASUREMENT DEVICES

Device	Measurement
Normal incident pyrliometer	Direct
Hemisphere pyranometer with an occluding disc	Diffuse
Hemisphere pyranometer	Total (direct plus diffuse)

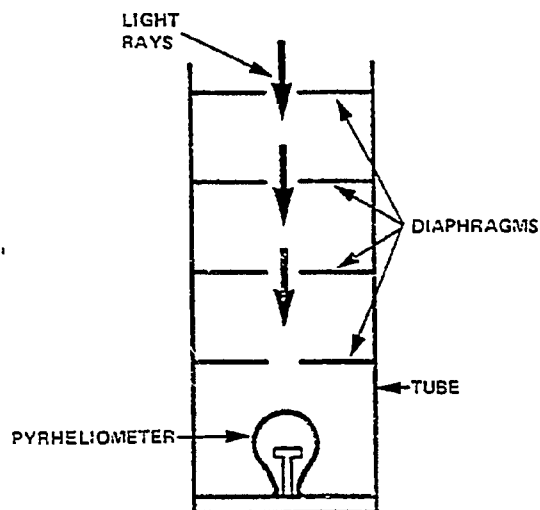


Figure XVII-5. NORMAL  
INCIDENCE PYRHOLIOMETER

## SOLAR ENERGY FLAT-PLATE COLLECTORS

The simplest and most readily available type of solar energy collector is a large black surface that converts short wavelength solar radiation to long-wave heat radiation. The heat is conducted from the collector to air or

water, which can then be used for space heating or for producing hot water for a variety of applications.

A typical flat-plate collector is illustrated in Figure XVII-6. A large flat plate of sheet metal is painted black

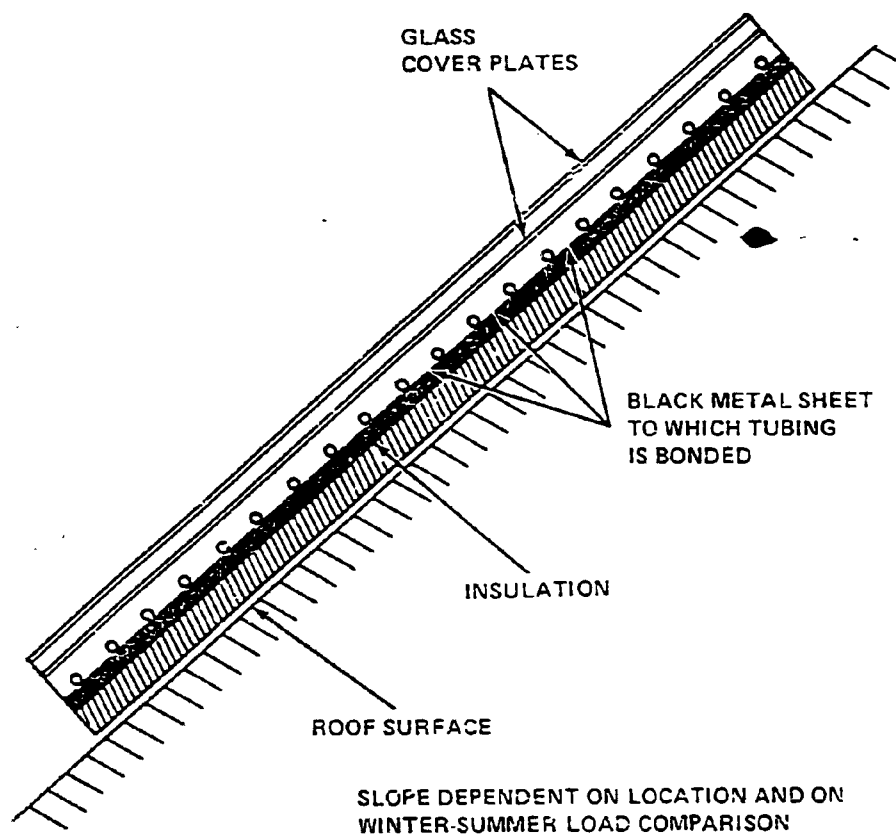


Figure XVII-6. SOLAR ENERGY FLAT-PLATE COLLECTOR

on the side that will face the sun. Tubing bonded to the sheet metal circulates water to the plate, which collects heat conducted from the plate. The flat plate is enclosed in an air-tight chamber, which is covered with at least one pane of clear glass (or plastic) so that short-wave solar radiation can pass easily through the transparent covering. The black surface will tend to convert the short-wave solar radiation to long-wave infrared radiation, which is emitted from the black surface. The glass coverings are poor conductors of heat, which trap the infrared radiation and, therefore, reduce heat loss from the flat-plate collector. Flat-plate collectors can produce water temperatures of 150° F to 200° F under normal solar intensity, and temperatures approaching boiling are feasible on exceptionally hot days.

As solar radiation is converted by the flat-plate collector, a steady-state temperature is reached where the rates of heat recovery and loss are balanced by heat gain. Heat loss by convection to the surrounding air increases as wind velocity increases particularly at high collector

temperatures. Radiation losses also increase with high collector temperatures. Transmission losses through the glass-pane covers can be 15 to 20 percent. Between 80 and 95 percent of the solar energy passing through the glass pane covers can be absorbed. By using two or three layers of glass covering and insulating the panel, convection and conduction losses can be minimized. Selective surfaces with emissivities as low as 0.15 have been developed; therefore, infrared radiation losses could be reduced to 15 percent of the heat absorbed. Using optimistic performance factors, an overall collector efficiency of 68.5 percent may be achievable. However, practical commercial designs, which must keep material costs to a minimum, result in overall efficiencies considerably less than 50 percent.<sup>1</sup>

The flat-plate collector can convert both diffuse solar energy, which is generally omnidirectional, and direct

<sup>1</sup>Walter E. Morror, Jr., "Solar Energy—Its Time Is Near," *Technology Review*, December 1973, pp. 31-43.

solar radiation. Meteorological data which distinguishes the diffuse portion from the direct solar energy incident on a horizontal surface is available. In the northern latitudes, the diffuse energy can be a significant portion of the average solar energy available in winter months. Consequently, for flat-plate performance calculations, the diffuse energy for any region must be determined in calculating panel efficiency.

The amount of normal radiation that a flat-plate collector can convert to heat depends on panel orientation. A panel normal to the sun's rays will accumulate a maximum of available solar energy for a given size. However, since flat-plate collectors can convert diffuse radiation without the complicated mechanisms required to track the sun's path, they are usually fixed in inclined positions facing south to collect diffuse energy and a maximum practical portion of the available direct solar energy. Fixing the position of the flat-plate collector simplifies design but compromises the total daily energy that can be accumulated from solar radiation. Although mathematical models have been developed to determine normal radiation for a given orientation, a south-facing, fixed-position collector generally should be oriented for a compromise solar altitude that would convert solar energy to usable heat with reasonable effectiveness over as much of winter as practical. Where solar energy is to provide heat to a

dwelling in the winter, the collector should be tilted at the angle of the latitude plus  $15^\circ$ . However, if the primary function of the collector is to provide air cooling through an absorption air conditioning system in summer, the collector should be tilted at latitude minus  $15^\circ$ .

When the incidence angles to a collector surface are very high at certain periods of any day, much of the energy is lost by the reflective characteristics of the covering glass panes set at an oblique angle. Double panes reflect approximately twice the energy of a single pane at any angle of incidence. Consequently, where light strikes a flat-plate collector with single or double glass pane covers at incident angles greater than  $70^\circ$  or  $80^\circ$ , approximately 40 percent of the light energy is lost. During early morning and late evening hours, normal solar intensities are very low. A south-facing collector will receive these very weak solar energy levels at high incident angles. Therefore, much of the normal solar energy at the extreme hours of the day is lost. However, the normal energy component of the oblique rays can contribute cumulatively to the total daily solar energy that may be converted by a flat-plate collector. Orientation losses and transparent-covering reflection losses should be considered in estimating the daily energy accumulation performance of a given collector size.

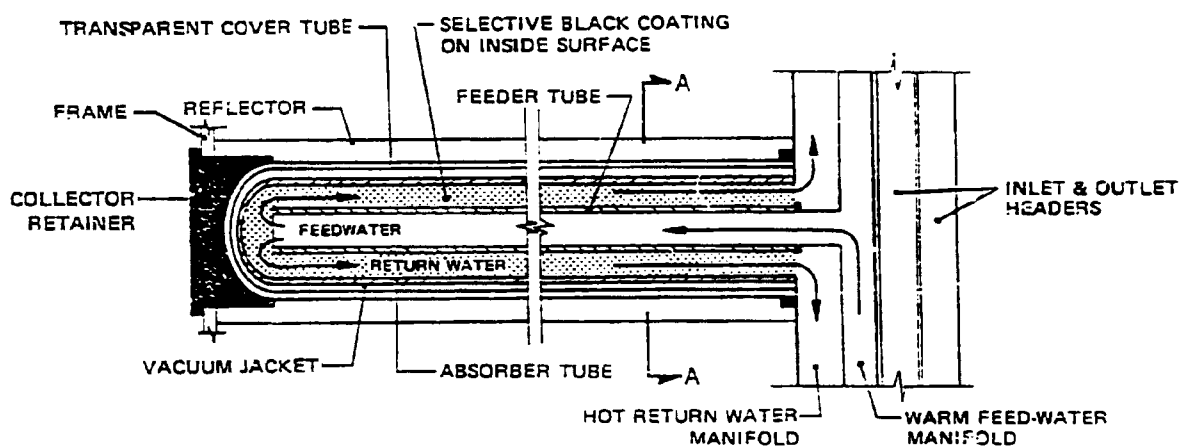
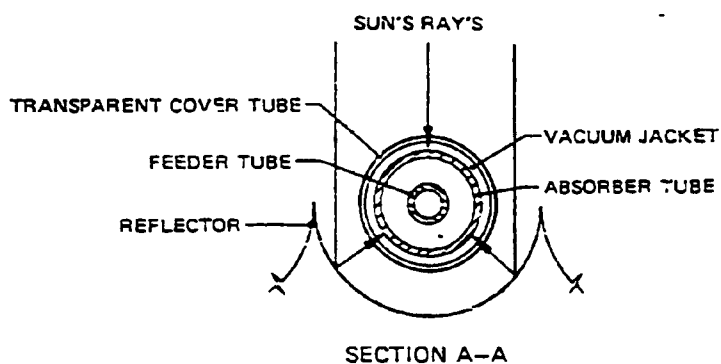
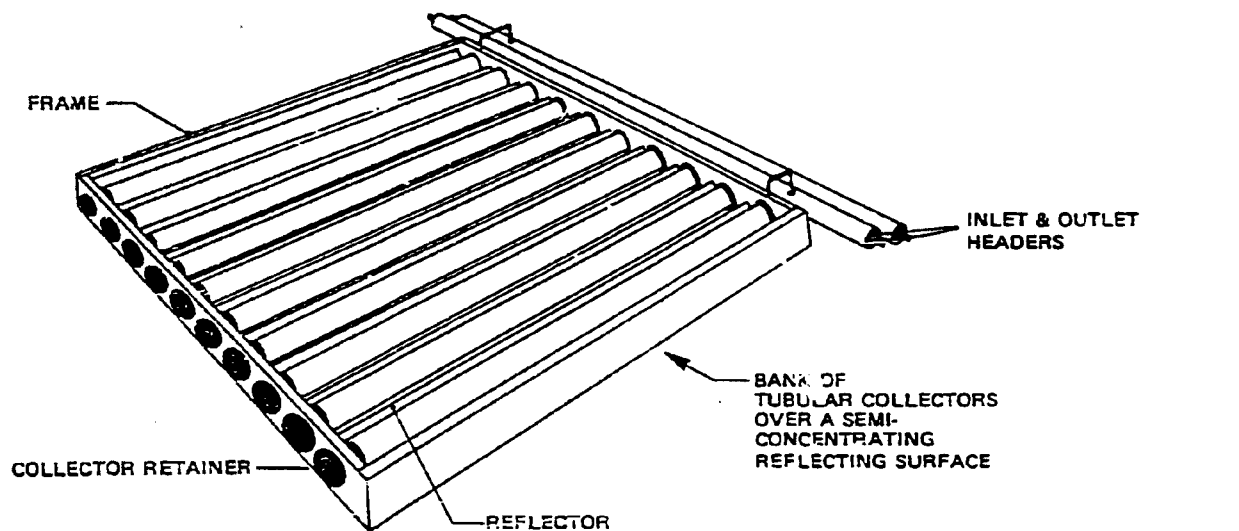
## SOLAR ENERGY TUBULAR COLLECTORS

The tubular collector, another type of solar collector, is still in the developmental stage. Commercial production of tubular collectors is expected to begin in one or two years. The tubular collector is made of three concentric glass tubes, using manufacturing techniques similar to those for fluorescent light tubes. (See Figure XVII-7.) The feeder tube is the innermost cylinder; the absorber tube surrounds it; and the cover tube is outermost. The transparent cover tube allows light to pass to the absorber tube through the evacuated space between the tubes. The absorber tube has a selective surface coating which enables it to absorb energy from the sun. The collector fluid flows in through the feeder tube and collects heat from the selective surface of the absorber tube as the fluid returns between the tubes.

Because of its tubular construction, high vacuum, and

selective coating, the tubular collector can produce temperatures above  $240^\circ\text{F}$ , with greater efficiency than flat-plate collectors. Low ambient temperatures and high winds have minimal effects on tubular collector performance because of the vacuum insulation. Also, the tubular symmetry and low loss coefficient enable these collectors to heat fluids to useful temperatures for longer periods of the day and under more diffuse conditions.

Tubular collectors are placed on trough-shaped reflective backgrounds to increase performance. Each tube the collector panel rests in a shallow aluminum parabolic trough providing a moderate degree of concentration without having to track the movement of the sun. The reflective surface directs more of the sun's diffuse and direct rays to the tubular collector than a flat reflective background.



CUT-AWAY SECTION OF A TYPICAL TUBULAR COLLECTOR

Figure XVII-7. TUBULAR COLLECTOR

## FLAT-PLATE AND TUBULAR COLLECTOR PERFORMANCE

Figure XVII-8 shows thermal performance curves for solar collectors. These curves are used to estimate collector size to match insolation levels and heating demand. The parameter of the abscissa,  $T_f - T_a/I$ , is dependent on ambient temperature,  $T_a$ ; mean collector fluid temperature,  $T_f$ ; and solar insolation level,  $I$ . The abscissa is measured in international system units (SI units) as well as English units. Much insolation data and national heating and cooling statistics are in English units; consequently, English units are the most practical reference units until the U.S. Weather Bureau and the American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE, Inc.) convert their extensive national statistics into international system units. (Since SI is becoming widely used in technical literature, the SI scale is shown for reference in Figure XVII-8.) Collector efficiency is the ratio of the heat collected to the incident energy on a unit area of the collector. Not all manufacturer's collector performance characteristics are depicted as shown in Figure XVII-8; however, National Bureau of Standards (NBS) uses this performance notation and most published performance characteristics can be translated into these parameters.

Typical design regions are indicated in Figure XVII-8. By regulating fluid flow, a solar collector should be able to produce temperatures greater than 140° F if it is to provide water heating or to supply heat to a water tank for thermal storage for a space heating system. At a solar insolation of one Langley per minute (221 Btu/ft<sup>2</sup> hr) and a winter ambient temperature of 40° F,  $(T_f - T_a)/I = 0.45^\circ \text{F hr ft}^2/\text{Btu}$ . Notice that at 140° F, the efficiency of a tubular collector system slightly exceeds that of a flat-plate collector. A solar collector which heats air under similar conditions may produce temperatures of approximately 100° F during winter months; at lower output temperatures, the flat-plate collector is more efficient than a tubular collector.

The overall efficiency of cooling systems will tend to increase as heat source temperatures increase. Consequently, the goal for solar cooling system design is to provide temperatures well in excess of 200° F from the solar collector. At higher output temperatures, the tubular collector can perform at much higher thermal efficiencies than a flat-plate collector. Based on these performance characteristics, tubular collectors appear to be more versatile; they can perform as well as flat-plate collectors for heating water in all seasons and yet produce the higher temperatures for efficient solar cooling in the summer. However, tubular collectors are relatively new and un-

proved. The cost of tubular collectors has been estimated at \$25 per square foot, which is more than twice the cost of higher grade flat-plate collectors.

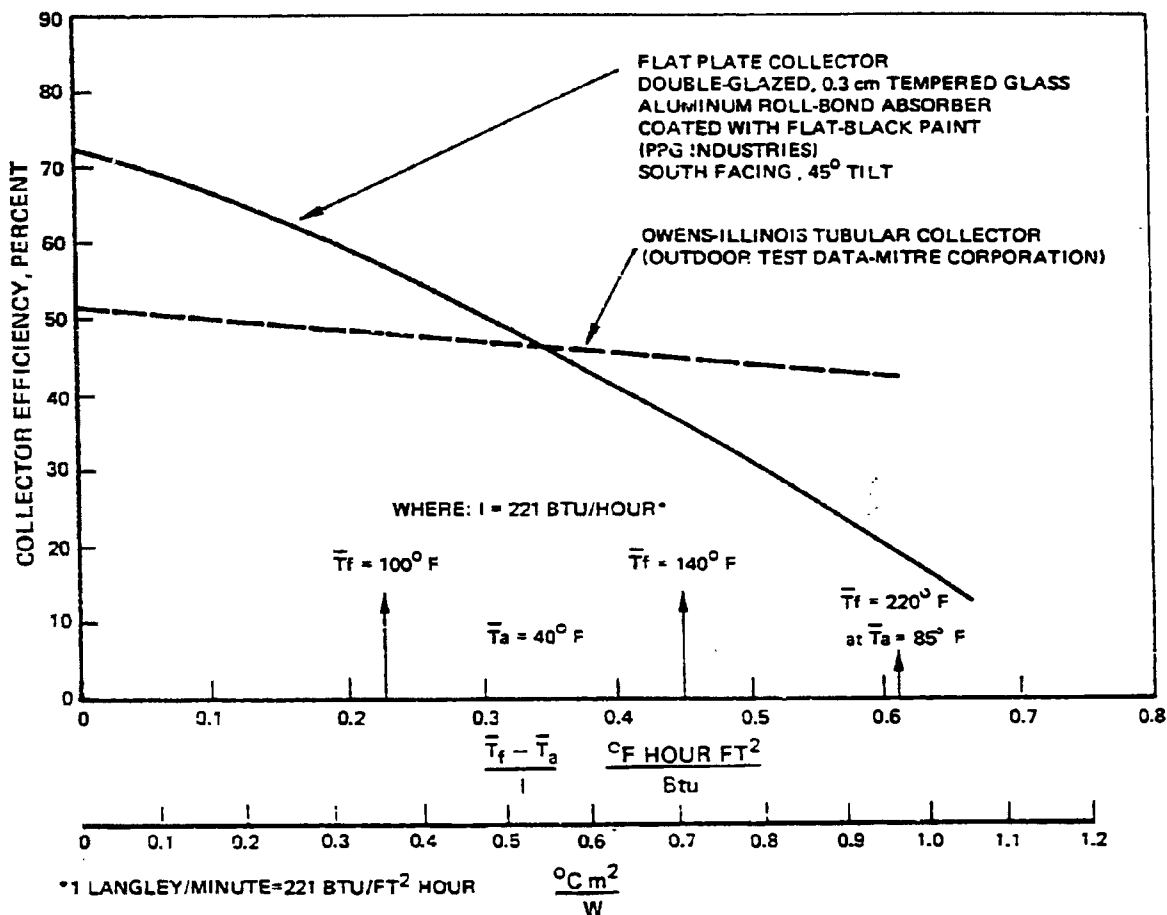
Tubular collectors and high grade flat-plate collectors capable of producing working fluid temperatures above 200° F in summer may be configured to provide total, or nearly total, year-round residential comfort conditioning in a configuration illustrated in Figure XVII-9. This rather elaborate installation includes special system components such as large thermal storage tanks, two-loop hot water heaters, and absorption air conditioning units. Each of these component options adds to the initial capital cost of a solar system. As the total system initial cost increases, payoff periods may extend well beyond ten years. Consequently, a high-grade solar conversion system, depicted in Figure XVII-9, may provide a large portion of winter space heating, summer cooling, and year-long water heating—possibly over 75 percent of a residence's total annual energy requirements. But the system may not pay for itself in fuel savings in less than 15 years.

Air heating collectors produce low temperatures and, therefore, should operate at the higher collector heating value; they may be operated with limited thermal storage in a bed of crushed rock. Although air systems are limited to space heating, they are simple and inexpensive compared to the more elaborate water heating systems. Because of their low initial cost, simple air heating systems pay for themselves in a shorter time, but they provide smaller portion of the overall heat demand.

The selection and sizing of a solar system for any application is a complex procedure which must account for many factors. A few of the many considerations in comparing various solar collector types and systems can be deduced from the performance curves in Figure XVII-8.

A step-by-step approach for estimating the size and cost of a solar collector system based on the use of the performance curves of Figure XVII-8 has been published by the Civil Engineering Laboratory of the Naval Facilities Engineering Command. Their report, *Solar Heating of Buildings and Domestic Hot Water* (Technical Report No. R835, January 1976, by E. J. Beck, Jr. and R. L. Field) is based on design procedures developed by leading authorities in solar energy conversion.<sup>1</sup>

<sup>1</sup>S. A. Klein, et al., "A Design Procedure for Solar Heating Systems," *Solar Energy*, V 18 (1976), pp. 113-127.



Source: Civil Engineering Laboratory, Naval Facilities Engineering Command,  
Technical Report No. R235, January 1976.

Figure XVII-8. FLAT-PLATE AND TUBULAR COLLECTOR  
PERFORMANCE CHARACTERISTICS

## SOLAR COOLING

Solar cooling systems have the advantage that demand and supply tend to be in phase. When the sun shines hottest, the need for refrigeration and air conditioning is greatest. Cooling units that are being considered for integration with solar collectors to provide space cooling include absorption cycles, organic Rankine cycles, and desiccant absorption units. Solar powered systems for space cooling require a refrigeration or cooling cycle that will give good performance at the relatively low temperature levels provided by low cost solar collectors, and equipment suitable for low-cost production and long life operation with minimum maintenance.

The efficiency or coefficient of performance (COP) of any air conditioning system is a function of maximum cycle temperature (the temperatures produced by the

solar collector or other heat source) and the condensing temperature. The greater the difference of these two temperature, the higher the COP. Tubular collectors and high-grade flat-plate collectors using selective surfaces and two or three transparent covers may be able to produce the cycle temperatures required for a relatively efficient and practical air cooling or dehumidification system.

Of the various cooling systems in consideration, the absorption cycle is being applied in several demonstration projects sponsored by ERDA. HUD solar driven organic Rankine cycles are under development and may not be available commercially for some time. However, active desiccant systems such as the Munters Environmental Control may be available for solar dehumidification and cooling in the near future.



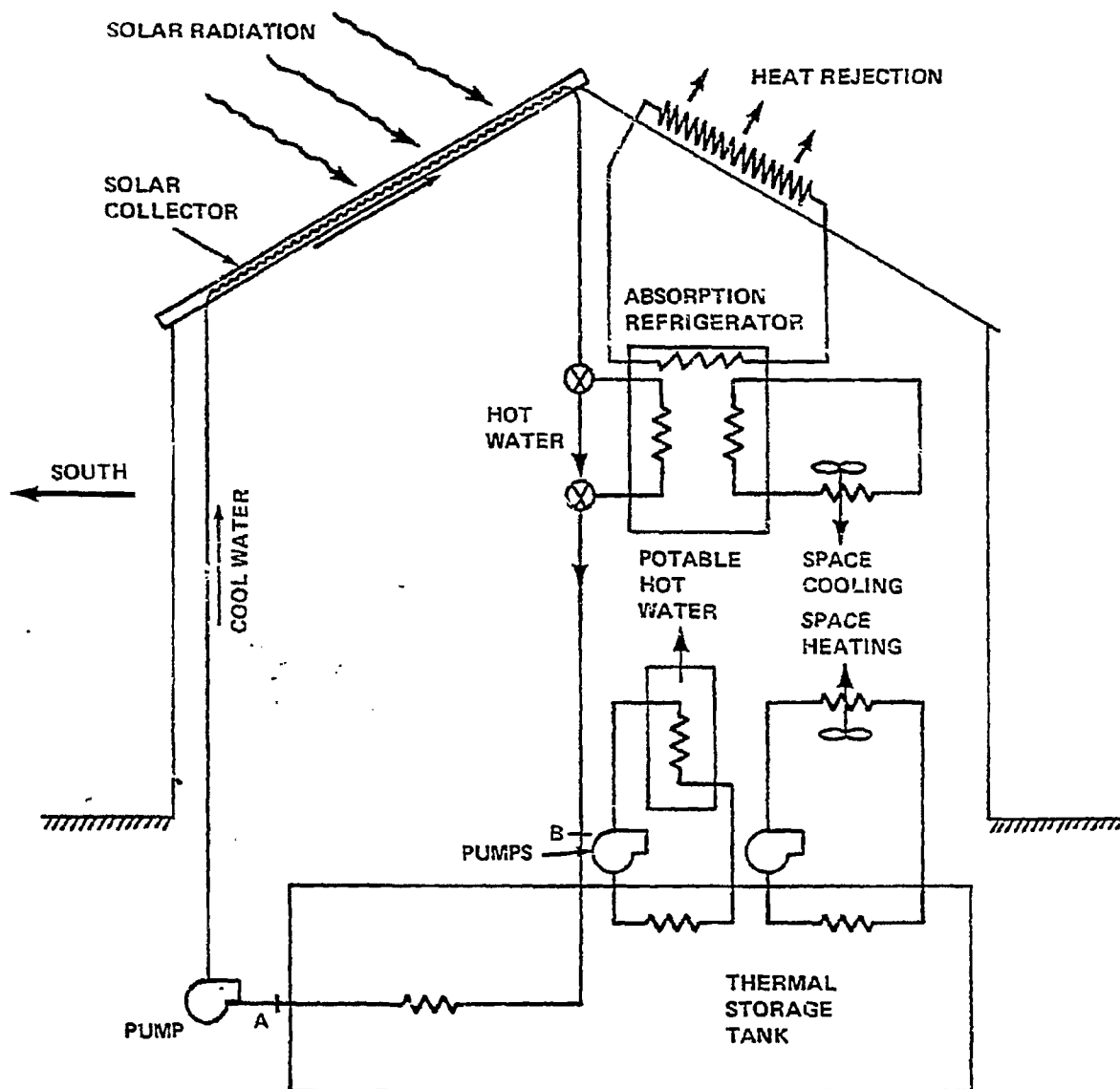


Figure XVII-9. HOUSEHOLD SOLAR HEATING AND COOLING SYSTEM

### LOW-TEMPERATURE ENERGY STORAGE

The flat-plate collector used for residential space heating, Figure XVII-9, utilizes a storage system that provides a day or two of heating capacity to compensate for night-heating requirements and overcast conditions. Thermal storage systems may be either sensible-heat storage or latent-heat storage types. Sensible heat storage

means heating a material and causing a temperature rise, then releasing the accumulated heat as the material cools to ambient temperature. Water has the highest specific heat (62 Btu/ft<sup>3</sup> °F) of any thermal storage material up to 200° F. Raising the temperature of 3 cubic feet of water (22.5 gallons) 100° F stores the heat equivalent of

one pound (~pint) of fuel oil (heating value ~18,600 Btu/lb). Crushed stone is an inexpensive material commonly used for storing sensible heat. Depending on how tightly the stone is packed, it can have a heat capacity of 5 to 36 Btu/ft<sup>3</sup> °F, about half the heat storage capacity of water. Other materials that could be used for sensible heat storage are not as cheap as water or crushed stone.

Another form of thermal storage utilizes the latent heat or phase-change properties of various compounds. Glauber's salt ( $\text{Na}_2\text{SO}_4 \cdot 10\text{H}_2\text{O}$ ) has high heat of fusion characteristics at transition temperatures of 90° F. These salts have a heat capacity of 9,700 Btu/ft<sup>3</sup> resulting from phase change. However, Glauber's salt cannot retain its heat for any practical length of time, and 24-hour storage of heat may not be feasible. Other materials displaying latent heat storage superior to Glauber's salt are available but usually at a much higher cost.

The cost of thermal storage systems is critical in the decision to adopt solar heating even when the cheapest materials are used. To meet average winter heating requirements of a dwelling usually requires use of most of the roof area for solar collectors. In January and February, residential heating requirements are considerably higher than the average winter heating load, and solar

intensity is at its lowest during those two exceptionally cold months. The high heat demand and the low solar intensity of the two coldest months amplify the size requirements of solar panels required. Because roof-size limitations restrict the amount of heat that can be collected practically from solar radiation during the coldest two months, very little or no reserve can be accumulated for overnight use. Solar heating must be supplemented with an electrical or fossil-fuel fired home heating system during exceptional demand. With the requirement for an auxiliary heating system, it becomes difficult to justify the capital investment for a thermal storage system with a capacity greater than the average overnight heating demand. Practical solar heating systems are sized for compromise conditions to accumulate possibly up to 24 hours of reserve heat during "average" winter heating and solar intensity months. A tank of 157 cubic feet of water elevated 100° F in temperature may be able to provide one day of reserve heat for a typical house. This 4.5x4.5x8 foot tank would require a large closet in a basement.<sup>1</sup>

<sup>1</sup> H. F. Hottel and J. B. Howard, *New Energy Technology. Some Facts and Assessments*, 1973.

## ECONOMIC CONSIDERATIONS FOR HEATING AND COOLING SYSTEMS

About half the energy consumed by residential, commercial, and industrial users is in the form of hot air, hot water, or low-quality steam.<sup>1</sup> A very large portion of this domestic energy demand could be met without particularly advanced development. Flat-plate collectors could produce nearly all of the energy required for individual residential heating requirements. The primary disadvantage of solar heating panels is their size. A one-floor house 30 by 30 feet in a central U.S. location would require approximately 500 square feet of collector area to provide 70 percent of winter space-heating and hot water requirements. Thermal storage by heating water would require a tank capacity of 750 to 1,000 gallons. The total system could cost from \$5,000 to \$15,000. Where electric heating is the alternative, \$500 to \$800 a year can be saved in fuel costs. Where oil heating is the alternative, \$200 to \$350 can be saved.<sup>2</sup> Consequently, solar heating may become economically competitive with electric heating in the near future as the cost of electric energy increases and as the cost of mass produced solar heating systems decreases.

In view of estimates that existing houses will provide approximately 50 percent of the housing needs in 2000,<sup>3</sup> newly constructed solar homes will probably not be able to contribute significantly to residential or building heating requirements for the near future. However, many

houses may be able to retrofit modular systems on existing roof surfaces. Panels of limited size could be installed on roofs or elsewhere on the property to provide possibly only 25 to 30 percent of winter heating requirements. If the scope of supplemental heating were kept within these limits, a home could be heated while the sun shines and no thermal storage system would need to be incorporated. With this approach, at least daytime heating requirements could be offset to some extent. The overall effect could be a significant reduction in annual heating requirements and costs by the individual homeowner. The initial capital cost of a limited-size panel then may be justified over a long-term fuel cost savings. As the cost of fuel for heating increases, individual houses, schools, commercial buildings, and factories may convert to limited solar heating to offset conventional fuel requirements. Several relatively portable units, some containing limited thermal storage, are currently being sold. Various commercial units are being introduced for residential application.

<sup>1</sup> *Exploring Energy Choices—A Preliminary Report*, Energy Policy Project of the Ford Foundation, 1974, pp. 1-4; S. David Freeman, "Energy," *The New Era*, August 1974, p. 206.

<sup>2</sup> "Solar Energy for Space Heating and Hot Water," ERDA Division of Solar Energy Pamphlet No. SE101, May 1976.

<sup>3</sup> S. David Freeman, "Energy," *The New Era*, August 1974, p. 206.

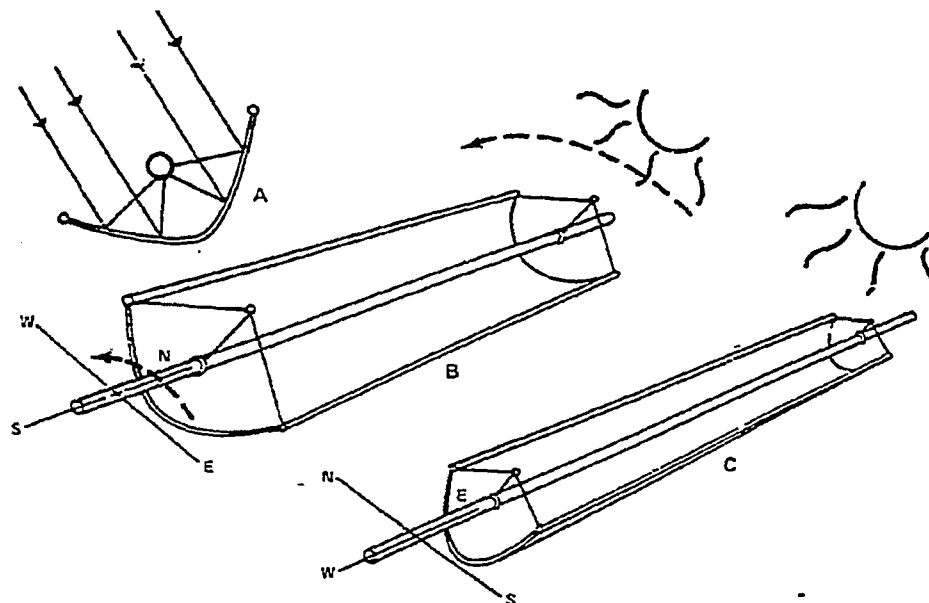


Figure XVII-10. PARABOLIC CONCENTRATOR CONFIGURATIONS

### HIGH-TEMPERATURE CONCENTRATOR COLLECTORS

A concentrator collector focuses the sun's energy on a relatively small area, creating very high temperatures at the focal point. The typical concentrator collector is a parabolic prism reflector with a heat absorbing pipe at the focal line. See Figure XVII-10. Water flowing through the collector pipe is heated to steam, which can be used to drive a turbine to produce power. Temperatures above  $4,000^{\circ}\text{C}$  can be generated by a parabolic collector; however, steam temperatures of only  $600^{\circ}\text{C}$  are required for the turbines used by electric utilities. Concentrator collectors can be configured to convert solar to electric energy.<sup>1</sup>

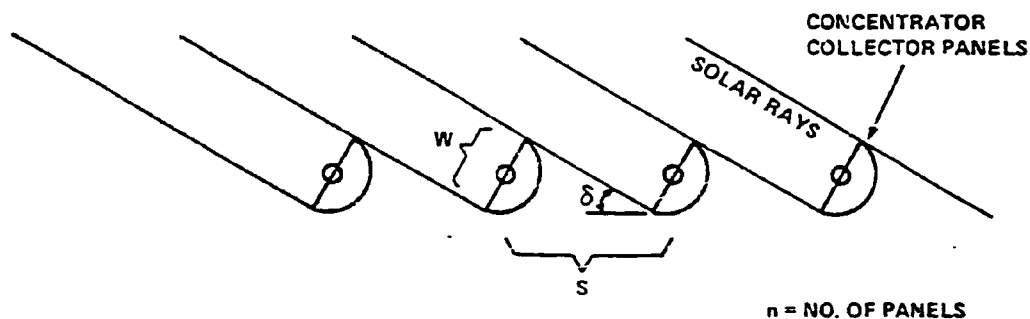
The collector pipe at the focal point of the parabolic concentrator reaches a steady-state temperature at which the rates of heat recovery and losses are balanced by the heat gain. As with flat-plate collectors, the highest collector efficiencies can be achieved when the concentrator collector temperatures approach ambient.

The concentrator collector cannot convert diffuse energy and must continuously face the sun if high conversion efficiencies are to be maintained throughout the day. Ideally, the line bisecting the concave angle formed by the parabolic prism (or a surface of revolution) collector must be parallel to all planes formed by the sun's rays to

maximize conversion of available normal radiation. A two-axis tracking collector can be mechanically synchronized by clockwork to follow the east-west travel of the sun and can be automatically adjusted to the sun's seasonal altitude changes. Although this is the most efficient concentrator collector configuration, it is the most complex mechanically. A practical compromise uses one-axis tracking, which will either pivot to east-west solar travel at a fixed inclination angle or pivot to altitude change about an east-west axis (B and C in Figure XVII-10). The one-axis tracking collector is simpler than the two-axis collector, yet can be designed to perform nearly as well for the high-intensity periods of the day.

A common solar power plant configuration using concentrator collectors is illustrated in Figure XVII-11. Banks of parabolic concentrators would be used to "farm" a large area of solar energy to produce the large quantity of steam required to drive a major electric utility.

Another common solar power plant configuration is the tower collector shown on Figure XVII-12. In this configuration, a large area of two-axis flat reflectors are coordinated to direct sunlight to a central collector where the solar energy is further concentrated to produce the high-cycle temperatures required of an efficient thermal



FOR  $\delta = 30^\circ$ ,  $S = 2w$

THEREFORE, FOR PANEL LENGTH  $L$ , TOTAL PANEL AREA,  $A_p = nwL$ .  
HOWEVER, TOTAL PLAN AREA BECOMES:

$A_o = nLS$ , FOR  $n \gg 1$ ; THAT IS, FOR  $n > 20$ .

(FOR SMALL  $n$ , ON AREA =  $LS$  CAN BE DEDUCTED FROM THE  
GENERAL EQUATION FOR  $A_o$ .)

Figure XVII-11. SOLAR FARM AREA RELATIVE TO COLLECTOR AREA

power plant. These solar farms would require large land areas to provide central-station power levels. A 1,000 MW(e) continuous-duty power station would require a collector area of 16 km<sup>2</sup>, assuming a steam system efficiency of 25 percent. However, banks of collectors on a solar farm will tend to shade each other during early morning and late evening hours when solar incident angles are very oblique. Consequently, if full collector utilization is to occur at solar altitude angles of 30 degrees or more, collectors will have to be spaced at least one panel apart, as shown on Figure XVII-11. As a result, the land area required can be double the collector area required if collector effectiveness is to be maximized for full-day solar energy conversion. The 1,000 MW(e) power station would therefore require approximately 32 km<sup>2</sup>, which is over 11 square miles. The reflectors of the tower top concentrating configuration in Figure XVII-12 are subject to the same spacing and plan area requirements of parabolic collectors.<sup>1</sup>

Because daytime peak loads of a typical power station are nearly twice as high as the continuous base loads,<sup>2</sup> a 1,000-megawatt solar plant may be more practical in off-setting some part of the daytime peak power require-

ments. Used this way, the solar plant would not have to be oversized to produce the storable energy for operating continuously during dark or overcast hours. A 1,000-megawatt intermittent load plant would require a collector area of approximately 8 km<sup>2</sup> (assuming a solar intensity of 1 Langley/min, a collector efficiency of 70 percent and a steam plant efficiency of 25 percent). The 16 km<sup>2</sup> land area required would be one-half that required for a continuous duty 1,000-megawatt plant. The overall area conversion efficiency of this example would be 17.5 percent, based on relatively optimistic assumptions. With more realistic collector efficiencies of less than 50 percent, overall area conversion efficiencies of the solar thermal powerplant will be less than 12 percent, which is only roughly competitive with photovoltaic area conversion efficiencies. The intermittent load solar powerplant would operate only when sufficient solar energy were available to supplement power requirements.

<sup>1</sup>Walter E. Morror, Jr., "Solar Energy—Its Time Is Near," *Technology Review*, December 1973, pp. 31-43.

<sup>2</sup>Federal Power Commission, *The 1970 National Power Survey, Part 1*, 1971, Chapter 3.

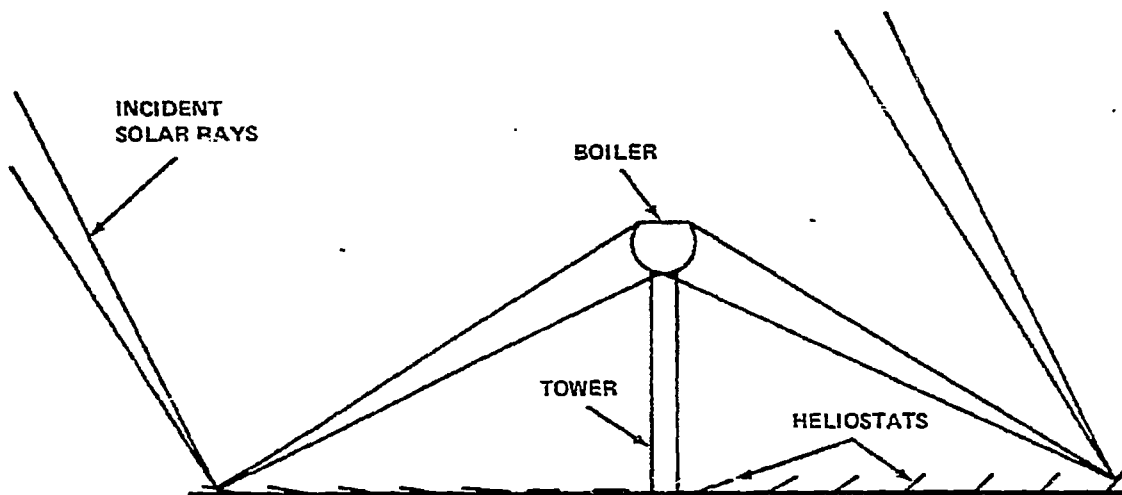


Figure XVII-12. TOWER TOP COLLECTOR

## HIGH-TEMPERATURE STORAGE

Energy storage systems used with concentrator collector powerplants are similar to those described for flat-plate collectors. However, efficient steam turbine generator systems require steam at  $600^{\circ}\text{C}$  ( $1,100^{\circ}\text{F}$ ). Scrap iron and magnetite (iron ore) are sensible-heat storage materials capable of storing thermal energy at these high temperatures.<sup>1</sup> A thermal storage tank filled with a large number of small iron pieces heated to  $1,500^{\circ}\text{F}$  will have a heat capacity of approximately  $20,000\text{ Btu/ft}^3$  (30 percent voids are assumed). Steam at  $600^{\circ}\text{C}$  ( $1,100^{\circ}\text{F}$ ) can be generated by this tank. An electric energy demand of 1 MW-hr is equivalent to  $3.4 \times 10^6\text{ Btu}$  (ideal conversion); therefore, 100 MW-hrs of electric energy would require an iron thermal storage tank volume of  $51,000\text{ ft}^3$  (based on a typical electric powerplant efficiency of 33 percent). In cubic form, such a tank would be 37 feet on every side. The iron in the tank would weigh over 7,100 short tons. Using iron or iron ore as a heat storage material for a solar thermal electric powerplant does not appear practical for even the simplest application because of size and weight.

Lithium hydride, a latent heat storage material, changes phase from solid to liquid at  $1,200^{\circ}\text{F}$  to  $1,300^{\circ}\text{F}$ . The heat of fusion of this material is  $92,000\text{ Btu/ft}^3$ .<sup>1</sup> With this form of heat storage, 100 MW-hr of electric energy would require a storage tank volume of  $11,000\text{ ft}^3$ . In cubic form, this tank would be 22 feet on

each side and would weigh about 30 tons. Although this tank would be much smaller and lighter than an equivalent iron thermal storage tank, lithium hydride thermal storage requirements would still require enormous volumes for large solar thermal electric powerplants. This high-temperature latent heat storage material is also much more costly than other thermal storage materials. In addition, transferring the heat of the phase change as molten lithium hydride crystallizes poses engineering problems. Latent heat storage does not appear practical for a solar thermal electric powerplant.

Electrochemical storage would appear to be a more direct method of storing electric energy for solar electric power stations. Several advanced battery concepts are being developed, having specific energy capacities of 200 watt-hours per pound.<sup>1</sup> A one megawatt-hour energy demand would require advanced batteries weighing 5,000 pounds. Lead-acid batteries would weigh 10 times as much as advanced batteries for the same energy demand. The cost of the materials for advanced batteries prohibits their practical consideration. Even though the cost per unit weight of conventional batteries may be relatively low, the greater quantities that would be required for

<sup>1</sup>H. F. Hottell and J. B. Howard, *New Energy Technology, Some Facts and Assessments*, 1973.

storing comparable energy levels would also result in high costs. Therefore, batteries do not appear practical for storing the large quantities of energy required by a central power station.

Rock or molten salt thermal storage systems for solar electric powerplants have been suggested.<sup>1</sup> This type of thermal storage would produce steam at only a few hundred degrees Fahrenheit. Much larger conventional turbines would be required to use the low-energy steam that would be produced at these temperatures. A plant operating with a maximum steam temperature of 300°F would have a thermal efficiency half that of a conventional plant using steam at 1,000°F. The inefficiency of a low-energy steam cycle would further amplify the size of the turbines required. The initial capital cost of a low-energy steam plant would be considerably higher than conventional power machinery. Although a rock or molten salt thermal storage system could be designed, such a system would not be practical or feasible for central power stations.

Instead of storing solar energy, it could be used to manufacture synthetic gaseous or liquid fuels. A solar electric powerplant could manufacture hydrogen by electrolysis with a portion of the day time electric power production.<sup>1</sup> The hydrogen could then be stored in metal

hydrides to be used as a fuel during night time and overcast operations.

Yet another possibility is that the concentrator panel could be used directly to provide the high temperatures to manufacture low-Btu gas or high-Btu methane from coal or solid waste. Methane could be liquefied to reduce the storage volume; the methane could then be piped in gaseous form to be used as a natural gas substitute for residential heating. Low-Btu gas could be compressed and stored for use by central power stations for power production during off-solar hours. Using solar energy to produce synthetic fossil fuels may be the most practical approach to energy storage, because the energy storage density of fossil fuels is very high compared to that of thermal or electrochemical energy storage systems. Synthetic fossil fuels are also more readily usable by conventional power systems. However, the feasibility and practicality of using solar energy to produce synthetic fossil fuels cannot be determined at this time.

<sup>1</sup> Walter E. Morror, Jr., "Solar Energy—Its Time Is Near," *Technology Review*, December 1975, pp. 31-43; *Solar Energy Projects of the Federal Government*, Federal Energy Administration, January 1975.

## ECONOMIC CONSIDERATIONS FOR ELECTRIC POWER SYSTEMS

If a major electric utility power station to provide 1,000 Mw continuously were driven by focusing solar collectors with an overall system efficiency of 25 percent, a collector area of at least 16 km<sup>2</sup> would be required.<sup>1</sup> However, because of collector spacing requirements, the land surface area required would be 30 km<sup>2</sup> (7,400 acres) which is a square area having 3.4-mile sides. Even if the cheapest construction materials were used for collector panels, the overall cost of a solar power station would be excessive. Focusing collectors having been optimistically estimated to cost \$60 per square meter.<sup>1</sup> However, the collector size is only part of the capital cost of solar power plants. Since the sun is an intermittent source of energy and power demand does not cease at night or during overcast or during short winter days, some form of energy storage to provide possibly 100 days of energy reserve would be required for solar central power stations; such storage requirements pose massive engineering problems, even for moderate-capacity power stations.

Closely related to the engineering problems are the economic problems of constructing these large solar energy farms. A 1,000 Mw, continuous-duty prototype solar power plant has been estimated to cost approxi-

mately \$1.4 billion (1973 dollars), which corresponds to \$1,400 per kw of capacity.<sup>1</sup> By comparison, nuclear power plants have typical construction capital costs of \$500 to \$615 per kw of capacity.<sup>2</sup> As new, more efficient or more economical solar collectors and energy storage systems are developed, the cost penalty usually associated with the improved performance characteristics will have to compete with the size and cost of state-of-the-art systems. Unless a technological breakthrough somehow dramatically reduces the large physical sizes required by major solar electric power systems, the hardware commitment involved will dominate the capital investment requirements of solar power systems. In summary, major solar electric power systems face economic as well as technical barriers. The best possible practical application of solar energy for electric requirements may be as peak-load boost plants.

<sup>1</sup> Walter E. Morror, Jr., "Solar Energy—Its Time Is Near," *Technology Review*, December 1973, pp. 31-43.

<sup>2</sup> Seymour Baron, "The LMFBR: The Only Answer," *Mechanical Engineering*, December 1974, pp. 12-20; S. David Freeman, *Energy*, *The New Era*, August 1974, p. 206.

Table XVII-3  
SOLAR CELL PERFORMANCE SUMMARY

Cell	Structure	Efficiency (%)	Open-Circuit Voltage (V)	Short-Circuit Current Density (mA/cm <sup>2</sup> )	Comments
Silicon	Conventional	12-16	0.55	35	Cost now \$15/W, commercially available
	Nonreflecting	18	0.6	36	Highest-efficiency conventional cell
	Heterojunction	6-10	0.5	15-25	Still in research stage
	Schottky barrier	8-10	0.55	24	—
	Indium-tin oxide on Si	12	0.5	32	Oxide semiconductor on Si structure
	Tin oxide on Si	10	0.54	28	Stability problems
Cadmium sulfide	Conventional	5-8	0.5	25	Lowest cost
	CdZnS	15	0.68	28	Single-crystal structure
	InP on CdS	12.5	0.65	20	Single-crystal structure
	CdTe on CdS	7	0.5	17.2	Single-crystal structure
	Cuprous indium selenide on CdS	5.7	0.4	27	—
Gallium arsenide	Heterojunction	23	0.9	35	Mainly for concentrator applications
	Schottky barrier	15	0.9	16	Metal-insulator conductor structure
Thin-film	Si on graphite	5	0.5	17	Polycrystalline Si structure
	Amorphous Si on glass	5.5	0.8	10	—
	CdS on plastic	5.2	0.4	20	—
	Indium tin oxide on CdTe	7.4	0.6	16	—

Source: *Electronics*, November 11, 1976, p. 90.

### SOLAR PHOTOVOLTAIC SYSTEMS

A photovoltaic cell is a device that converts light directly into electrical energy. The modern cell was invented in 1954, and many of the cells built in the 1950s continue to operate to this day. A typical silicon cell is shown in Figure XVII-13. An electromagnetic wave, such as light, is a shower of photons with each photon having its energy and momentum. When this shower of photons interacts with the junction of a semiconductor device, an electric current is generated.<sup>1</sup> Some of the current photovoltaic device uses are:

- Navigation warning lights.
- Horns on unmanned off-shore platforms.
- Maritime buoys.
- Remote educational television receivers.
- Radio repeater stations.
- Environmental monitoring equipment.

- Railroad warning and signaling systems.
- Battery charges on small boats.
- Remote telephone power.
- Water purification plants.
- Desert water-pumping stations.
- Light measurement instruments.

With the emergence of the energy crisis, however, it is desirable to use these devices to generate electrical power on a much larger scale. To accomplish this ERDA was funded \$22 million in FY 1976 and \$65 million in FY 1977. Among the ERDA planned goals are:

- By 1983, pilot plants capable of producing more

<sup>1</sup>For a more detailed technical discussion of photovoltaic cell operation see S. L. Chang, *Energy Conversion*, Prentice-Hall, Inc., Englewood Cliffs, N.J., 1963.

**Table XVII-4  
COST ESTIMATES FOR SILICON  
CELL PRODUCTION STEPS**

Steps	1977		1980	
	Cents per cell	Percent	Cents per cell	Percent
Crystal production	30	40.5	7	33.5
Cutting and shaping	13	16.5	5	23.5
Junction formation; coating and test	32	43.0	9	43.0
Total	75	100.0	21	100.0

Source: Statement of E. L. Ralph to Congress, Hearings before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives, June 6 and 11, 1974.

than 5 million square meters of silicon sheets per year at a value-added cost of less than \$18 per square meter.

- By 1984, plants capable of producing approximately 2,000 metric tons of silicon material at a market price of less than \$10 per kilogram.
- By 1985, plants capable of producing more than 500 peak kilowatts of encapsulated solar-array modules at a market price of less than \$500/peak kw.

Solar cell performance is shown in Table XVII-3.

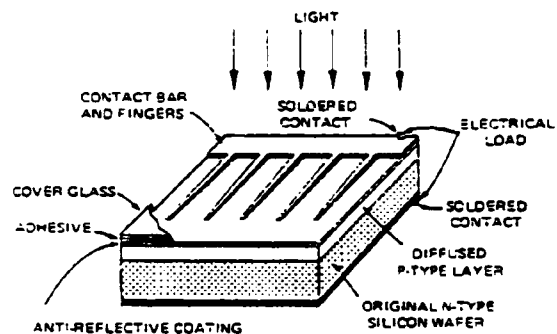
### Single Crystalline Silicon Cell

The single crystalline silicon solar cell is an efficient long-life photovoltaic device. This cell is used in the space program and nearly all the commercially available small terrestrial systems. While the wafer silicon cell meets every requirement for large-scale terrestrial use, its use is limited because of high cost. Table XVII-4 shows cost estimates for each production step.

Since sand is the raw material for silicon, a sufficient quantity exists to support all foreseeable solar cell production. It would take approximately 16 metric tons of silicon to make a 1 Mw power output (average power) solar array (15 percent conversion efficiency). The anticipated production of semiconductor-quality silicon alone in the United States in 1974 was estimated to be  $1.24 \times 10^3$  metric tons. The main limitation will not be raw material availability but the capacity to produce silicon of solar-cell quality at an acceptable price.<sup>1</sup> Metallurgical grade silicon currently sells for about \$1/kg, but

semiconductor grade sells for about \$60 to \$70/kg. It is ERDA's goal to reduce the cost of photovoltaic grade silicon, which is between these two, to about \$10/kg.

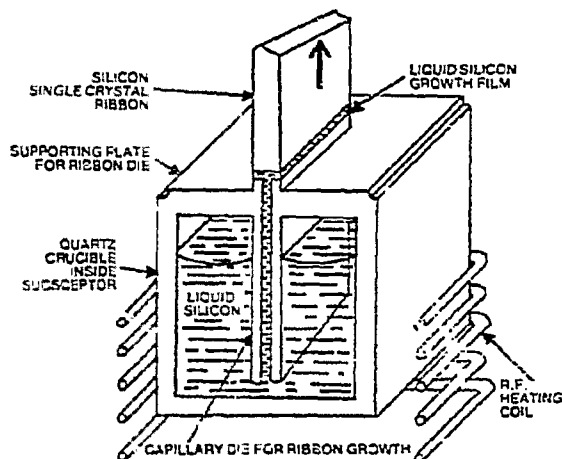
The present cost of space-rated solar cells is about \$100 to \$200 per peak watt of output. In 1974, before ERDA's involvement, solar cells for terrestrial applications were selling for well over \$30 per peak watt; ERDA recently purchased a total of 130 kw from five different



**Figure XVII-13. SILICON  
PHOTOVOLTAIC CELL**

<sup>1</sup> Statement of John V. Goldsmith to Congress, Hearings before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives, June 6 and 11, 1974.





Source: Martin Wolf, "Photovoltaic Power," *Astronautics and Aeronautics*, XIII, November 11, 1975.

Figure XVII-14. PRODUCING  
EDGE-DEFINED FILM SILICON

manufacturers for an average price of \$15 per peak watt. While the percent range of efficiencies is about 12 to 16, values above 20 percent should be attainable but probably at a higher cost.

### Silicon Ribbon Cell

The construction of the single-crystal silicon solar cell is comprised of a number of labor-intensive batch processes that defy significant cost reductions. This has led to a search for simpler ways to make silicon cells. About 1968, Tyco Laboratories, Inc. (the Mobil Tyco Solar Energy Corporation) began to develop a radically new crystal-growth process for the production of continuous-shaped single crystals of "sapphire" directly from the melt. The basic crystal-growth process, called "Edge-Defined, Film-Fed Growth (EFG)," has been adapted to the production of silicon ribbons, as shown in Figure XVII-14.<sup>1</sup>

Mobil Tyco has reported<sup>2</sup> recently that they have been able to grow one-inch wide ribbons about 8 to 10 mils thick continuously to various lengths up to 65 feet. The carbon dies used show no observable distortion or erosion, indicating that continuous ribbon growth can be achieved with carbon dies. Ribbon-cell conversion efficiencies between 6 and 10 percent have been attained with a current state-of-the-art material containing some imperfections. Improvements in ribbon characteristics can be achieved by more refined thermal design of growth systems, improved purity, and a reduction in and control of defect densities and distribution.

### Cadmium Sulfide/Copper Sulfide (CdS/Cu<sub>x</sub>S or just CdS) Cell

The cadmium sulfide (CdS) cell offers the promise of low costs but has in the past offered very low efficiency (2 to 3 percent) and very short life (two years). Within the last year, however, peak performances between 7.0 and 8.5 percent have been demonstrated,<sup>3</sup> and cell life has started to increase. The participants of the NSF workshop (reported on below)<sup>3</sup> indicated that efficiencies above 10 percent are possible in the near term and that lifetimes in excess of 20 years are achievable through improved encapsulation.

The steps in making thin-film cadmium sulfide cells are: 1) a thin layer of zinc is evaporated onto a plastic substrate; 2) spectroscopically pure cadmium sulfide is evaporated over this zinc layer; 3) the cadmium sulfide is dipped into a bath containing copper ions; this forms the copper sulfide, which is essential to the operation of the cell; 4) the edges of the cell are trimmed off; 5) a copper grid is placed in contact with the treated surface; 6) copper may be cemented to the copper sulfide with conducting epoxy; 7) a layer of transparent plastic is placed over the structure and the edges are sealed by heat. Contacts to both the cadmium sulfide and the copper grid are left exposed during the last step.<sup>4</sup>

The raw materials, sulfur and cadmium, are in sufficient supply to tolerate a significant production of CdS cells. Sulfur is plentiful, and the amount needed for a CdS solar-cell electricity-generating system would only make a small demand on the supply. A statement made at Congressional Hearings<sup>5</sup> indicates that present cadmium production in the United States is  $3 \times 10^3$  metric tons per year, and U.S. and world reserves<sup>6</sup> are  $205 \times 10^3$  and  $850 \times 10^3$  metric tons respectively; 8 percent efficient cadmium sulfide solar cells  $20 \times 10^{-4}$  cm thick would

<sup>1</sup> The statement of A. I. Mlavsky to Hearings before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives, June 6 and 11, 1974.

<sup>2</sup> K. I. Ravi, et al, *EFG Silicon Ribbon Solar Cells*, presented at the Eleventh IEEE Photovoltaic Specialists Conference, May 6-8, 1975, Scottsdale, Arizona, IEEE Catalog No. 75CH0948-OED.

<sup>3</sup> Karl W. Boer, *Assessment of U.S. International Workshop on CdS Solar Cells*, presented at the Eleventh IEEE Photovoltaic Specialists Conference, May 6-8, 1975, Scottsdale, Arizona, IEEE Catalog No. 75CH0948-OED.

<sup>4</sup> From a statement by Dr. Joseph J. Loferski at Hearings before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives, June 6 and 11, 1974.

<sup>5</sup> Statement of John V. Goldsmith to Congress, Hearings before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representative, June 6 and 11, 1974.

<sup>6</sup> Reserves indicate the cadmium that can be obtained through zinc mining. Actual cadmium resources are considerably greater but cannot be economically mined at present.

require approximately 4.5 metric tons of cadmium per megawatt of average power produced. The availability of cadmium is complicated because it is obtained as a by-product of zinc mining. The economic problems involved in increasing production to meet the cadmium need without a market for the zinc may constitute a major problem.

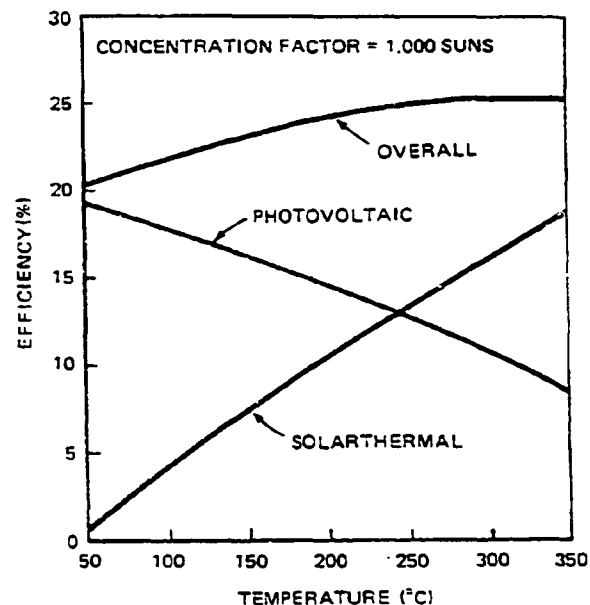
### Thin-Film Silicon Cell

Thin-film silicon photovoltaic cells should reduce the cost of manufacturing the silicon cell and significantly reduce the amount of high-grade silicon necessary for a cell. Unfortunately, the efficiency of these cells a few years ago was well below 2 percent. Recently efficiencies of about 4 percent have been reported; projections are that 10 percent efficiencies can be achieved by 1980.<sup>1</sup> If thin-film cells can achieve 10 percent efficiencies, they will probably be contenders for major solar cell applications. The fabrication steps for thin-film silicon cells are:

- Preparation of trichlorosilane.
- Deposition of solar-cell structure on low-cost substrates by the reduction of trichlorosilane.
- Contact and lead attachment.
- Encapsulation.<sup>2</sup>

### Gallium Arsenide (GaAs) Cell

GaAs cells are among the most promising of the photovoltaic cells. They have demonstrated efficiencies above 15 percent. Although the individual cells are not low-cost, systems using them might be very low in cost because they can be used with concentrators. Varian Associates recently reported<sup>3</sup> that experimental cells have operated at a concentration ratio of 1,735:1 with an output power density of 0.24 megawatts per square meter of cell area. In such a situation the cost of the concentrator, not the photovoltaic cell, becomes the important economic factor. The concentrator/GaAs also has good potential in combined photovoltaic-solar thermal systems where effi-



Source: *Electronics*, November 11, 1976, p. 89.

Figure XVII-15. EFFICIENCY OF A COMBINED GaAs PHOTOVOLTAIC-SOLAR THERMAL CONVERSION SYSTEM

ciencies over 25 percent are possible as shown in Figure XVII-15. In areas such as the U.S. southwest, where large amounts of direct sunlight are available, the concentrator/GaAs system seems very promising for large-scale use.

<sup>1</sup> T. L. Chu, *et al.* *Polycrystalline Silicon Solar Cells for Terrestrial Applications*, presented at the Eleventh IEEE Photovoltaic Specialists Conference, May 6-8, 1975, Scottsdale, Arizona, IEEE Catalog No. 75CH0948-OED.

<sup>2</sup> Statement Dr. Ting L. Chu at Hearings before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives, June 6 and 11, 1974.

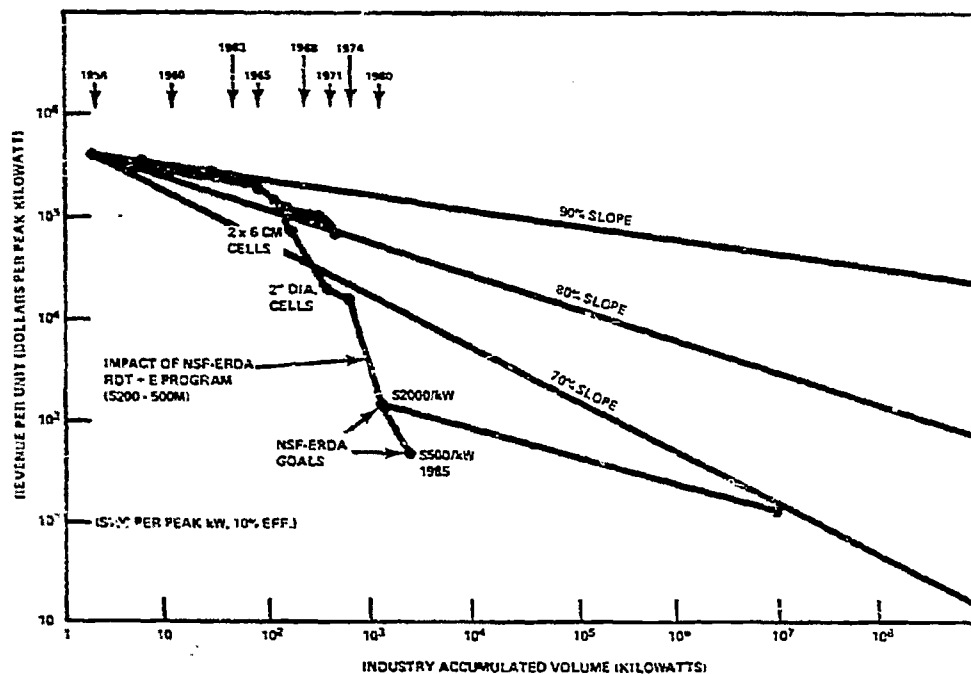
<sup>3</sup> L. W. James and R. L. Moon, *GaAs Concentrator Solar Cells*, presented at the Eleventh IEEE Photovoltaic Specialists Conference, May 6-8, 1975, Scottsdale, Arizona, IEEE Catalog No. 75CH0948-OED.

## TERRESTRIAL PHOTOVOLTAIC SYSTEM ECONOMICS

The computation of costs per kilowatt hour for a complete photovoltaic power system requires rather sophisticated computer programs. The Aerospace Corporation of El Segundo has been funded to develop a program under an NSF/RANN grant. Some preliminary cost estimates have been developed for these assumptions:

- Time of construction—1985
- System efficiency in solar collection—10 percent
- Array cost—50 cents per peak watt
- Plant size—100 MW

For a 10 percent system efficiency, the preliminary estimate of the array cost alone using an optimum sunlight concentration ratio of 7.6 is \$442/KW (peak), approximately \$500 per peak KWe. For a capacity factor (CF) of 0.4, where CF is the ratio of the number of hours at the rated output to the total number of hours per year, the total system cost is estimated to be \$1,410/KW (rated), including the six-hour storage required for CF of 0.4, as well as the power conditioning, etc. The busbar energy cost from such a system (10



Source: P. D. Maycock and G. F. Wakefield, "Business Analysis of Solar Photovoltaic Energy Conversion," Eleventh IEEE Photovoltaic Specialists Conference, May 6-8, Scottsdale, Arizona, IEEE 75CH0948-OED.

Figure XVII-16. BREAKTHROUGH STRATEGY FOR SOLAR PHOTOVOLTAIC ARRAY COST REDUCTION.

percent conversion efficiency and  $\$50/\text{m}^2$ ) would be 57 mills/KWH. For the same system with 14 percent photovoltaic conversion efficiency, the energy cost would be 42 mills/KWH, a function of photovoltaic device efficiency.<sup>1</sup> Further comparison costs developed by MITRE Corporation are shown in Table XVII-5.

Another economic consideration is the projection of costs for the solar cells themselves. Recent economic analyses<sup>2</sup> discuss cost reduction versus cumulative experience. Figure XVII-16 shows a plot for silicon solar cells. The plot is commonly called a "learning curve" or "experience curve." Economists theorize that in a stable, competitive industry, the experience curve has a slope

between 70 and 80 percent. Integrated circuits, for example, followed a 70 percent curve. Exactly what solar cells will do is not known, but Figure XVII-16 should serve as a guide.

<sup>1</sup>Statement of H. Guyford Stever at Hearings before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives, June 6 and 11, 1974.

<sup>2</sup>Paul D. Maycock and Gene F. Wakefield, *Business Analysis of Solar Photovoltaic Energy Conversion*, presented at the Eleventh IEEE Photovoltaic Specialists Conference, May 6-8, 1975, Scottsdale, Arizona, IEEE Catalog No. 75CH0948-OED; Lecture by E. L. Ralph, Sponsored by IEEE, Washington Academy of Sciences, and Washington Society of Engineers, Washington Section, March-April-May 1974.

## SPACE SATELLITE PHOTOVOLTAIC POWER SYSTEMS

After each availability factor is tabulated for the solar power available on the earth at a fixed site, a satellite in synchronous orbit is a good possibility; this is shown in Table XVII-6. A proposed space satellite power system is shown in Figure XVII-17 with an overall efficiency estimate in Figure XVII-18. Figure XVII-19 contains a variant satellite power system using concentrators. When the

efficiency of 68 percent is combined with the availability gain of 15, the space satellite offers about a 10 to 1 gain in the use of solar cells. The problem is that with the cost of available space boosters, the project would be economically prohibitive, and there are some environmental questions about the microwave beam. It does, however, provide a possible energy source.

Table XVII-5  
COMPARISON OF COST OF ELECTRICITY FROM  
VARIOUS GENERATING SYSTEMS

Type of System	Initial Investment, Power Generation	Fuel Costs <sup>5</sup>	Initial Investment, Conversion & Storage	Other Costs	Total 20-Year Cost	Plant Factor	Average Cost of Electricity At Plant
	Year 2000	Years 2000 to 2020	Year 2000	Years 2000 To 2020	Years 2000 To 2020	Years 2000 To 2020	Years 200 To 2020
Hydro-Electric	\$392 to <sup>1</sup> \$1230/KW	—	—	\$970 to \$2661/KW	\$1362 to \$3891/KW	0.60	13m/KWH to 37m/KWH
Gas-Fired	\$392/KW <sup>1</sup>	\$2451/KW	—	\$1323/KW <sup>7</sup>	\$4166/KW	0.60	45m/KWH
Oil-Fired	\$458/KW <sup>1</sup>	\$2451/KW	—	\$1517/KW	\$4426/KW	0.60	42m/KWH
Coal-Fired	\$442/KW <sup>2</sup>	\$1666/KW	—	\$1475/KW <sup>7</sup>	\$3583/KW	0.60	34m/KWH
Nuclear-Fueled	\$560/KW <sup>3</sup>	\$412/KW <sup>6</sup>	—	\$2134/KW <sup>8</sup>	\$3106/KW	0.60	30m/KWH
Photovoltaic (Without Storage)	\$368/KW <sup>4</sup>	—	—	\$1145/KW <sup>9</sup>	\$1512/KW	0.25	34m/KWH
Photovoltaic (With H <sub>2</sub> Storage)	\$368/KW <sup>4</sup>	—	\$328/KW	\$2100/KW <sup>9</sup>	\$2796/KW	0.25	64m/KWH
Photovoltaic Plus Wind Energy (With H <sub>2</sub> Storage)	\$307 to \$429/KW	—	\$105/KW	\$1273 to <sup>9</sup> \$1623/KW	\$1685 to \$2162	0.275	35m/KWH to 45m/KWH

<sup>1</sup> Cherry data for 1968, *Generation of Pollution-Free Electrical Power From Solar Energy*, ASME paper no. 71-WA/SOL-2, adjusted to 1970 by factor of 1.07. Then adjusted to year 2000 by factor of 2.45.

<sup>2</sup> Simpson data for 1965, "The Case for Nuclear Energy," *IEEE Spectrum*, September 1972, adjusted to 1970 by factor of 1.14 plus pollution control cost of \$56/KW (from Simpson, *ibid*). Then adjusted to year 2000 by factor 2.45.

<sup>3</sup> Cherry data for 1968, (*ibid*) adjusted to 1970 by factor of 1.07 plus pollution control cost of \$15/KW (from Simpson, *ibid*). Then adjusted to year 2000 by factor of 2.45.

<sup>4</sup> Assumes investment cost of \$2.70 per square foot (1970 dollars) for solar cell array, 4% efficiency, x5 light concentration.

<sup>5</sup> Fuel costs based upon FPC 1965 data, adjusted to 1970 by factor of 1.07, and adjusted to year 2000 to 2020 using scenario plant efficiency is assumed to be equal to 10.2 M Btu/MWH.

20 yr production: 1.6) (8760) (20) (1) = 105.120 MWH = 1072.2 MBtu

		COAL	OIL	GAS
FPC	1968	25.5/MBtu)	32.8	25.1
	1970	27.2	35.1	26.9
	1975	32.75	44.1	61.9
	1985	41.0	63.2	67.3
	2000	54.6	80.7	80.7

<sup>6</sup> Fuel cost for nuclear, in 1970 dollars, is assumed to be constant over time.

<sup>7</sup> Based on fixed charge rate given in FPC (I-19-6)

Coal, Oil and Gas = 14.2% per year

Hydroelectric = 9.7% per year

Nuclear = 14.7% per year

Nuclear Fuel = 12.4% per year

O&M Cost Rates based upon FPC data, i.e., \$3.00 per kw; Administrative and general expenses \$.75/kw and working capital -\$.3.4% of Investment Needed Per Working capital (10.2% Cost of Capital) (Investment) (20) = .069 (Investment).

<sup>8</sup> Assumed life of nuclear fuel - 5 years.

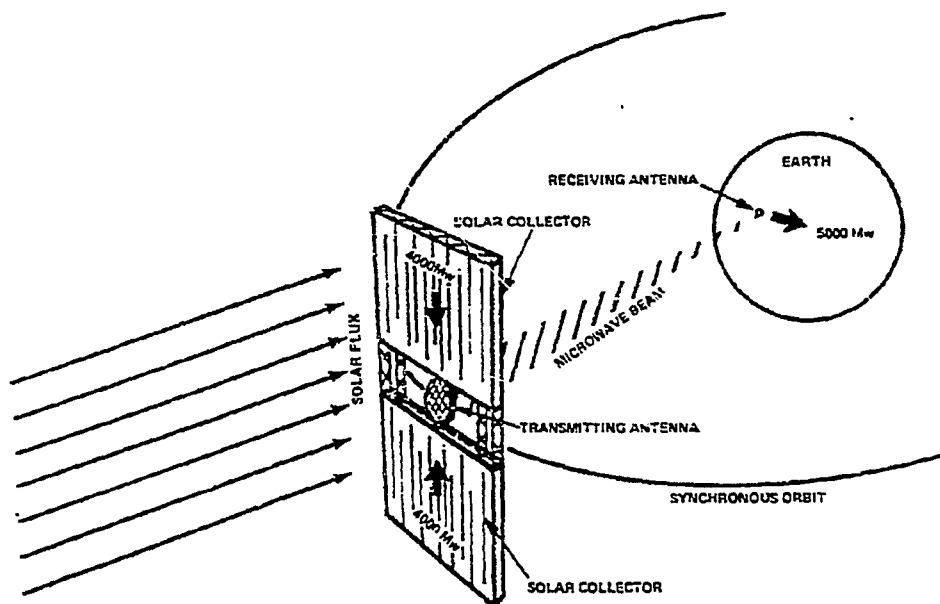
<sup>9</sup> Based on fixed charge rate of 14.2% per year (i.e., same as coal, oil and gas; see above).

Source: Statement of Frank R. Eldridge at Hearings before the Subcommittee on Science and Astronautics, U.S. House of Representatives, June 6 and 11, 1974.

Table XVii-6  
AVERAGE AVAILABILITIES OF SOLAR ENERGY

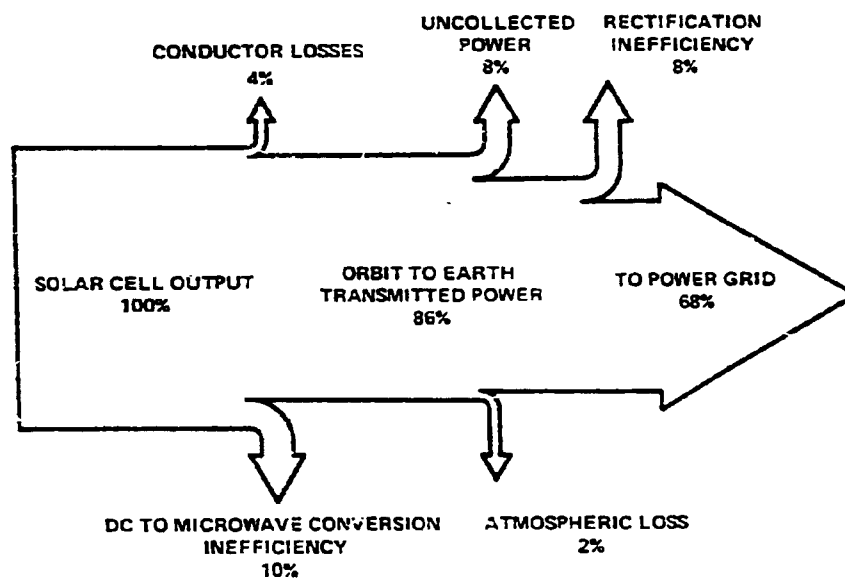
Availability factor	Average on earth	In synchronous orbit	Average ratio, ground/orbit
Solar energy density, $\text{kW/m}^2$	1.1	1.4	4/5
Hours of useful radiation/day	8	24	1/3
Percentage of clear skies	50	100	1/2
Cosine of angle of incidence	0.5	1	1/2
Product of all factors			1/15

Source: J. T. Patha and G. R. Woodcock, "Feasibility of Large-Scale Orbital Solar/Thermal Power Generation," *Proceedings IECEC*, 1973, pp. 312-319.



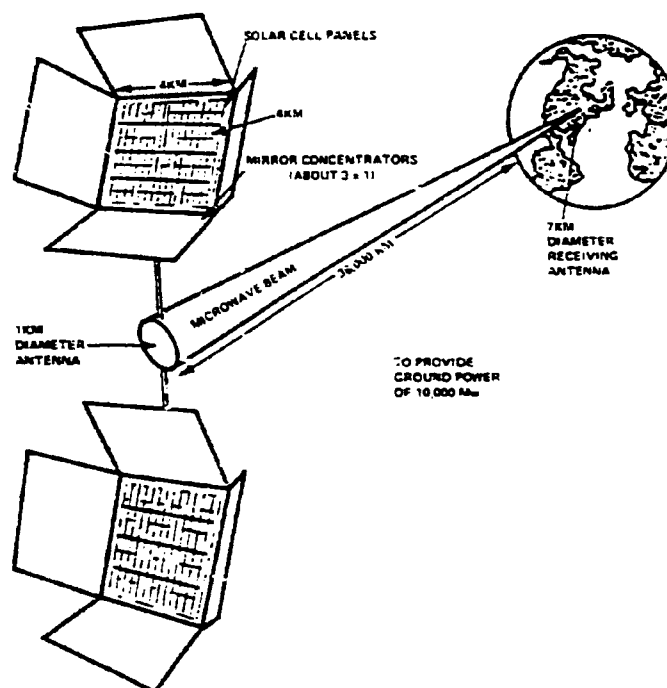
Source: Peter E. Glaser, "Space Satellite Power System," Solar Energy Lecture III, IEEE Washington, March 28, 1974.

Figure XVII-17. SPACE SATELLITE POWER SYSTEM



Source: Peter E. Glaser, "Space Satellite Power System," Solar Energy Lecture III, IEEE Washington, March 28, 1974.

Figure XVII-18. SPACE SATELLITE POWER SYSTEM EFFICIENCY ESTIMATE



Source: Martin Wolf, Hearings before the Subcommittee on Energy of the Committee on Science and Astronautics, U.S. House of Representatives, June 6 and 11, 1974.

Figure XVII-19. SPACE SATELLITE POWER SYSTEM WITH CONCENTRATORS

## KEY FACTORS AFFECTING COMMERCIALIZATION OF SOLAR ENERGY TECHNOLOGIES

FACTORS INHIBITING COMMERCIALIZATION OF SOLAR ENERGY	FACTORS OR ACTIONS PROMOTING COMMERCIALIZATION OF SOLAR ENERGY
<p><b>Legal</b></p> <p>Solar system installations may be hampered by restrictions of existing local building codes.</p> <p>Three-dimensional zoning to protect solar collectors against shading by neighboring development and to prevent nuisance reflections must be worked out, tested, and adopted. A fourth dimension, temporal variations in illumination, must be defined and assessed.</p> <p>Some solar technologies are regionally specific in their application and may produce benefits usable only in particular areas, thus raising the question of equitable distribution of the benefits from federally funded programs.</p> <p>A paradox exists in the patent rights area in that the investments by private companies need to be protected in terms of exclusivity of RD&amp;D results while at the same time assuring the widespread dissemination of these results to ensure extensive commercialization.</p> <p>Several international problems associated with solar energy systems include the questions of international boundaries and jurisdictions, the security of marine facilities and the establishment of policies on export of solar energy technologies.</p> <p>A dense concentration of solar systems in a small area may pose some aesthetic and legal problems that will need to be resolved through new concepts in community planning.</p>	<p><b>Legal</b></p> <p>To date, several states have enacted legislation that promotes the installation and use of solar energy and enhances its economic viability. This was accomplished by modifying building codes and tax deduction rights as well as by allocating funds for solar energy promotion.</p> <p>PL 93-577 provides a framework for a flexible patent policy to expedite commercial application of inventions and innovations developed under the federal program.</p> <p>The fact that exclusivity will be granted by the government for commercial application of specific technologies will be a major incentive for private industrial involvement in solar technologies.</p>
<p><b>Institutional</b></p> <p>Inexperience of building code administrators in dealing with new requirements.</p> <p>Local, state, and federal regulatory authorities will have to understand and accept solar technologies to assist in removing the barriers to implementation.</p> <p>The building design, construction and marketing industry is diverse, complicated, fragmented, and highly resistant to innovation. Even with technical and economic problems resolved, solar systems could still fail in the marketplace.</p> <p>Tendency of contractor to bid conservatively on any new technology.</p> <p>Lack of standardization of component parts for solar systems adds confusion to the industry and makes rational operation difficult.</p> <p>Traditional labor-management jurisdictional procedures vary widely across the nation and may hamper introduction of solar systems into the building industry.</p>	<p><b>Institutional</b></p> <p>ERDA is launching a major public information program using both electronic and print media.</p> <p>Educational resource grants and manpower training programs are being established by ERDA.</p> <p>PL 93-409 establishes a Solar Heating and Cooling Information Data Bank under Secretary of HUD to promote and perform the collection and dissemination of information related to solar energy.</p> <p>Technology transfer teams, expert in each solar technology, are being formed by ERDA.</p> <p>A solar energy advisory group and an interagency panel are being created by ERDA.</p> <p>Information centers at solar energy field sites are being formed by ERDA.</p> <p>ERDA Technical Information Center, Oak Ridge, Tennessee 37830, will serve as the central archive and wholesale distribution center for the results of the Federal Program for Solar Heating and Cooling.</p>

FACTORS INHIBITING COMMERCIALIZATION OF SOLAR ENERGY	FACTORS OR ACTIONS PROMOTING COMMERCIALIZATION OF SOLAR ENERGY
<p><b>Institutional (cont)</b></p> <p>To develop sufficient industrial capability to manufacture solar heating and cooling systems, architects, engineers and the building trades must have information available on design, installation, and operation of these systems.</p> <p>Lack of data and system simulation capabilities required to optimize solar system designs for use in specific buildings and locations.</p> <p>Expanding solar industry must find way of self-policing if government role is to be minimized.</p> <p>Reluctance of private and government financial institutions to provide mortgages for new dwellings or retrofit installations involving solar systems.</p>	<p><b>Institutional (cont)</b></p>
<p><b>Societal</b></p> <p>Lack of trained personnel to install, start-up, and operate solar systems.</p> <p>The tendency of the purchaser in the housing market is to place a higher priority on first costs, whereas the advantages of solar systems are realized over a long-term payout.</p> <p>Uncertainties in the minds of potential users and the general public because of unavailable or unknown information on the eventual costs, reliabilities, lifetimes and other operational factors associated with solar systems.</p> <p>Consumer resistance to the new technology.</p> <p>Consumer concern about warranties and maintenance of solar energy products.</p> <p>Before solar technologies can become market successes they must shed their "experimental" image which was created in part because solar energy development has been centered around the experimental community rather than in industry.</p> <p>Vulnerability of the market to rapid introduction of poor quality equipment, and the absence of laws, criteria, consumer information, etc., to protect the public and industry from such equipment.</p>	<p><b>Societal</b></p> <p>Manpower requirements should not be significantly different from those for conventional energy technology, although specialized training will be required.</p> <p>In its programs, ERDA will ensure the participation of those segments of the economy whose acceptance of solar technology will be essential to its general adoption.</p> <p>National solar energy demonstration program aims at providing a government-supported market for new technology, which should encourage independent industry participation and private investment in later cycles.</p>
<p><b>Environmental</b></p> <p>Although the sun's energy is non-polluting, there will be environmental impacts related to conversion and storage of this energy and to the construction of facilities.</p> <p>Because certain solar energy systems require large land areas, careful consideration must be given to site prepara-</p>	<p><b>Environmental</b></p> <p>Use of solar energy does not require solid waste disposal, fuel storage, or pipelines, transmission lines or other forms of fuel transportation, and does not create potential hazards.</p> <p>Solar energy, applied to heating and cooling, does not</p>



FACTORS INHIBITING COMMERCIALIZATION OF SOLAR ENERGY	FACTORS OR ACTIONS PROMOTING COMMERCIALIZATION OF SOLAR ENERGY
<p><b>Environmental (cont)</b></p> <p>tion, land use and potential environmental impacts in the development of any large central or distributed solar power systems that are not located on the roofs or walls of structures.</p> <p>Alternative land and water uses may restrict site availability for solar energy system use.</p> <p>Sizable solar installations within certain areas may cause local atmospheric perturbations.</p> <p>Need for local governments to develop new land-use patterns based on "sun rights."</p>	<p><b>Environmental (cont)</b></p> <p>introduce any new materials requirements, is pollution free, and reduces pollution to the degree that it replaces conventional energy sources.</p> <p>Recent legislative trends that have increased the responsibility of energy producers for detrimental environmental impacts should generally improve the competitive position of solar energy as compared to other energy sources.</p>
<p><b>Economic</b></p> <p>Solar technologies are still in the early stages of demonstration.</p> <p>Limitations in build-up of an industrial capability to supply and maintain solar systems at a cost and level of performance and reliability that will provide economic viability.</p> <p>Energy costs and availability are subject to substantial volatility.</p> <p>Energy pricing policies may give competitive edge to other systems.</p> <p>Need to develop ways to achieve maximum beneficial effect on utility systems: load leveling, new rate structures, etc.</p> <p>Higher initial cost of solar heating and cooling systems, which needs to be amortized by savings in operating costs over the lifetime of the systems.</p> <p>The need for energy backup systems during bad weather for solar energy installations increases the cost over conventional heating and cooling or conservation alternatives.</p> <p>Need for long-term guaranteed markets in order to achieve the cost reductions necessary for economic viability through improvements in industrial productivity.</p> <p>The risk facing a private company is accentuated by the fact that many companies may have access to the same information, and may develop similar technologies which will be in competition, limiting each company's potential market share.</p> <p>Potential inability of producers to obtain adequate capital to finance production of solar equipment and to develop markets.</p>	<p><b>Economic</b></p> <p>Analyses of life-cycle costing indicate that in the near future, solar heating may have an advantage over conventional systems in many areas of the country.</p> <p>The quantity of solar heating and cooling systems purchased by the Federal Government for new buildings and renovations could be substantial enough to foster the development of a solar industrial capability.</p> <p>Large-scale commercial production is expected to cut capital costs by a factor of 50 or greater for photovoltaic applications and to a significant but lesser degree for other technologies.</p> <p>Architectural techniques geared to making buildings into total energy conserving systems will reduce costs by ensuring proper physical placement of the structure, sufficient insulation, proper building materials, and proper roof placement. This approach should also eliminate the necessity for expensive conventional backup systems.</p> <p>To promote the solar market, tax incentives, interest subsidies, and loan guarantees applied to solar system installations are being considered.</p> <p>To promote solar equipment manufacturing, an industrial tax credit and an accelerated write-off of capital costs (60 months) are being considered.</p> <p>Since future fossil fuel supplies are uncertain, solar energy technologies have basic advantages over conventional ones because they offer long term stable energy prices based principally on initial capital costs.</p> <p>In the short term, the opportunity exists for exporting solar technologies developed in the United States.</p> <p>In the future, the nation's solar energy production may exceed domestic needs and permit export of energy in such forms as hydrogen or synthetic fuels.</p> <p>The principal material resources for solar systems, aluminum, copper, steel, plastics, and glass, all have alternative replacements and thus it is not expected that materials will be supply-limited.</p>

**Sources for Key Factors Affecting Commercialization  
of Solar Energy Technology**

*National Program for Solar Heating and Cooling*, ERDA-23A, October 1975.

Norman Lutkefedder, "International Solar Industry Expo 75," 27-29 May 1975.

*Solar Energy Research Program Alternatives*, Mitre Corporation, NSF/RA/N-73-111B, NTIS distributed (PB-231 141), December 1973.

*Solar Energy Projects of the Federal Government*, FEA/C-75/247, January 1975, (PB-241 620) National Energy Information Center.

*A National Plan for Energy Research, Development and Demonstration*, ERDA-48, Vol. 1, June 1975.

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CHAPTER XVIII

WIND ENERGY

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## INTRODUCTION

Next to sunlight, wind is the most commonly experienced and universally distributed manifestation of solar energy on earth. Wind is the movement of the atmosphere in a pair of gigantic convection loops, one in the northern hemisphere and the other in the southern hemisphere. The basic wind flow is along the surface of the earth from the polar regions to the tropics where it is heated and rises, then returns at high altitude toward the poles where it is cooled, sinks, and returns again along the surface to the tropics, completing the cycle. This basic flow is modified by the earth's rotation so that, in the northern hemisphere, the prevailing surface winds are from the northeast in the trade-wind belts near the tropics, and from the northwest in the temperate zone. Secondary and tertiary factors further modify these essentially constant winds; heat is added over deserts and removed over large bodies of water, generating variations and modifications in the wind. Boundary layer effects, mountain ranges, local obstructions, etc., add to the confusion to the extent that large microgeographic variations as well as variations over time in fixed locations exist in the wind's direction and speed.

Despite the combined disturbing effects of the secondary and tertiary factors, the variations are normally of quite short duration, and the long-term average winds are very constant. Hourly readings may exhibit extreme variations, and daily averages commonly vary widely. But monthly and yearly averages are surprisingly constant. In fact, Thomas and other researchers have reported that even weekly averages show a great deal of constancy.<sup>1</sup>

Figure XVIII-1 illustrates the long-term average wind velocities in the United States.

Man has long recognized and utilized wind energy. Windmills were known in China and Japan as early as 2000 B.C. and have been in common use for at least 700 years in parts of Europe; wind energy systems were in wide use in the western United States until about 1950. Some are still to be found in remote regions, pumping water into stock tanks or generating electricity for individual farm houses. Figure XVIII-2 summarizes U.S. energy production since 1840 and compares the contribution of wind energy with that of other energy sources.

From 1935 to 1955, a number of large experimental wind-powered generators were constructed. Most of these units were located in Europe; the Smith-Putnam unit at Grandpa's Knob, Vermont, was the only U.S. effort. Putnam's narrative<sup>2</sup> of the Smith-Putnam wind turbine project remains a classic study of wind-power engineering. On October 19, 1941, this unit was the first ever to feed wind-generated power synchronously into a utility power grid. Rated at 1250 Kw in a 30-mile-per-hour wind, it was operated experimentally for 1100 hours over four and one-half years. Put out of commission by a blade failure in March 1945, the project was discontinued for economic reasons.

<sup>1</sup>Percy H. Thomas, *Electric Power From the Wind: A Survey*, Federal Power Commission, Washington, D.C., 1945.

<sup>2</sup>Palmer C. Putnam, *Power From the Wind*, New York: Van Nostrand Reinhold Co., 1948.

## EXTRACTING ENERGY FROM THE WIND

The total kinetic energy of a moving body is expressed by:

$$E = \frac{1}{2}mV^2 \quad (1)$$

But if we are speaking of a fluid body, the mass  $m$  must be expressed in terms of the density (mass per unit volume)  $\rho$  and the volume of the fluid that passes a given reference point per unit time. Thus, for a fluid such as air,  $m = \rho AV$ , where  $A$  is the cross-sectional area of interest.  $A = \pi D^2/4$  for a circular configuration of diameter  $D$  such as a turbine. Combining terms gives

$$E = \frac{1}{8} \rho \pi D^2 V^3 \quad (2)$$

which gives the total kinetic energy contained in a wind stream  $D$  units in diameter.

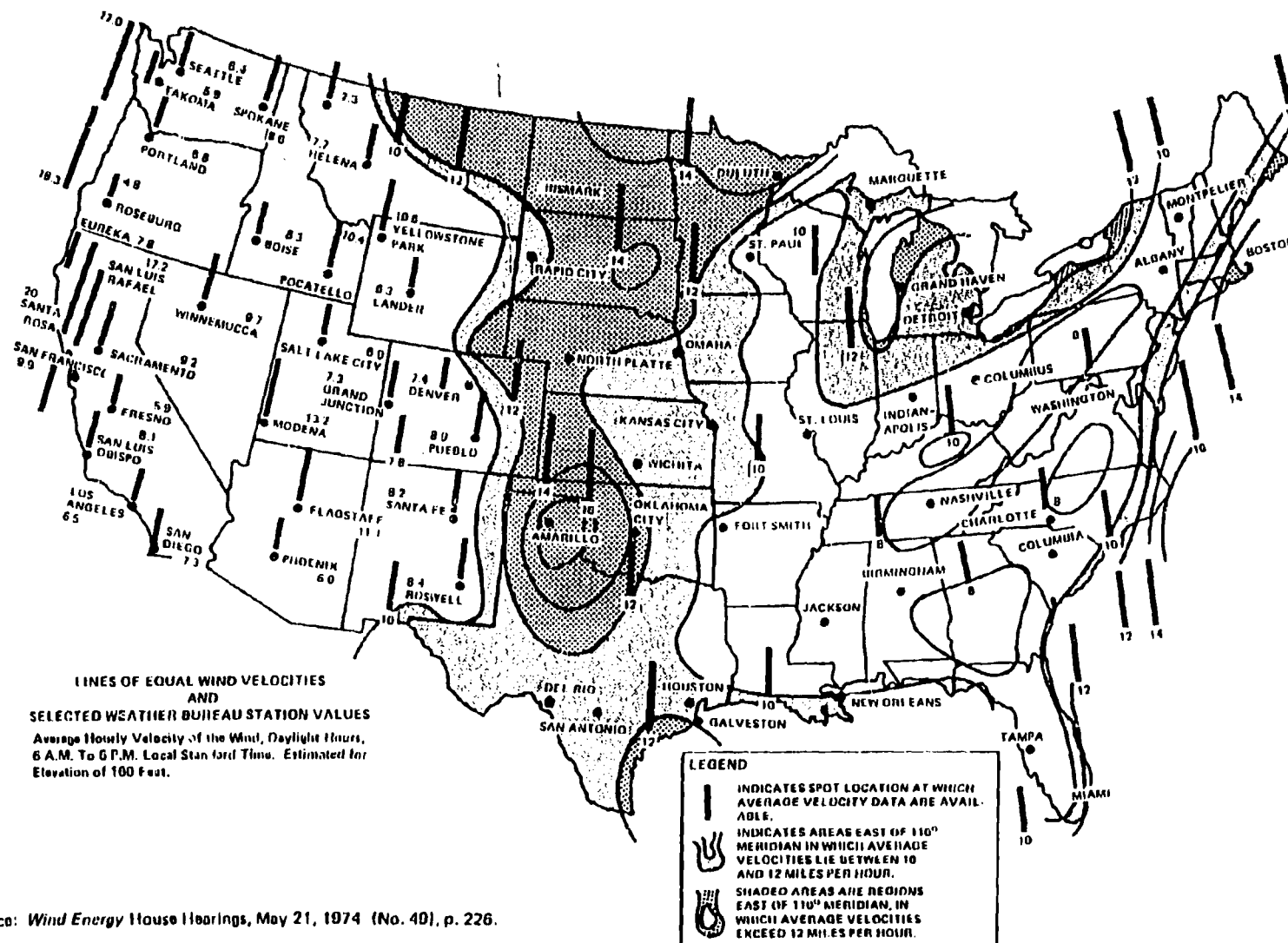
Equation (2) suggests that extracting power from the wind reduces wind velocity. The Betz momentum theory describes the deceleration of air traversing a windmill disk, and has been demonstrated. A column of air velocity  $V$  arriving at a windmill is slowed, and its boundary becomes an expanding envelope; see Figure XVIII-3. The interference factor  $a$  is the proportion by which the wind is slowed in traversing the windmill disk ( $0 \leq a \leq 1$ ). It can be shown that the wind ultimately slows by a factor of  $2a$ , at which time the pressures have equalized and the diameter of the air stream has expanded correspondingly.

Disregarding drag and rotational losses, the maximum power obtainable from the wind can be shown to be

$$P_m = 4a(1-a)^2 P = \frac{1}{2} \rho \pi D^2 V^3 [a(1-a)^2], \quad (3)$$

which is maximized when  $a = 1/3$  and the term  $4a(1-a)^2 = 16/27$ , or 0.592. Thus, the maximum power that can be removed from the wind is only 59.2 percent of the total power contained in the wind. The factor  $4a(1-a)^2$  is termed the power coefficient.  $C_p$ .  $C_p$  is usually defined as the ratio of the power delivered by a wind turbine to the power contained in the wind.

Under normal conditions, the total power contained in an air stream of one meter cross-sectional area is, from



Source: Wind Energy House Hearings, May 21, 1974 (No. 40), p. 226.

Figure XVIII-1. AVERAGE WIND VELOCITIES IN THE UNITED STATES

equation (2).

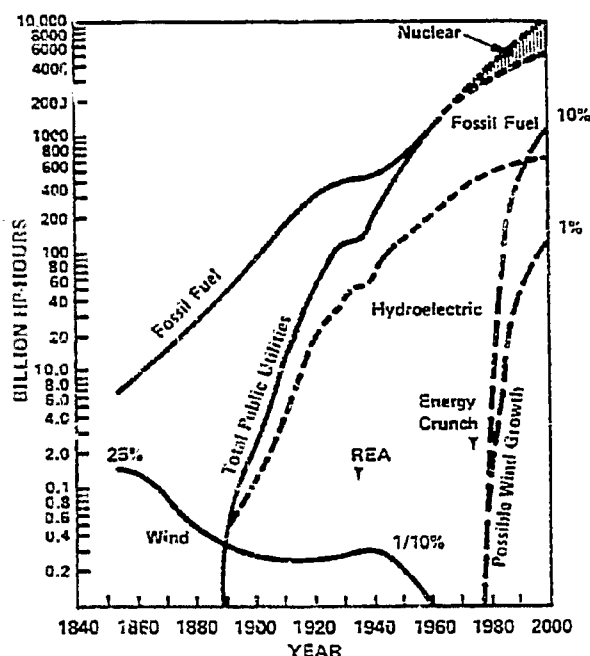
$$P_T = 0.000613 V^3,$$

so that the maximum theoretically obtainable power is, from equation (3) with  $a = 1/3$ ,

$$P_m = 0.000364 V^3.$$

When drag, rotational and other losses are considered, the actual amount of power that can be usefully extracted will vary with design and application and may decrease by 20 to 50% of the theoretically obtained value. Assuming 70% efficiency, only 0.000255  $V^3$  kilowatts can be extracted from a square meter of windmill area, or only about 41% overall efficiency. These values are compared in Figure XVIII-4 as functions of wind speed  $V$  in meters per second. These curves also demonstrate the cubic relationship between power and wind speed: doubling wind speed increases power by a factor of 8. Figure XVIII-5 illustrates the effect of increasing the diameter of the windmill. Since power available increases with the square of the diameter of the windmill, doubling the diameter increases the power available fourfold. For additional information, see Fales.<sup>1</sup>

<sup>1</sup>E. N. Fales, "Windmills," *Mechanical Engineers Handbook*.



Source: NSF/NASA/Utility Wind Energy Conference Report, December 17, 1974.

Figure XVIII-2. U.S. ENERGY PRODUCTION SINCE 1840 - EXCLUDING ENERGY FOR TRANSPORTATION

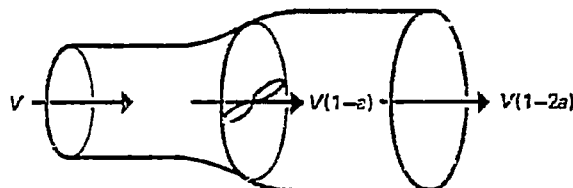
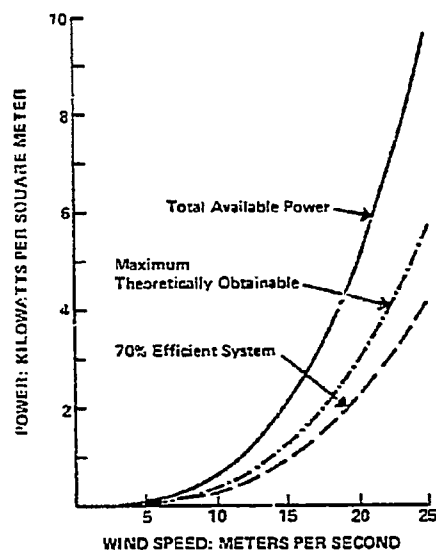
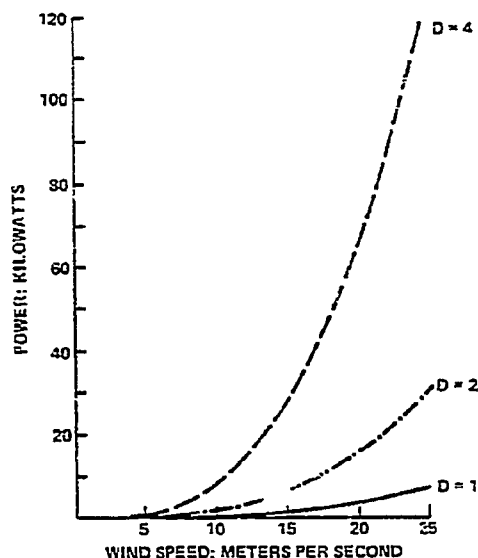


Figure XVIII-3. DIMINUTION OF WIND VELOCITY WHEN TRAVERSING A WINDMILL DISK



Note: 25 Meters/Second Is Approximately 56 Miles/Hour

Figure XVIII-4. ENERGY CONTENT OF WIND



Note: 25 Meters/Second Is Approximately 56 Miles/Hour

Figure XVIII-5. WIND POWER AS A FUNCTION OF TURBINE DIAMETER

## WIND TURBINE DESIGN

There are two primary wind turbine designs: horizontal axis and vertical axis. The horizontal axis designs include the oldest, most common types and generally have been the most comprehensively studied; the vertical axis designs date only from around 1930 and have not been studied as thoroughly. A still more recent third design is represented by the wheeled carriage moving on an oval or circular track of the Madaras<sup>1</sup> (1933) and Montana State University<sup>2</sup> projects. The Madaras project examined the feasibility of using a vertically oriented spinning cylinder to develop the Magnus effect to move the carriage. The Montana State University project examines the use of vertical rigid wings to power the carriage. Electrical power can be generated by the moving carriage in several ways.

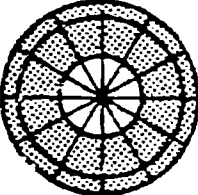
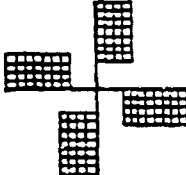
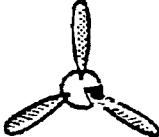
Horizontal axis turbines are typified by the American farm wind turbine commonly used to pump water in the western United States, the Dutch four-arm windmill used to pump water and for light industrial purposes in the Netherlands, and the modern propeller designs with two or three blades commonly used on small generator sys-

tems. Recent large-scale experimental power generation systems have used propeller designs almost exclusively. Figure XVIII-6 compares the general characteristics of these representative designs. The power coefficients ( $C_p$ ) shown are the theoretical maximums for the approximate interference factors of these rotors [from equation (3)] and do not include inefficiencies of the transmission and driven devices.

All three types of horizontal axis designs require some means of keeping the turbine oriented into the wind, usually by a tail or vane. Another system uses a small auxiliary horizontal-axis turbine (fantail) mounted perpendicular to the primary turbine and geared to drive the

<sup>1</sup>D. M. Simmons, *Wind Power*, Noyes Data Corporation, Park Ridge, New Jersey, 1975.

<sup>2</sup>S. J. Savonius (ed), *Wind Energy Conversion Systems*, Workshop Proceedings June 11-13, 1973, NSF/RA/W-73-006, December 1973, PB-231 341.

ROTOR TYPE	$C_{pMAX}$	COMMENTS
 FARM	0.25	HIGH TORQUE, LOW RPM, HIGH LOSSES. HIGH WEIGHT/POWER OUTPUT RATIO. MUST BE TURNED PARALLEL TO HIGH WINDS FOR PROTECTION.  TIP SPEED TO WIND SPEED: ~1
 DUTCH	0.19	HIGH TORQUE, LOW RPM, INEFFICIENT BLADE DESIGN. FABRIC COVER MAY BE REMOVED FROM ARMS FOR PROTECTION IN HIGH WINDS.  TIP SPEED TO WIND SPEED: 2-3
 MODERN PROPELLER	0.47	LOW TORQUE, HIGH RPM, EFFICIENT BLADE DESIGN. THREE-BLADE UNITS GENERALLY LIMITED TO SMALLER APPLICATIONS. TWO-BLADE UNITS OF 200 FEET DIAMETER ARE FEASIBLE. VARIABLE PITCHED BLADES ALLOW SPEED REGULATION, FEATHERING FOR PROTECTION.  TIP SPEED TO WIND SPEED: 6-8

Source: NSF/NASA/UTILITY Wind Energy Conference Report, December 17, 1974.

Figure XVIII-6. COMPARISON OF COMMON HORIZONTAL AXIS WIND TURBINE CHARACTERISTICS



primary turbine into the wind while driving itself out of the wind. By coning the blades—mounting them at an acute angle to the axis rather than perpendicular to it—the turbine can be made to track downwind without the use of a vane.

Vertical axis turbines do not require orientation to the wind because they are omnidirectional, with the axis of rotation perpendicular to the wind regardless of the wind's direction. This omnidirectional characteristic and a capability of delivering power directly to ground level are the primary assets of these turbines. Figure XVIII-7 shows

two types, the Darrieus and Savonius, or S-Rotor. No vertical-axis wind turbine has yet been applied to large-scale commercial projects, although the Savonius rotor has been used as an ocean current meter and for hand-held anemometers.

The Darrieus rotor is becoming commercially available, and is being tested in a few small-scale power-generation applications. Although the Darrieus rotor is not self-starting, it has been combined with the Savonius rotor in experiments at Sandia Laboratories in Albuquerque, New Mexico, to develop a self-starting hybrid unit.

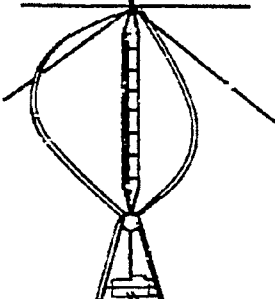

ROTOR TYPE	$C_{pMAX}$	COMMENTS
 DARRIEUS ROTOR	~ 0.35	PATENTED IN 1931 (U.S. AND FRANCE) CURRENTLY UNDER STUDY AT NATIONAL AERONAUTICAL ESTABLISHMENT, OTTAWA, CANADA; AEC's SANDIA LABORATORIES IN ALBUQUERQUE, N.M.; AND NASA's LANGLEY, VA. LABORATORIES. SMALL COMMERCIAL UNITS NOW AVAILABLE  TIP SPEED TO WIND SPEED ~6 TO 8 POTENTIALLY LOW CAPITAL COST CURRENTLY NOT SELF STARTING
 S-ROTOR	~ 0.31	PATENTED IN 1929 (U.S. AND FINLAND) BY S. J. SAVONIUS CURRENTLY USED AS AN OCEAN CURRENT METER OTHER APPLICATIONS SHOWN FEASIBLE DEVELOPMENTAL ALTERNATIVES NOT FULLY INVESTIGATED  TIP SPEED TO WIND SPEED ~.8 TO 1.8 SELF STARTING
VERTICAL AXIS ROTORS OPERATE INDEPENDENTLY OF WIND DIRECTION AND THUS HAVE A POTENTIAL FOR HIGH EFFICIENCY IN CHANGING WINDS		Source: W. Vance, <i>Wind Energy Conversion Systems Workshop Proceedings</i> , June 11-13, 1973, PB-231-341.

Figure XVIII-7. REPRESENTATIVE VERTICAL AXIS WIND TURBINE CHARACTERISTICS

## TURBINE FORCES

Regardless of the configuration, all rotors share the same design problem: they must endure certain stresses and forces induced during operation. Resonance and vibratory forces may be minimized by careful design engineering of the rotor, driven machinery, and support-

ing structure, but aerodynamic and inertial forces must be either countered by strength and rigidity or protected against, or both. Aerodynamic loads are generated by the nonuniformity of wind speed. The mean axial wind component generates thrust forces that deflect the blades

downwind (forced coning), and variations in wind speed induce variations in the coning angle (flapping). Gradients in axial velocity (primarily vertical due to the boundary layer effect) tend to tilt the rotor disk with respect to the shaft, contributing to flapping and aggravating resonance problems at certain rotor speeds. Uneven loading of the blades also induces twisting stresses in the blades. Velocity components perpendicular to the rotor axis produce disk tilting and higher harmonic loadings.

Inertial blade loadings include centrifugal tension due to rotation, lead-lag, and flapping loads due to Coriolis forces arising from blade oscillations. Changes in wind direction produce gyroscopic precessional forces in horizontal-axis turbines as the unit pivots to maintain alignment with the wind vector. Although vertical-axis rotors do not need to track the wind, changes in the angle and direction of tower deflection produce small precessional loadings.

Gravitational forces cause lead-lag bending stresses in large-diameter horizontal-axis turbines, but their effects on most vertical-axis turbines, other than structural loading, have not been fully analyzed and reported.

Two vertical-axis wind turbines under study, i. "Circulation Controlled Panemone" and the Giromill<sup>1</sup>, use variable-pitch blades to flip the blades from a positive to a negative angle of attack. In this concept, the aerodynamic lift force and centrifugal force will alternately reinforce and counter each other during each revolution of a blade, causing abrupt changes in the blade-bending stresses. The severity of the problem has not been fully analyzed, but will depend in part on the abruptness of the blade flips.

<sup>1</sup> Frank R. Eldridge (ed), *Wind Workshop 2. Proceedings of the Second Workshop on Wind Energy Conversion Systems*, The MITRE Corporation, Washington, D.C., June 9-11, 1975, NSF-RA-N75-050, MTR-6970.

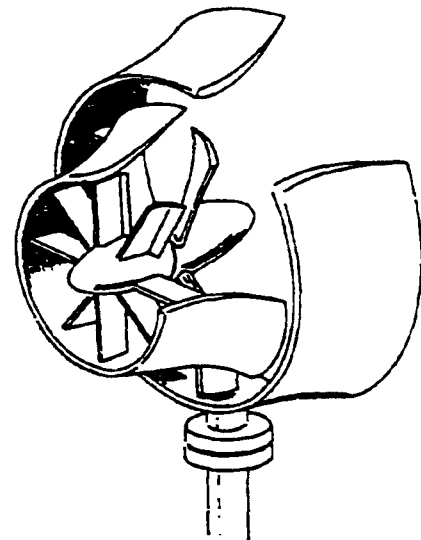
## TURBINE AUGMENTATION

The blades of the wind turbine rotor represent one of the major cost elements; the economics of scaling to larger-diameter turbines have not been fully explored, and they cannot be until the design problems related to aerodynamic and rotational forces in larger systems are solved. Therefore, if a relatively inexpensive method can be devised to increase the energy density of the wind, considerable economic benefits may be realized. Augmentation studies have centered on two primary concepts: shrouding and vortex generation.

### Shrouding

Shrouding consists of constructing a circular tube around the turbine, with the turbine located near the narrowest diameter. A bell-shaped intake and conical tail diffuser complete the device. The axial wind velocity is increased in the throat, thus increasing the power density, or augmenting the turbine. Ozer Igra reported<sup>1</sup> that in wind tunnel experiments conducted at Ben Gurion University in the Negev, Israel, power density was increased by as much as 3.5 times over an equivalent unshrouded turbine operating in the same free-flow velocity. However, optimum shroud geometry required an overall length-to-turbine diameter ratio of approximately 7:1, which would result in unwieldy and probably cost-prohibitive designs in large-scale applications. The main contributor to shroud length was the diffuser cone, so follow-on investigations concentrated in replacing the cone with one or more circular airfoils.

R. A. Oman and K. M. Foreman of Grumman Aerospace Corporation reported<sup>1</sup> encouraging cost-effective studies of diffuser augmentation systems based on preliminary calculations of systems having length-to-turbine diameter ratios on the order of 4:1. Figure XVIII-8 illustrates one type of diffuser-augmented wind turbine.



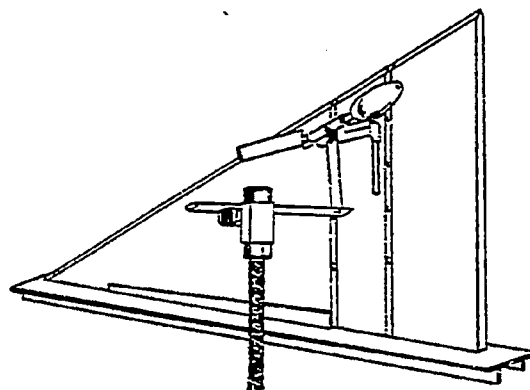
Source: R. Oman and K. Foreman, *Proceedings of the Second Workshop on Wind Energy Conversion Systems*, Washington, D.C., June 9-11, 1975, NSF-RA-N75-050.

Figure XVIII-8. DIFFUSER-AUGMENTED WIND TURBINE

## Vortex Generation

Vortex augmentation uses a wing or other aerodynamic shape to generate a vortex and places the wind turbine in the vortex where the wind energy density is highest. Wind tunnel experiments conducted by P. M. Sforza at the Polytechnic Institute of New York<sup>1</sup> have used delta-shaped surface. Results showed from two to four times the power of an identical unaugmented turbine with 6 m/sec winds, and an ability to run and carry a load at much lower velocities. Figure XVIII-9 shows the basic experimental configuration. Other configurations are being studied in an effort to amplify the vortex generation. Other vortex generation concepts are under study.

<sup>1</sup> Frank R. Eldridge (ed), *Wind Workshop 2*, Proceedings of the Second Workshop on Wind Energy Conversion Systems, The MITRE Corporation, Washington, D.C., June 9-11, 1975. NSF-RA-N-75-050. MTR-6970.



Source: P. Sforza, *Proceedings of the Second Workshop on Wind Energy Conversion Systems*, Washington, D.C., June 9-11, 1975, NSF-RA-N-75-050.

Figure XVIII-9. DELTA SURFACE  
VORTEX AUGMENTOR

## ENERGY CONVERSION

Although in the earliest applications of wind energy there was direct mechanical coupling of the wind turbine to the driven machinery or water pump, such applications severely limit site selection and system configuration, and are of limited potential today. Consequently, all large-scale experimental systems are designed to generate electricity. Although this is less efficient than direct mechanical drive, the advantages more than compensate for the energy conversion losses, particularly in energy transmission and storage. Compressed air conversion offers some of the advantages of electrical generation in that the compressor is relatively light-weight and can be mounted in the power head, and short-range energy transmission and storage are easily done. This concept is within technological capability, but has not yet been fully tested.

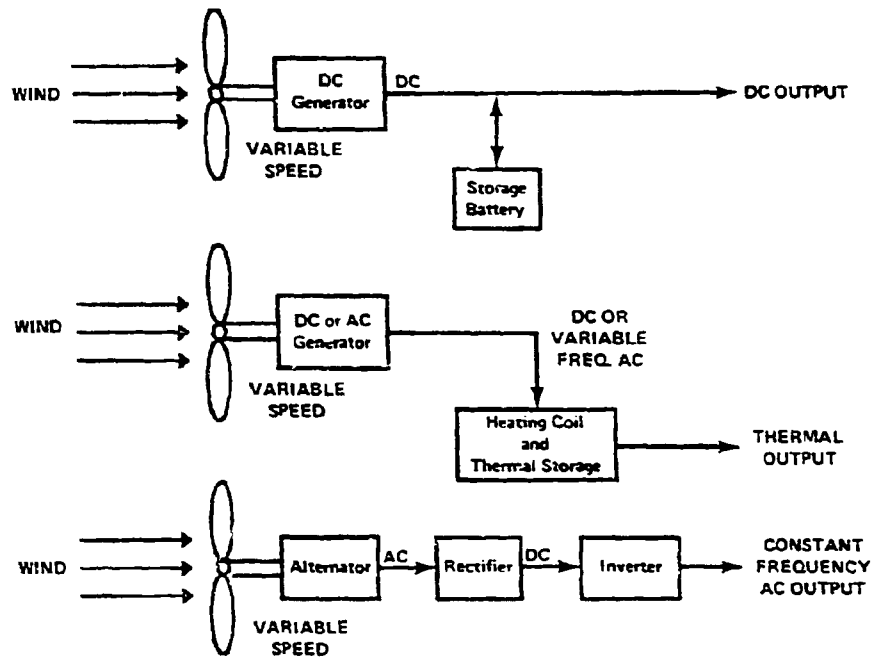
When electrical power is to be generated at remote sites or for local consumption not connected with a power grid, the system can be relatively simple. Either AC or DC may be generated as required. Figure XVIII-10 illustrates several system design schemes.

If the electrical power generated is to be used to supplement a power grid, the output must be fixed-frequency AC (50 or 60 Hz, depending on location). Figure XVIII-11 illustrates three possible schemes. They are significantly more complicated than all but the third

design in Figure XVIII-10. While the use of variable-pitch blades to drive constant speed turbines is costly and complicated, it does provide a blade-feathering capability for securing the turbine and protecting it during high winds. Other systems of speed control do not have this feature, and other means of protection must be provided.

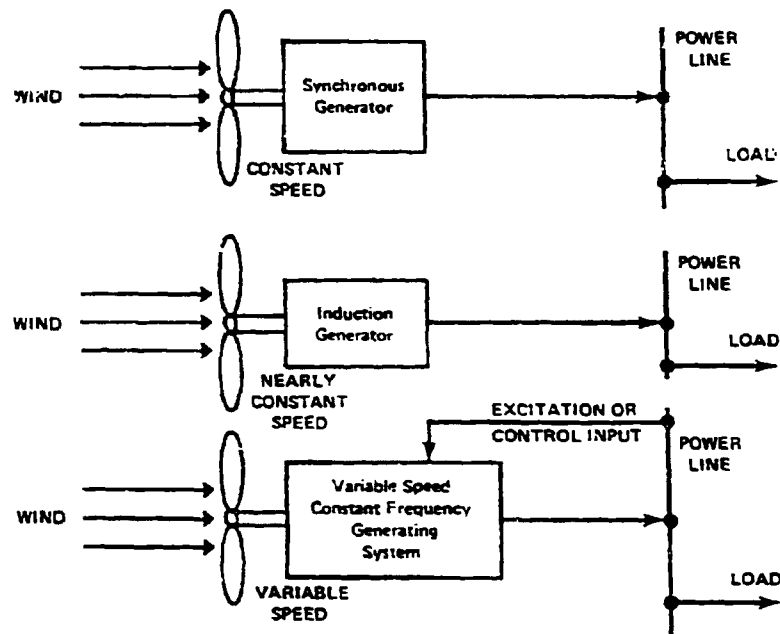
Even though high wind speeds give disproportionately high outputs, it is often not economical to design electrical generating equipment to absorb all the rotor power at maximum wind speeds. Since high winds occur only infrequently, it is more cost-effective to use a small generator that maintains a flat rating and, in most cases, does not seriously degrade overall system performance. K. H. Bergey testified before the House Subcommittee on Energy,<sup>1</sup> that, based on University of Oklahoma wind data, a generator of only half the size required to absorb the maximum wind turbine output will still produce 90 percent of the total wind-turbine power potential at the site. He also noted that the choice of startup speed has very little effect on total power output since the energy content of low-speed winds is quite small.

<sup>1</sup> *Wind Energy*. Hearing before the Subcommittee on Energy of the Committee of Science and Astronautics May 21, 1974, 93rd Congress.



Source: R. Rama Kumar and W. Hughes, *Proceedings of the Second Workshop on Wind Energy Conversion Systems*, Washington, D.C., June 9-11, 1975, NSF-RA-N-75-050.

Figure XVIII-10. SCHEMES TO CONVERT WIND ENERGY TO ELECTRICITY



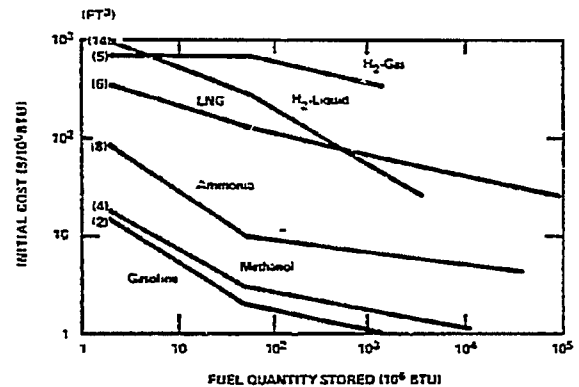
Source: R. Rama Kumar and W. Hughes, *Proceedings of the Second Workshop on Wind Energy Conversion Systems*, Washington, D.C., June 9-11, 1975, NSF-RA-N-75-050.

Figure XVIII-11. SCHEMES TO USE WIND ENERGY AS A SUPPLEMENTARY ELECTRICAL ENERGY SOURCE

## ENERGY STORAGE

Some source of supplementary energy must be available when wind speed is below turbine cut-off speed and when demand is greater than can be provided by the prevailing wind. An energy storage system may also take advantage of those periods when available wind-generated power exceeds demand. Thus, an energy storage/retrieval system is essential if the full potential of wind power is to be realized.

When wind-generated power is used to supplement a power grid, the energy storage problem is reduced to the existing fuel storage problem; but in a self-sufficient wind-power system, excess energy must be stored when available and retrieved during periods of insufficient wind. Table XVIII-1 lists the characteristics of current storage techniques, and Table XVIII-2 compares the energy density of representative storage systems. Figure XVIII-12 compares the investment required for storage of equivalent energy forms.



Source: W. Hauze, *Wind Energy Conversion Systems Workshop Proceedings*, June 11-13, 1973, PB-231-341.

Figure XVIII-12. FUEL STORAGE INVESTMENT (1972 BASIS)

Table XVIII-1  
CHARACTERISTICS OF ENERGY STORAGE TECHNOLOGY

Technology	Typical Economic Module (MWe)	Characteristics		Remarks
		Earliest Commercial Availability	Storage Efficiency (%)	
Batteries	1	1975-82	70-80	Proven Technology
Flywheels	1	1985	70-90	
Hydrogen/Fuel Cells	1	1985	40-60	Storage Options for Hydrogen
Compressed-Air (Adiabatic)	10 (30 MWh)	1982	70-80	High-Grade Thermal
Compressed-Air (Isothermal)	10	1975	NA	Required Fuel
Pumped Hydro	100 (?)	1975	70-75	Special Situations
Superconducting Magnets	500	1995	90	

Source: M. Zlotnick, *Proceedings of the Second Workshop on Wind Energy Conversion Systems*, Washington, D.C., June 9-11, 1975, NSF-RA-N-75-050.

**Table XVIII-2**  
**ENERGY DENSITY OF REPRESENTATIVE STORAGE SYSTEMS**

Means of Storage	Storage Conditions		Energy Density Btu/ft <sup>3</sup>
Mechanical Flywheel Pumped Storage	Optimized Steel 100 ft head		< 43,000 14
Thermal Hot Rocks/Metal	60-500° F		8,000-12,000
Molten Salts	60-500° F		10,000-20,000
Steam	15 psi	212° F	40
	120 psi	347° F	340
	500 psi	467° F	1,270
Water	15 psi	212° F	9,000
	130 psi	347° F	16,000
	500 psi	467° F	21,000
Chemical			
Hydrogen			
• Gas	15 psi	60° F	280
	1,000 psi	60° F	18,500
• Liquid	15 psi	-425° F	200,000
• Hydride (Mg <sub>2</sub> Ni or FeTi)			250,000
Ammonia			340,000
Methanol			430,000
Gasoline			830,000
Batteries			10,000-80,000

Source: W. Hauze, *Wind Energy Conversion Systems Workshop Proceedings*, June 11-13, 1973. #5-231-341.

### FEDERAL WIND ENERGY PROGRAM

The objective of the federal wind energy program is to advance through research, development, tests, and demonstrations, the technologies necessary for implementation by the mid-1980's of commercial wind energy conversion (WEC) systems.<sup>1</sup>

#### Near-Term: 1985

A successful RD&D program whose results would be implemented at an early date by industry could be capable of supporting commercial energy production of 2.5 to 5 x 10<sup>9</sup> kW<sub>e</sub>h per year, saving from 3 to 6 million barrels of petroleum per year.

#### Mid-Term: 2000

Continued commercial implementation of the WEC technology being developed could supply from 120 to 210 x 10<sup>9</sup> kW<sub>e</sub>h of energy annually, saving between 230 million and 410 million barrels of petroleum per year. The equivalent power production capacity contributed by WEC systems, as normalized to an improved equivalent load factor of 0.7, would be 20 to 35 GW<sub>e</sub>.

#### Long-Term: Beyond 2000

By 2020, with continued commercial implementation of WEC technology, power capacity from these systems could be further increased, depending upon availability of suitable wind sites.

The general strategy of the WEC program is to advance the development of WEC technology and performance, stimulate industrial efforts to lower the production cost of WEC units through the use of prefabrication and other techniques, and accelerate, through demonstrations, the application and integration of reliable, economical wind energy systems capable of rapid commercial implementation. This will require the early involvement of potential manufacturers and users to ensure the definition of proper requirements and facilitate the application of WEC systems.

Initial emphasis will be placed on developing and testing systems to establish the feasibility of using large unshrouded horizontal-axis wind turbines for generating

<sup>1</sup>A *National Plan for Energy R&D: Creating Energy Choices for the Future*, ERDA75-1, Vol. 2, June 1976.

electricity at prices competitive with conventional generating systems. Alternative WEC technologies also being developed include vertical-axis rotors, ducted systems, and vortex generators. Alternative energy applications of WEC systems are being considered, and small-scale systems are also being developed for farms and rural homes. With the exception of small-scale heating and irrigation systems, most applications will likely use electricity as an intermediate step, although in some cases unconditioned power may be used leading to lower system costs.

The first systems will be developed for high wind zones with later systems for the larger, more moderate wind zones. The geographical regions for initial applications of WEC have been selected, and major farm demonstrations are planned for the early 1980's.

The principal federal role is to assist the private sector in development of improved WEC technology, and to provide a stimulus for private industry to produce such systems and for utilities and others to use them in suitable applications.

## Program Organization

To accomplish the many tasks involved, this structure of program elements was adopted:<sup>1</sup>

1. Program development and technology
  - Mission analyses
  - Applications/systems analyses
  - Legal/social/environmental issues
  - Wind characteristics
  - Technology development
  - Advanced system concepts
2. Farm and rural home systems
3. 100 kW scale systems
4. MW scale systems
5. Large-scale multiunit systems

<sup>1</sup>Energy Research and Development Administration, *Federal Wind Energy Program Summary (Interim)*, May 1, 1975.

## Program Development and Technology

The objectives of the program development and technology element are to assess the national wind energy potential and identify promising applications, investigate specific systems applications, investigate the wind char-

acteristics associated with the siting and design of single and multiple-unit wind turbine systems, study promising components that have potential for lowering costs of horizontal-axis wind systems, and pursue the development of advanced turbine concepts.

### Mission Analyses

Analyses consist of basic system studies to refine the estimates of wind energy potential of the United States; identify and compare general application, sizes, and systems requirements; determine the impact of various sys-

tems; and assess the general institutional and nontechnical problems involved with achieving acceptance of wind energy systems by public utilities and other users. Included are tasks that support the planning, direction, and integration of the program.

Institution (Project Manager)	Title (Agency, Contract or Grant No.)	Effective Date (Program Dura- tion - months)
General Electric Company Space Systems Organization (E. W. Williams)	Wind energy mission analysis (ERDA, E(11-1) - 2578)	April 14, 1975 (12)
Lockheed-California (Ugo A. Cory)	Wind energy mission analysis (ERDA, AT (04-3) - 1075)	April 23, 1975 (12)
Mitre Corporation (Frank Eldridge)	Dissemination, utilization and coordination of wind energy research (NSF, AER 75 12937)	March 1, 1975 (10)

### Applications of Wind Energy

Application/systems analyses will be made of particular applications and regions (e.g., public utility districts, states) to determine user requirements, wind potential, cost and cost uncertainties, user economic parameters, and system performance, and interface requirements. Specific tasks funded for FY 75 include an investigation of the specific problems associated with the integration of

wind energy systems into an existing electric utility grid, application of wind systems for water pumping in an aqueduct system, and the utilization of wind systems by small municipal utility. Additional regional studies were performed in FY 76. In FY 77-79, these studies will be supplemented by planning activities whereby utilities and users can assess future joint-funded or primarily industry-funded system installations.

Institution (Project Manager)	Title (Agency, Contract or Grant No.)	Effective Date (Program Duration — months)
Southwest Research Institute (Robert K. Swanson)	Operational, cost, and technical study of large wind-power systems integrated with existing electric utilities (ERDA, E(11-1) — 2621)	(12)
Honeywell, Inc. (O. H. Lindquist)	Application of wind systems to the service area of the Minnesota Power and Light Co. (ERDA, E(11-1) — 2618)	
Aerospace Corporation (A. B. Greenberg)	Wind machines for the California aqueduct (ERDA)	
Michigan State University (J. Asmussen)	Application study of wind power to a small city (ERDA, E(11-1) — 2603)	February 1, 1975 (12)

### Legal/Social/Environmental Issues

This subelement will deal with the environmental impact of wind energy systems, legal and regulatory

issues, and the response of the public to the utilization of wind turbines and associated questions on aesthetics and land use.

Institution (Project Manager)	Title (Agency, Contract or Grant No.)	Effective Date (Program Duration — months)
Battelle Memorial Institute Battelle Columbus Laboratories (Sharon E. Rogers)	An evaluation of the potential effects of wind energy systems development (NSF, AER 75 07378)	March 1, 1975 (12)
To Be Determined	Public acceptance and aesthetics issues (NSF)	
To Be Determined	Legal and institutional issues (NSF)	
To Be Determined	Radio frequency interference problem assessment (ERDA)	



## Wind Characteristics

Wind characteristics studies are directed toward improving our ability to locate and evaluate wind sites and will investigate the potential of using short-term wind speed measurements for predicting long-term energy production, wind tunnel modeling of flow over various types of terrain, use of earth resources satellite data for locating

favorable wind energy sites, the effects of spatial averaging of power output from wind turbine arrays, and the effect of terrain on atmospheric boundary layer development. This subelement will derive overall site selection techniques and methods, instrumentation requirements, and basic wind data.

Institution (Project Manager)	Title (Agency, Contract or Grant No.)	Effective Date (Program Duration — months)
Northwestern University (R. B. Corotis)	Stochastic modeling of site wind characteristics (NSF, AER 75-00357)	February 15, 1975 (12)
Colorado State University (R. N. Meroney)	Sites for wind-power installations (NSF, AER 75-00702)	March 1, 1975 (12)
University of Wyoming (R. Marrs)	Locating areas of high wind energy potential by remote observations of aeolian geomorphology (NSF, AER 75-00598)	February 1, 1975 (12)
Science Applications, Inc. (B. E. Freeman)	Research on wind energy conversion systems (NSF-C 1006)	March 17, 1975 (12)
Georgia Institute of Technology (C. G. Justus)	National wind energy statistics for large arrays of aerogenerators (NSF, AER 75-00547)	January 15, 1975 (12)
University of Oklahoma (C. E. Duchon)	Wind velocity as modified by geomorphology (NSF, AER 75-00619)	February 15, 1975 (12)
Research Triangle Institute (Fred M. Vukovich)	An optimum meteorological and air pollution sampling network selection in urban areas: phase II test and evaluation (NSF, AER 75-03230)	(12)

## Technology Development

Technology research is directed toward advancing the performance and lowering the cost of subsystems and components, primarily those of the horizontal-axis, rotor-

type wind energy systems. Specific tasks include advanced rotors and rotor fabrication techniques, innovative generator concepts, aerodynamic and aeroelastic studies, analytical tools, and other systems technology activities.

### Mechanical Subsystem Technology

Institution (Project Manager)	Title (Agency, Contract or Grant No.)	Effective Date (Program Duration — months)
Martin Marietta Laboratories (Peter Jordan)	Improved wind generator rotors through utilization of aeroelastic effects (ERDA, E(11-1) — 2613)	May 1, 1975 (12)
United Aircraft Research Laboratory (M. C. Cheney)	Wind energy conversion system rotor (ERDA, E(11-1) — 2614)	May 15, 1975 (12)
Boeing Vertol Company (Glidden S. Doman)	Structural and dynamic limits to rotors for wind energy conversion (ERDA, E(11-1) — 2612)	May 1, 1975 (12)
NASA/Lewis Research Center (R. L. Thomas)	Testing and evaluation of composite rotor blades at the 100 kW scale	

### Electrical Subsystem Technology

Institution (Project Manager)	Title (Agency, Contract or Grant No.)	Effective Date (Program Duration — months)
Oklahoma State University (R. Ramakumar)	Development and adapta- tion of field modulated generator systems for wind energy applications (NSF, AER 75-00647)	March 15, 1975 (12)
University of Wisconsin, Madison (D. K. Reitan)	A wind power supplementary electric source employing a non-synchronous AC/DC/AC link as an aid in energy management (NSF, AER 75-00812)	March 15, 1975 (12)
University of Wisconsin, Milwaukee (T. S. Jayadevaiah)	Novel electric generation schemes for wind energy systems (NSF, AER 75-00653)	March 15, 1975 (12)

### System Technology

Institution (Project Manager)	Title (Agency, Contract or Grant No.)	Effective Date (Program Duration — months)
Massachusetts Institute of Technology (Rene H. Miller)	Research on wind energy conversion systems (NSF, AER 75-00826)	February 15, 1975 (12)
Boston University (Luigi Morino)	Non-potential aerodynamics for windmills in shear-winds (NSF, AER 75-00548)	February 15, 1975 (12)

Institution (Project Manager)	Title (Agency, Contract or Grant No.)	Effective Date (Program Duration — months)
United Aircraft Corporation Hamilton Standard Division (Carl Rohrbach)	Experimental and analytical research on the aerodynamics of wind-driven rotors (ERDA, E(11-1) — 2615)	May 5, 1975 (12)
Oklahoma State University (W. L. Hughes)	Proposal for continued research on useable windmill power systems (NSF, 75-15722)	(18)
Princeton University (Thomas E. Sweeney)	An advanced technology windmill concept (NSF, AER 75-07908)	(12)
University of Alaska (Tunis Wentink)	Study of Alaskan wind power and its possible applications (NSF, AER 74-00239 A01)	May 1, 1975 (4)
Oregon State University (Robert E. Wilson)	Applied aerodynamics of wind power machines (NSF, AER 74-04014 A03)	April 1, 1975 (12)

#### Advanced Systems

The objective of this subelement is to determine the feasibility and potential of alternative concepts and con-

figurations to obtain significant improvements in cost and performance. Specific studies for FY 75 include diffuser augmentation, vertical axis rotors, and vortex machines.

Institution (Project Manager)	Title (Agency, Contract or Grant No.)	Effective Date (Program Duration — months)
Grumman Aerospace Corporation (R. A. Oman)	Cost effective diffuser augmentation of wind turbine power generation (ERDA, E(11-1) — 2616)	(12)
Sandia Laboratory (B. F. Blackwell)	Vertical axis wind turbine research program (ERDA)	April 15, 1975 (9)
Polytechnic Institute of New York (Pasquale M. Sforza)	Vortex augmentor concepts for wind energy conversion (NSF, AER 75-00850)	(12)
West Virginia University (Richard E. Walters)	Innovative vertical-axis wind machines (NSF, AER 75-00367)	March 1, 1975 (12)
McDonnell Douglas Aircraft (Robert V. Brulle)	Feasibility investigation of the Giromill for generation of electrical power (ERDA, E(11-1) — 2617)	April 1, 1975 (12)
AAI Corporation (R. Bruce Young)	Production of methane using offshore wind energy (NSF — C993)	April 1, 1975 (18)

### Farm and Rural Home Systems

The objectives of the farm and rural use systems are to identify potential applications of wind energy on farms, perform system studies of those applications with high potential, and to develop systems for them. Specific tasks funded for FY 75 include investigation of hydrogen pro-

duction and utilization, stream and pond aeration, and wind-powered space heating. Other potential applications include crop drying, refrigeration of dairy products, and fertilizer production. Many wind energy projects in this element will be coordinated and managed by USDA for ERDA.

Institution (Project Manager)	Title (Agency, Contract or Grant No.)	Effective Date (Program Duration - months)
Institute of Gas Technology (J. B. Panghorn)	Wind-powered hydrogen electric systems for farm and rural use (NSF, AER 75-0072)	(9)
University of Massachusetts (W. E. Heronemus)	Investigation of the feasibility of using windpower for space heating in colder climates (NSF, AER 75-00603)	March 15, 1975 (12)
Colorado State University (Anthony L. Frey)	Wind powered aeration for remote locations (NSF, AER 75-00833)	March 15, 1975 (18)

### 100 kW Scale Systems

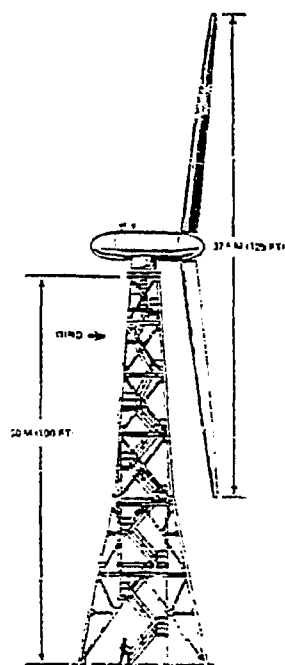
The objectives of the 100 kW scale systems program are to develop systems of this size for both direct use and to support the development of much larger systems. Initial objectives are to determine the accuracy and validity of present performance- and cost-estimating techniques; identify and investigate technical, operational, environmental and maintenance problems; develop experience for planning, contracting, and managing larger and more advanced systems; and provide a tool for testing present and future components.

The Model 0 100 kW system has been designed by NASA-Lewis Research Center. The system, which is the largest constructed in 30 years, started test operations in September 1975. The system continued in use in FY

1977 for a lifetime and operating problem test program and as a testbed for components, particularly those developed under the technology research subelement. Additional 100 kW systems will be erected in future years with the designs based on the results of the MW scale systems studies. Except for Model 0 and small experimental systems, future systems in this and larger sizes will be constructed by industry and installed for testing in user applications at field sites, under contracts from ERDA.

Figure XVIII-13 is an illustration of the Plumbrook 100 kW installation, Figure XVIII-14 summarizes its operational power specifications. Table XVIII-3 summarizes the costs of the experimental unit.

Institution (Project Manager)	Title (Agency, Contract or Grant No.)	Effective Date (Program Duration - months)
NASA/Lewis Research (R. L. Thomas)	100 kW Scale System (Model 0) (ERDA, AG-518)	March 12, 1975 (24)
Lockheed Aircraft Company	Rotor blade design and manufacture	



General Specifications of 100 kW Test Sec

Power:	
Blade Power (Assuming 7° Casing, 0° Inclination), kW	133
Generator Output, kW	100
Desired Rotor Power Coefficient	3.275
Cut-in Wind Speed (First Load Applied), M/Sec	3.52 (8 MPH)
Rated Wind Speed (100 kW Bus), M/Sec	7.32 (16 MPH)
Feather Wind Speed, M/Sec	28.4 (63 MPH)
Hurricane Wind Speed, M/Sec	66 (150 MPH)
Location To Rotor with Respect to Tower	Downwind
Direction of Rotation (Looking Up-Wind)	Counterclockwise

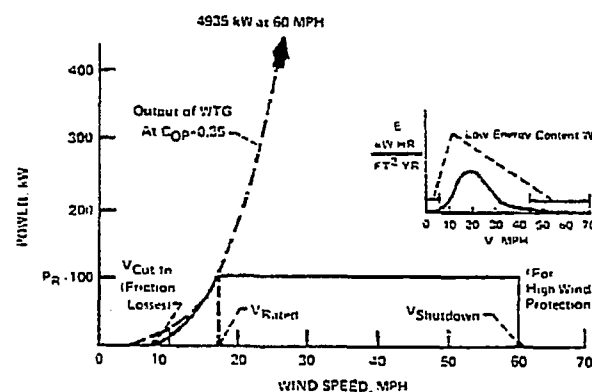
Source: R. Thomas, et al., *Plans and Status of the NASA-Lewis Research Center Wind Energy Project*, NASA TM X-71701, 1975.

Figure XVIII-13. 100-KW EXPERIMENTAL WIND TURBINE GENERATOR (WTG)

Table XVIII-3  
SUMMARY OF COSTS FOR 100 kW EXPERIMENTAL WTG AND SIMILAR FOLLOW-ON WTG SYSTEMS

	First 100 kW Experimental WTG		Follow-On 150 kW WTG Systems	
Rotor				
Blades	160 K	50.4%	140 K	64%
Hub Pitch/Change	95 K		50 K	
Mechanical				
Gear Box	11.5 K	10.8%	11.5 K	10.5%
Bearing, Shafts, Etc.	43 K		20 K	
Electrical Generator, Controls	68 K	13.5%	25 K	8.5%
Tower, Foundation	120 K	25.3%	50 K	17%
Total	\$505 K		\$296.5 K	
	\$/kW ~ \$5000/kW		~ \$2000/kW	

Source: R. Thomas, et al., *Plans and Status of the NASA-Lewis Research Center Wind Energy Project*, NASA TM X-71701, 1975.



Source: R. Thomas, et al., *Plans and Status of the NASA-Lewis Research Center Wind Energy Project*, NASA TM X-71701, 1975.

Figure XVIII-14. POWER OUTPUT OF 125-FT DIAMETER WTG RATED AT 100 KW IN WINDS OVER 18 MPH

### MW Scale Systems

Individual systems between 1 and 3 MW are estimated to be the minimum sizes required for proof of practicality and economic feasibility for eventual large-scale use. Under the project management of NASA-Lewis Research Center, two

parallel contracts are under way for the preliminary design of MW scale systems. At least one MW scale system will be erected in the next few years to obtain performance and cost data.

Institution (Project Manager)	Title (Agency, Contract or Grant No.)	Effective Date (Program Duration - months)
NASA/Lewis Research Center (R. L. Thomas)	MW scale systems (Model 1) (NSF - CA 139)	October 18, 1974 (12)
General Electric Company	Conceptual and preliminary design	
Kaman Aerospace Corporation	Conceptual and preliminary design	

### Large-Scale Multiunit Systems

The eventual large-scale use of wind turbines for commercial power production will be in multiunit systems. The optimum economical size for individual wind turbines will be determined from the MW scale systems studies. Two problems with multiunit systems are the interconnection, stability, and interfacing requirements and the

spatial distribution requirements of networks of large wind energy systems. Both the minimum possible spacing and the effect of spatial wind distribution on the smoothing of power output are important. These problems are under investigation. Several large-scale multiunit systems are planned for operation by 1980.

**CHAPTER XIX**

**ELECTRIC POWER GENERATION**

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## INTRODUCTION

At the end of 1975, electric power accounted for 28 percent of the total annual energy consumption in the U.S.<sup>1</sup> In 1970, the electric utilities industry in the continental United States was comprised of approximately 3500 privately and publicly owned systems. Over 2400 of these systems provided distribution only, indicating that about 1100 generating systems provided all of the electric power.<sup>2</sup>

In the period 1945 through 1973, electric energy production increased at an average annual rate of nearly 8 percent, as shown in Table XIX-1. The drastic increase in oil prices by the Organization of Petroleum Exporting Countries (OPEC) in the last quarter of 1973, combined with the growing economic recession, had a significant impact on national energy demands. In 1974, electric energy production increased only 0.38 percent over the previous year and in 1975 production grew only 2.57 percent. During the first eleven months of 1976, electric energy production increased 6.3 percent compared with the same period in 1975, as the nation partially recovered from the economic slump. Electric utility analysts and energy forecasters, both within and outside government, are not confident, however, that the electric energy production growth rate will, at any time during the next ten years, or perhaps ever, return to the historical growth rate. Federal Power Commission staff, having examined various projections, consider that through 1985, a reasonable median projection of electric energy production will be that shown in Table XIX-1.

This median projection represents an average 6.5 percent annual rate of growth during the 1975-1980 period and an average rate of slightly more than 6 percent annually for the entire 10-year period through 1985. Actual growth is likely to remain within 4 to 7 percent.

Table XIX-1

### U.S. NET ELECTRIC ENERGY PRODUCTION 1945 THROUGH 1985

Year	Billions of Kilowatt Hours
1945	222
1960	753
1970	1494
1973	1860
1975	1916
1980	2618
1985	3487

Source: *Factors Affecting the Electric Power Supply, 1980-85*, Federal Power Commission, December 1, 1976.

<sup>1</sup> *Factors Affecting the Electric Power Supply, 1980-85*, Federal Power Commission, December 1, 1976.

<sup>2</sup> *The 1970 National Power Survey, Part I*, Federal Power Commission, 1971.

## FUEL SOURCES FOR ELECTRIC POWER

The anticipated growth and power generation mix is shown in Figure XIX-1. In 1975 coal-fired generation accounted for 44 percent of total generation; nuclear generation accounted for nearly 9 percent; the remainder was almost equally divided among oil-fired, gas-fired, and hydroelectric generation.

Consumption of gas for electric power generation peaked in 1971-72. Its use by electric utilities is expected to decline at an average annual rate of 4 percent. In spite of national policy to reduce oil demand and imports, electric utility use of oil will increase until the mid 1980's. The additional quantities of oil will be required to satisfy the needs of new oil-fired, steam-electric units,

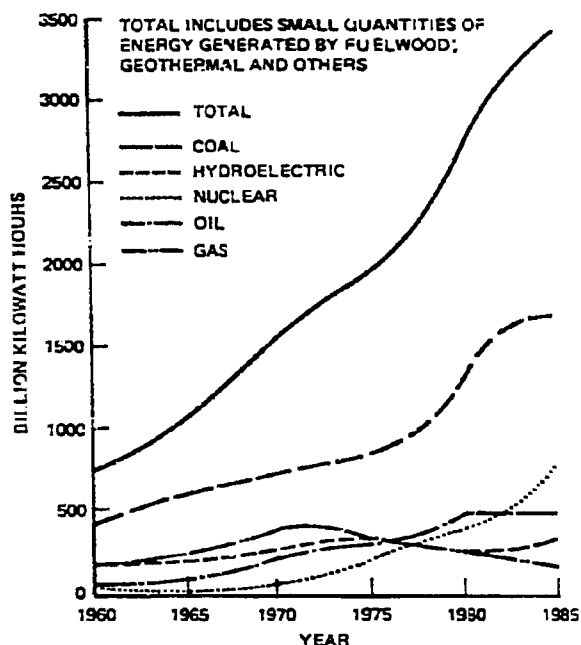
which were under construction before the oil embargo, of new combustion turbine and combined-cycle units to replace gas in plants where gas is being curtailed, and of filling energy gaps when they arise.

Electric utility oil use will stabilize during 1980-85 at a level of nearly 60 percent above that of 1975. A steady

decline in oil use should take place after 1985. With most of the hydroelectric potential already exploited, future growth in generation will come from coal-fired and nuclear plants.

The projected electric utility fossil and nuclear ( $U_3O_8$ ) fuel use corresponding to the power generation mix projected in Figure XIX-1 is shown in Table XIX-2 and Figure XIX-2.

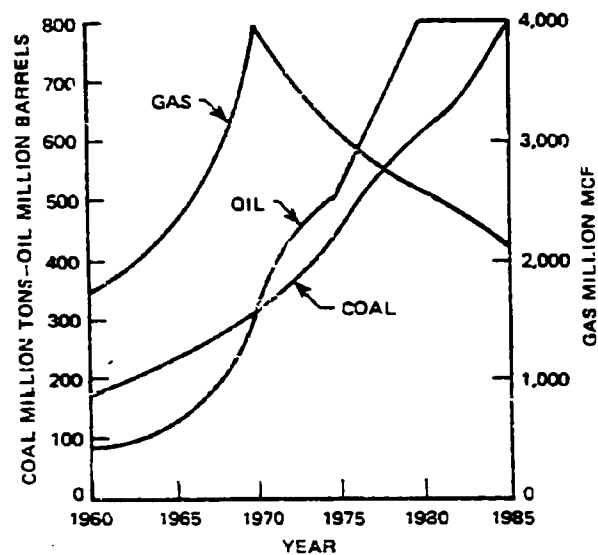
In 1975 other energy sources, principally geothermal, wood fuel, and small quantities of solid waste accounted for 0.2 percent of the total power generation. Geothermal generation and the use of refuse-derived fuels mixed with coal are expected to increase, while solar, wind, and tidal generation continue to remain essentially in the research and development stages. By 1985, these forms of generation will contribute only about 0.6 percent of the total. However, solar energy in its thermal form has enormous potential and is likely to make significant contributions to overall energy demands in the period after 1980.



Note: Fuel demand projections are based on the general assumption that electric energy demand will grow at an average growth rate of 6% per year during the period to 1985.

Source: *Factors Affecting the Electric Power Supply, 1980-85*, Federal Power Commission, December 1, 1976.

Figure XIX-1. NET GENERATION



Note: Fuel demand projections are based on the general assumption that electric energy demand will grow at an average growth rate of 6% per year during the period to 1985.

Source: *Factors Affecting the Electric Power Supply, 1980-85*, Federal Power Commission, December 1, 1976.

Figure XIX-2. FOSSIL FUEL CONSUMPTION BY ELECTRIC UTILITIES

## CONSERVATION

Actions to reduce electric energy and peak load requirements are essential to minimize the need for new capacity, to improve the adequacy of the electric power supply, and to hold down rate increases. Improving the insulation of existing houses is an effective conservation measure. Analyses demonstrate that the cost of additional insulation can be recovered through reduced utility

bills. Active promotion of consumer conservation will continue to be one of the most effective tools to hold demand growth to the lowest levels consistent with reasonable growth of the economy. Conservation is just one of the actions that must be taken to ensure future power supplies.

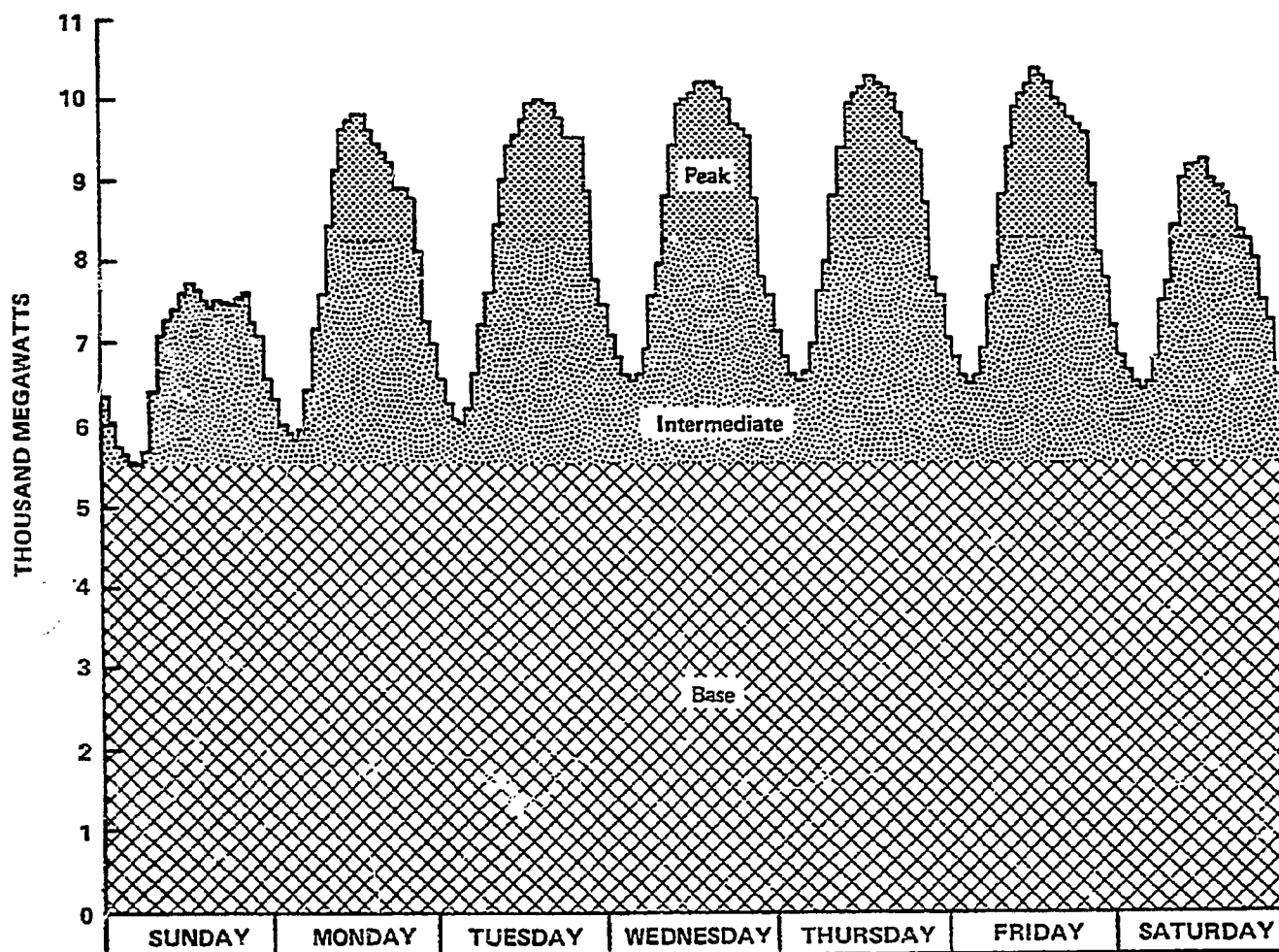
## COST OF ELECTRIC POWER

Cost of electricity remained relatively constant for the 10 years before 1970 at mean national levels of 2 cents per kilowatt hour for commercial users and 3 cents per kilowatt hour for residential users. However, recent increases in the cost of fossil fuels have resulted in corresponding rate increases. Average industrial, commercial and residential rates were 3.7, 4.7, and 4.7 cents per kilowatt hour, respectively, at the end of 1976.<sup>1</sup>

As the size of generating units increases, the cost per kilowatt hour of energy delivered decreases. Conse-

quently, steam-electric generator unit sizes have been increasing from an average unit rating of 35 megawatts in 1955, to 66 megawatts in 1968, to an expected 160 megawatts in 1980. The largest steam generator unit in service in 1970 was rated at 1,150 megawatts. By 1990, the size of single-shaft turbine generators may exceed 2,000 megawatts. A powerplant may use two or more

<sup>1</sup> Federal Power Commission, *Typical Electric Bills*, December 1976.



Source: *The 1970 National Power Survey, Part I*, Federal Power Commission, December 1971.

Figure XIX-3. WEEKLY LOAD CURVE

large fossil-fueled or nuclear steam-powered generators to provide base load service and other smaller electric generators to meet peak load and intermediate services Figure XIX-3 shows a typical weekly load curve.

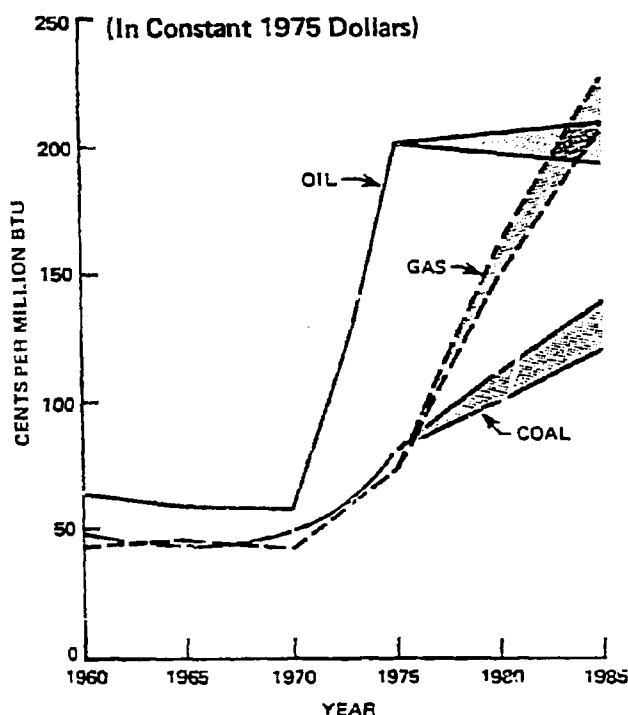
By 1985, gross energy consumption by electric utilities is expected to reach the equivalent of 36 quadrillion Btu. The declining use of natural gas conforms with national policy. The increasing use of oil, however, does not, and utilities will for the time being depend more heavily on foreign oil, adding to the dollar drain. Coal resources are plentiful, and the projected increase in coal demand should not present any mine supply problems. However, the ability of the transport industry to deliver enough fuel to meet the growing electric utility industry require-

Table XIX-2

PROJECTED FOSSIL AND NUCLEAR ( $U_3O_8$ )  
FUEL REQUIREMENTS  
1980 AND 1985

Fuel	Units	1975 Actual	1980	1985
Coal	Million tons	406	570	770
Oil	Million barrels	507	800	800
Gas	Million mcf	3113	2600	2100
$U_3O_8$	Thousand tons:			
	No recycle	12.7	30.7	61.5
	With recycle	12.7	29.6	54.5

Source: *Factors Affecting the Electric Power Supply, 1980-85*, Federal Power Commission, December 1, 1976.



Source: *Factors Affecting the Electric Power Supply, 1980-85*, Federal Power Commission, December 1, 1976.

**Figure XIX-4. COST OF FOSSIL FUELS TO STEAM ELECTRIC PLANTS**

ments without significant renovation and additions is in some doubt. Indigenous uranium resources appear to be adequate to satisfy the cumulative requirements of the industry through 1985, but in the absence of acceptable breeder technology the domestic resources will be strained severely in the 1990s.

**Table XIX-3**

**NATIONAL AVERAGE FOSSIL FUEL PRICES TO ELECTRIC UTILITIES**

	Actual Costs In Cents Per Million Btu			Projected Costs In Constant 1975 Dollars		
	1973	1974	1975	1980	1982	1985
Coal	40.5	71.0	81.4	110	120	130
Oil	80.3	192.2	202.0	200	200	200
Gas	34.7	48.7	75.4	155	180	220

Source: *Factors Affecting the Electric Power Supply, 1980-85*, Federal Power Commission, December 1, 1976.

The strong demand for coal will increase the price as the marginal cost of mining the less advantageous resources increases. Although overall gas use for electric power generation will decline, the price of gas to electric utilities will continue to increase rapidly as the bulk of the gas is used by utilities in the southwest region where it is sold in unregulated intrastate markets. The already high price of oil probably will remain relatively stable and future prices will increase only to adjust for global inflation. Table XIX-3 and Figure XIX-4 show FPC staff estimates of future electric utility fossil fuel prices expressed in constant 1975 dollars.

The Energy Research and Development Administration (ERDA) estimated the 1974 nuclear fuel cost at 2.15 mills/kwhr (1974 dollars), including a 0.49 mills/kwhr plutonium credit. The Nuclear Regulatory Commission (NRC) projects the 1982 cost at 5.14 mills/kwhr (1974 dollars), including a 0.68 mills/kwhr credit.

## TYPICAL ELECTRIC POWER STATION

As Figure XIX-5 shows, a typical fossil-fueled steam plant burns coal or residual fuel oil in large boilers. Water heated into high-pressure steam expands in tandem-compound turbines, which convert fuel energy into mechanical power and then to electric power through electric generators. Low-energy steam leaving the turbines is condensed and pumped back to the boilers, where it is heated into steam again; the cycle is then repeated. Exhaust from combustion is treated through cyclone

separation or electrostatic precipitation to reduce particulate contents. Limestone scrubbing processes are being studied to reduce particulate and sulfur oxide content emissions. Condensing systems can use river water, a cooling pond, and wet or dry cooling towers to dispose of waste heat from the powerplant. In a nuclear power station, controlled nuclear fission provides heat for producing high-pressure steam. Chapter XII provides details of nuclear reactor types and cycle characteristics.

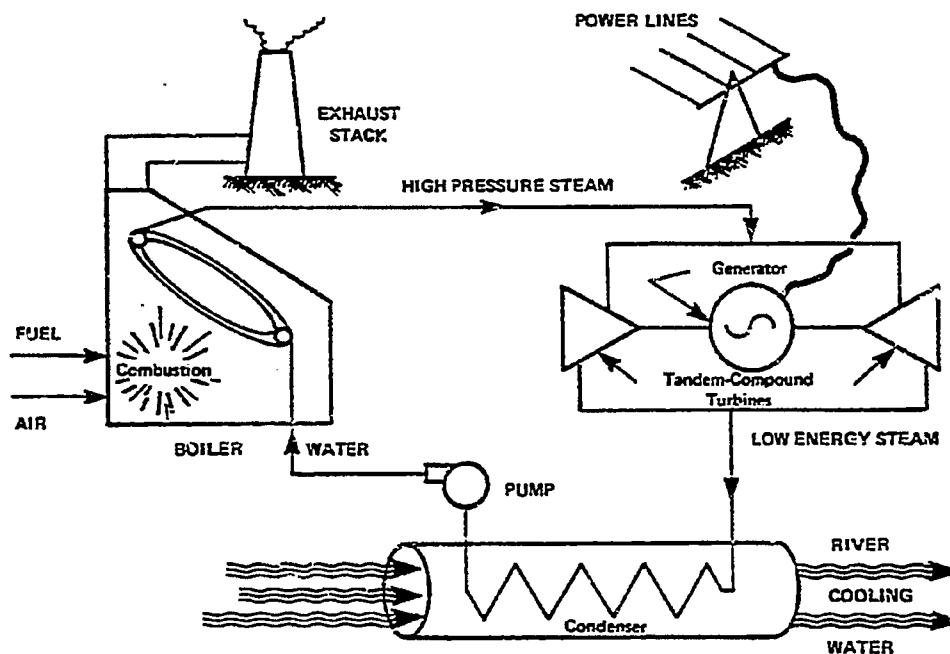


Figure XIX-5. SCHEMATIC OF FOSSIL-FUEL-FIRED STEAM PLANT

### STEAM TURBINE EFFICIENCY

The efficiencies of steam turbines have been relatively constant since 1964 with initial pressures of up to 3500 psi and initial and reheat temperatures of 1000° F. Plants designed to these conditions have achieved heat rates (Btu's required to produce one kilowatt hour) as low as 8,633 Btu per kilowatt hour. This heat rate reflects a 39.5 percent overall thermal efficiency. The current average heat rate of fossil fuel steam plants is approximately 10,000 Btu per kilowatt hour, which is equivalent to a thermal efficiency of 34 percent. Steam turbines have been designed for maximum initial steam conditions of 6,000 psi and 1,200° F, but special metals are required to withstand these conditions. One turbine-generator unit

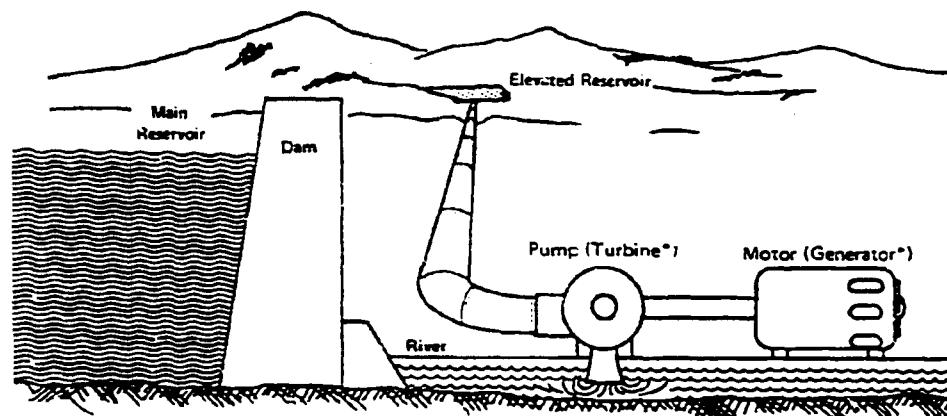
that has been in operation with initial steam conditions of 5,000 psi and 1,200° F has established the national heat rate record of 8,534 Btu per kilowatt hour, which reflects a 40 percent overall thermal efficiency. However, the electric power industry has determined that the expense of installing and maintaining the special metals required for high-performance steam has not been justified by the small efficiency gains. Consequently, utilities are reverting to the 3,500 psi and 1,000° F maximum steam conditions as practical design limits.<sup>1</sup>

<sup>1</sup> Federal Power Commission, *The 1970 National Power Survey, Part I*, December 1971.

### HYDROELECTRIC POWER

The largest hydroelectric plant in the United States is the Grand Coulee plant on the Columbia River in Washington, with an installed capacity of 2,066 megawatts. Only 10 of the approximately 120 hydroelectric plants over 100 megawatts in the United States have installed

capacities greater than 800 megawatts, and less than 20 plants have installed capacities greater than 500 megawatts. A major utility system may be required to provide a maximum of several thousand megawatts, and only the largest of hydroelectric plants can produce the base load



\*When water is allowed to flow back down to river, pump becomes turbine and motor becomes generator.

Figure XIX-6. TYPICAL PUMPED STORAGE CONFIGURATION

power that is typically half the maximum power required of a major utility system. Hydroelectric plants are, therefore, often used to provide intermediate or peak load power rather than base load power.

Pumped storage installations, depicted in Figure XIX-6, normally use reversible pump-turbine units to pump receiving basin water to an upper reservoir. After losses, approximately two-thirds of the pumping energy can be recovered through hydroelectric conversion of the potential energy stored in the elevated reservoir.

Pumped storage reservoirs are normally designed to provide 10 to 20 hours of full load operation. In the load profile, illustrated in Figure XIX-7, nuclear- or fossil-fueled steam units provide power for the base and inter-

mediate loads, and conventional hydroelectric power supplies part of the peak load. Pumped storage and other peaking units would then provide the very peak load power requirements. As shown in the figure, pumped storage capacity may be equivalent to the conventional hydroelectric power capacity. Also shown in Figure XIX-7 is the timing of the pumping cycle: pumping occurs during off-peak hours at night through the week, with extra pumping time during the lower weekend loads.<sup>1</sup>

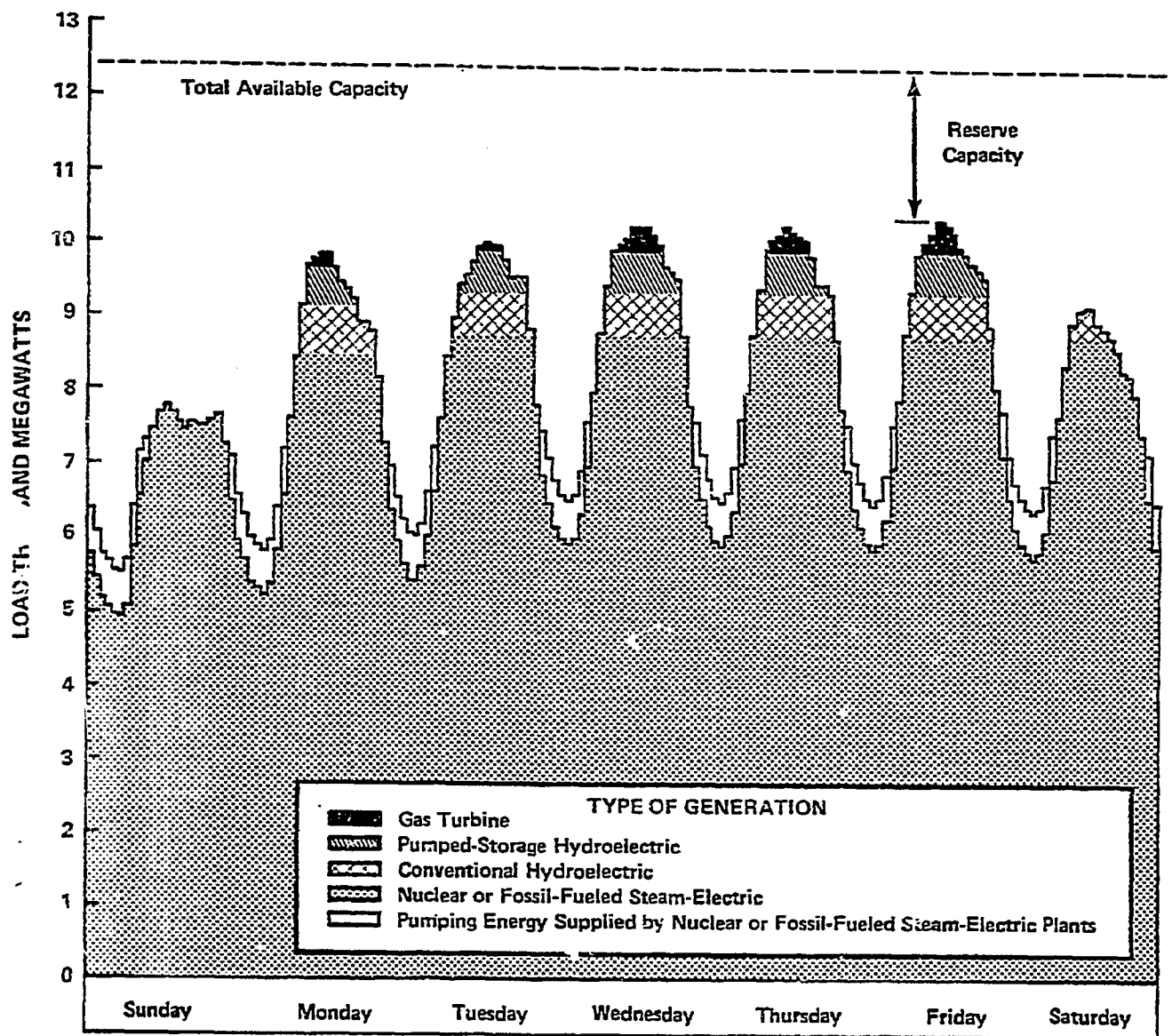
<sup>1</sup> Federal Power Commission, *The 1970 National Power Survey, Part I*, December 1971.

## GAS TURBINES

Gas turbines are used primarily for peak loads, as indicated in Figure XIX-7. Adapted from jet aircraft technology, gas turbine units may be rated at up to 100 megawatts (134,000 horsepower). Large generators may be driven by multiple turbine units. While frequent maintenance inspections are required, repair is facilitated by the light weight of most commercial units. Overhaul intervals may range from 2,000 to 5,000 hours.

The life of critical components such as the first stages of turbine vanes and blades depends on the maximum

operating gas temperatures for the turbine. Maximum gas temperatures today are limited to 1800° F to 2000° F to achieve reasonable life spans for components. The maximum operating temperature also establishes the maximum potential efficiency of the gas turbine. Heat rates of gas turbine plants can range from 12,500 to 15,500 Btu per kilowatt hour at full load, reflecting thermal efficiencies of 27 to 22 percent, respectively. As turbine materials are developed to accept maximum gas temperatures of 2,500° F, as may be feasible with ceramics in the near



Source: *The 1970 National Power Survey, Part I*, Federal Power Commission, December 1971.

Figure XIX-7. POWER GENERATION TO MEET WEEKLY LOAD

future, turbine thermal efficiencies will increase significantly.<sup>1</sup>

The initial low cost of gas turbine generators, \$70 to \$130 per kilowatt, is offset by the higher operating costs of using light petroleum distillates or natural gas fuels.

<sup>1</sup>Federal Power Commission. *The 1970 National Power Survey, Part I*. December 1971; J. W. Sawyer and R. C. Farmer. *Gas Turbines in U.S. Electric Utilities*, January-February 1975, pp 21-39; *Part II*, March-April 1975, pp 13-25.

## DIESEL GENERATORS

Heavy-duty, low-speed diesel generators available from domestic manufacturers are rated at power levels up to 6 megawatts. Foreign manufacturers offer units rated up to 25 megawatts. Intermediate-speed, light-weight units are generally available at power levels up to 2 megawatts. Diesel engines are used in multiples for base-load and for peak-load operations. Diesel generator heat rates range from 12,000 to 13,500 Btu per kilowatt hour, comparable to the heat rates of gas turbine generators at full-load conditions; however, diesels can maintain their design point efficiencies at reduced power levels. Diesels

use the lighter, more expensive fuels that gas turbine use. The low capital cost, modularity, high response and ease of maintainability advantages of gas turbines, are also found with diesels. However, compared to gas turbines, the specific power (hp/lb) and power density (hp/ft<sup>3</sup>) characteristics of diesel units are very low. Diesels are, consequently, very large and very heavy for the power they produce, compared with gas turbines.<sup>1</sup>

<sup>1</sup> Federal Power Commission, *The National Power Survey, Part I*, December 1971.

## TOTAL ENERGY SYSTEMS

A typical "total energy system" (TES) is comprised of a gas turbine or a diesel generator that uses waste heat to provide water heating, space heating, steam production or air conditioning for a self-dependent facility. By recovering this exhaust energy, the independent electric utility service of the TES may become economically attractive. The simple-cycle gas turbine is able to convert only 10 to 25 percent of the heat energy of the fuel to shaft-horsepower. Gas turbine exhaust temperatures may range from 600° F to 1200° F, relatively high temperature for space heating, water heating or for producing low-pressure steam. Low-pressure steam can be used to drive an absorption air conditioning system.<sup>1</sup>

A well-designed heat exchanger can recover over 85 percent of the exhaust heat from the prime turbine mover. Consequently, waste-heat recovery systems can have total thermal efficiencies above 80 percent. The exhaust gases from the turbine are relatively clean and normally contain no measurable quantities of carbon monoxide, oil, or other pollutants. Total energy systems are being applied to apartment complexes, shopping centers, educational institutions, office buildings, and certain commercial and industrial functions that require hot air or process steam. The gas turbines for these systems can be designed for "dual fuels;" that is, for either natural gas or diesel fuel oil interchangeably. The "dual fuels" option allows a user to buy natural gas at the more economical interruptible rates and still maintain availability through switching to diesel fuel oil as necessary. Total energy systems have been designed for steam plant prime units and for combinations of several different prime unit types.<sup>1</sup>

Although a TES appears very attractive from its efficiency and flexibility characteristics, total energy systems are not expanding their share of the total power supplied in the United States. To cope with normal maintenance or unscheduled outages, provisions for utilizing power from a local central power station may be required. The cost of having auxiliary power available to compensate for outages tends to offset the advantages of the independence of the TES. The light fuels used by total energy systems are relatively expensive, and operation and maintenance of gas turbine units require specialized skills. The cost of maintenance and special skills per unit of energy produced will be higher with a TES than the cost of a central power station. Consequently, the TES may be economically competitive with central power only in certain special applications and where the economic environment encourages expanding to marginal applications. However, central power stations may themselves enter the total energy systems market where a concentrated demand for heating and cooling accompany electric power requirements.<sup>3</sup>

<sup>1</sup> Federal Power Commission, *The 1970 National Power Survey, Part I*, December 1971; H. Richmond D. Sage, "The Challenge of Total Energy," 1964 *Gas Turbine Catalog*, 1964; J. J. Kennedy, "The Application of Total Energy," 1965 *Gas Turbine Catalog*, 1965.

<sup>2</sup> H. Richmond and D. Sage, "The Challenge of Total Energy," 1964 *Gas Turbine Catalog*, 1964; J. J. Kennedy, "The Application of Total Energy," 1965 *Gas Turbine Catalog*, 1965.

<sup>3</sup> Federal Power Commission, *The 1970 National Power Survey, Part I*, December 1971.



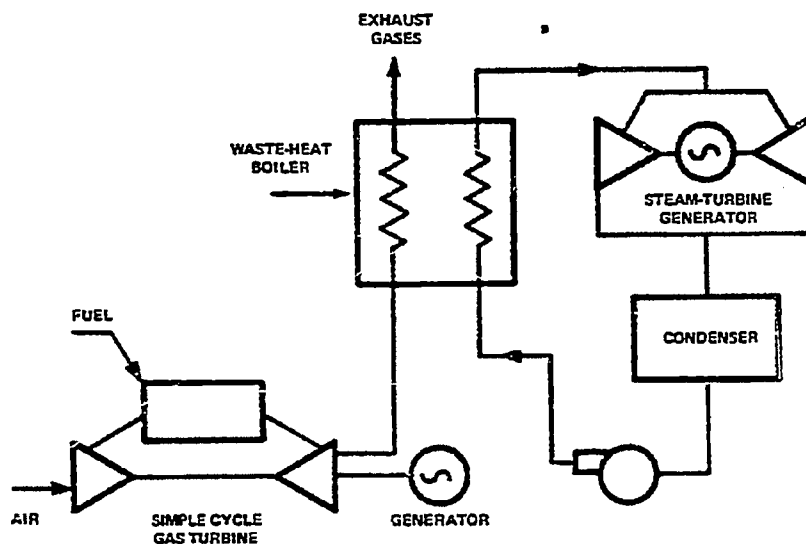


Figure XIX-8. COMBINED CYCLE SCHEMATIC

### COMBINED CYCLE SYSTEMS

A gas-turbine/steam-turbine combined cycle is illustrated in Figure XIX-8. A waste-heat boiler recovers high-temperature heat from gas turbine exhaust gases. The boiler generates steam, which drives a steam turbine generator. This cycle is essentially a total energy system that uses product steam to generate additional power. The gas turbine uses the highest temperatures of combustion to extract power at 10 to 25 percent efficiency; the lower temperature exhaust energy is then used by a steam plant to generate power in excess of 30 percent efficiency. By "topping" the steam plant with a gas turbine plant this way, overall combined cycle efficiencies above 45 percent are feasible. However, very few combined cycle systems

are being installed because of the relatively high cost of the natural gas or the light fuel oil required by the gas turbine. Unless gas turbines can be developed to burn coal, conventional steam plants will continue to have an economic advantage over combined cycle systems because of the higher combined cycle fuel costs. Although the direct burning of coal by a gas turbine does not appear technically practical, coal gasification technology may eventually provide a relatively inexpensive low-Btu synthetic gas as a future gas turbine fuel. The use of residual fuels by gas turbines is also being developed, and this alternative fuel may also favorably change the economic competitiveness of the combined cycle.

### AIR POLLUTION CHARACTERISTICS OF FOSSIL-FUELED ELECTRIC PLANTS

Electric utilities are major contributors to air pollution.<sup>1</sup> The Environmental Protection Agency has estimated that the electric utilities were responsible for 50 percent of sulfur oxides, 20 percent of the nitrogen oxides, and 20 percent of particulate matter discharged in

1968 on a nationwide basis. Most of this air pollution product was the result of burning coal as a basic fuel.

<sup>1</sup>Federal Power Commission, *The 1970 National Power Survey*, Part I, December 1971.

However, despite this pollution by-product of the electric utilities, the amount of carbon monoxide from transportation was over twice (by weight) the total pollution by-product of the utilities.

Recent legislation specifically restricts the amounts of various air pollutants that electric utilities may emit per million Btu's of fuel consumed. Cyclone separators and electrostatic precipitators are widely used by the electric utilities to remove particulate matter. These devices can be used effectively in meeting the existing air quality standards for maximum acceptable particulate discharge rates. Paradoxically, the presence of sulfur oxide in the boiler flue gases enhances efficient particulate removal. A method of removing sulfur from coal involves the use of limestone or dolomite to absorb the sulfur oxides in the combustion chamber of the boiler. A wet limestone

scrubbing process is currently being developed for use in the combustion chamber of the exhaust stack to efficiently remove both the sulfur oxides and the particulate matter. Nitrogen oxides are the result of high temperature, excess air combustion. Lower furnace temperatures would reduce nitrogen oxide emissions but would also reduce plant efficiency and increase emission of the particulates and tend to produce carbon monoxide emissions. Limited studies have indicated that the wet limestone scrubbing process to absorb  $\text{SO}_2$  may also reduce nitrogen oxide emissions. Prevention of sulfur and nitrogen oxides and particulate emissions from coal-burning powerplants requires a well-designed total emissions control system to reduce each of these components to acceptable discharge rates for the power produced.

**CHAPTER XX**

**OCEAN ENERGY SOURCES**

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## INTRODUCTION

The amount of energy potentially available in the sea — both visible and invisible — is practically limitless. Some of the estimates of this energy are truly staggering: 25 billion kw of energy are constantly being dissipated along the world's shorelines by waves; tides could be harnessed to produce 1240 billion kwh per year; the Gulf Stream off Florida has a volume flow of over 50 times the total discharge of all the rivers of the world; enough electricity could be generated from heat engines operated on the temperature differential between surface and deeper ocean waters to provide more than 10,000 times the world's yearly electric power requirements.<sup>1</sup>

The transformation of hydraulic water power energy into mechanical and electrical energy is a relatively simple

and efficient process. The efficiency of a hydraulic turbine can be as high as 96 percent. Water power requires a simple energy conversion process, compared with thermal, chemical, or nuclear conversion.

Various approaches to extracting some part of this vast energy potential are discussed in this chapter under five headings: tidal energy, wave energy, ocean current energy, ocean thermal energy conversion (OTEC), and salinity gradient energy. Converting energy from giant kelp grown in ocean farms is discussed in Chapter XXI.

<sup>1</sup>A. Fisher, "Energy from the Sea—Part II, Topping the Reservoir of Solar Heat," *Popular Science*, June 1975.

## ENERGY DENSITY

Water is a working fluid with a low energy density. This means that the machinery needed to extract the energy and the volume of water required to be processed must both be very large. Fuel oil and uranium on the other hand are both substances with high energy densities. The cost of extracting energy therefore varies inversely with its density.

Water power is a function of  $\bar{\omega}QH$ , where  $\bar{\omega}$  is the specific gravity,  $Q$  is the fluid discharge and  $H$  is the head or elevation. Energy density is proportional to the head  $H$ , which is

$$H = z + \frac{p}{\bar{\omega}} + \frac{V^2}{2g},$$

where  $z$  is the elevation about a fixed datum,

$p$  is the pressure,

$V$  is the velocity, and

$g$  is the gravity acceleration.

The higher the head, the cheaper the energy.

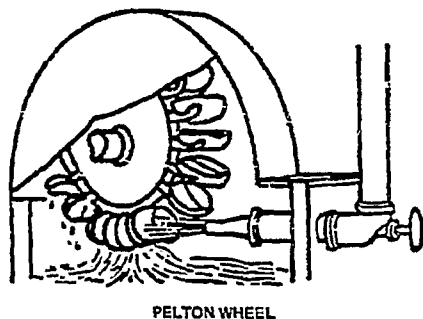
One of the cheapest forms of energy is provided by water flowing from mountains through narrow penstocks and ejectors and splashing the buckets of a simple Pelton

water-wheel turbine. As the head decreases, the more bulky Francis radial turbines must be used, and then Kaplan turbines with variable blades (See Figure XX-1.) The cost of energy generally increases as the head decreases, and there is a point beyond which such a plant is considered economically unattractive. If the head is below about 2 meters, even a small turbine built to satisfy local needs is presently not considered economical.

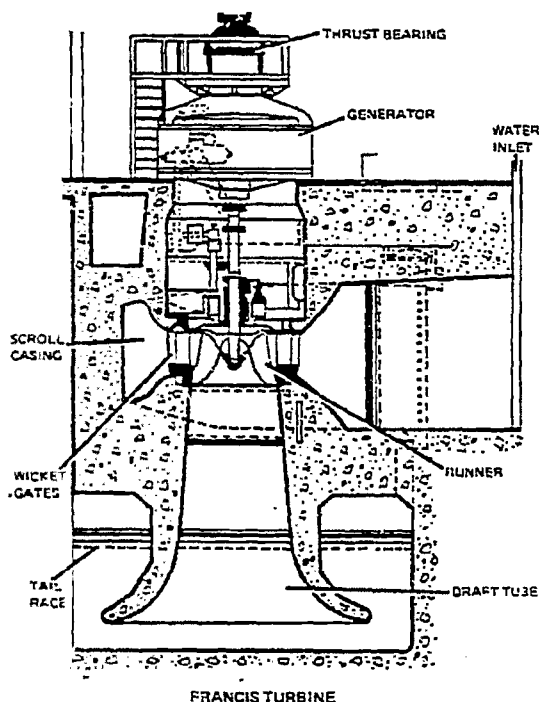
Although the total amount of power available in a water wave is large, it is very diffused. Thus, the energy density per unit of volume at the free surface, or equivalent head, is so small that it is now only considered for special purposes such as floating buoys.

In tidal power the head is linearly related to the tidal amplitude and the energy available is proportional to its square. Tidal head is generally near the lower limit of an economical level, making it a marginal form of energy, for use at special sites.

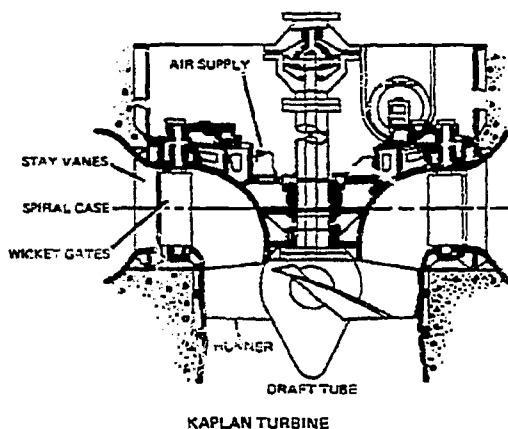
The energy density over a thermal gradient is very large. Each 10° C of temperature difference corresponds to an equivalent head of 426 meters, implying a potentially high energy density.



PELTON WHEEL



FRANCIS TURBINE



KAPLAN TURBINE

Figure XX-1. HYDRAULIC TURBINES

## TIDAL ENERGY

Tidal energy is one of the oldest forms of energy used by man. A tidal mill built centuries ago in the Deben Estuary, in Great Britain, and mentioned as early as 1170, is still in operation. Engineering ingenuity has resulted in a large number of schemes which make tidal power a very reliable source of energy. The energy is available, at will, as peak power or as steady power regardless of the time for ebb and flow. It is predictable, as far ahead as needed, as are the movements of the celestial bodies which govern the tides.

Tidal energy requires large capital investments, but compared to thermal or nuclear power plants which will have to be replaced every 30 years, tidal power installations, once built, may last forever with small maintenance costs.

The tidal power generating facilities which are now in operation are the tidal power plant of Rance in France and Kislaya Guba on the White Sea, in the USSR. The average tidal range at Rance is 9 meters, and at Kislaya Guba, 4 meters.

Tidal power is being seriously considered today by many countries for alternate sources of energy. Active investigations are being undertaken in France at the Bay of Mt. St. Michel, in Canada at the Bay of Fundy, in England in the Bristol Channel, in Korea and in the USSR. In the United States, both ERDA and the U.S. Army Corps of Engineers are reappraising the Passamaquoddy project in Maine originally submitted in 1967.

### The Source of Tides

Tides are caused by the attraction of the earth by the moon and the sun. The attraction of the moon is 2.2 times more significant than that of the sun. The moon's gravity acts on the entire earth mass but pulls the nearest part away from its center. The furthest part is also pulled away because it is subjected to smaller gravitational force than its center. Thus a high tide is produced beneath the moon and at the "anti-moon." High tides occur on opposite sides of the earth, and, because the earth rotates, each side experiences two high tides and two low tides every day.

This simplified picture is complicated by several phenomena:

- The sun's attraction reacts with the moon's attraction. When the sun's attraction reinforces the moon's, spring tides occur; when it opposes it, neap tides are produced.

- The orbit of the moon and the sun with respect to the earth are not quite circular but elliptical with varied inclinations with respect to the earth. The tidal amplitude is largest when the moon or sun is closest to the earth.
- The earth is not covered uniformly by water, and each basin has its own varying dynamic response.
- The solid earth itself undergoes tidal distortion, typically 0.5 meter. What is observed to be ocean tide is actually ocean tide minus earth tide. Earth tides also interact with ocean tides in a complex and still not fully-understood manner.

Tidal amplitude in deepwater is not very well known, but the subject is of less practical importance. The wide deep ocean basins respond directly to the external gravitational disturbances created by the moon and the sun. The shallow seas and bays surrounding the continents are subjected to and respond to the tidal motion prevailing in the deep ocean. The responses of the shallow tidal basins are a function of size and depth. Large tidal ranges are generally the result of a matching of periods between deepwater tidal excitation and the free natural oscillation of large embayments.

Much progress is now being made in predicting shallow water amplitude by analyzing deepwater tides and shallow water response to deepwater excitation. But the tidal basin boundaries are not fully reflective, like vertical walls, but contain a dissipative feature. Turbulent energy dissipation is a non-deterministic phenomenon.

Despite all these complexities, tidal amplitudes and time predictions along the coastline can be made with great accuracy. The error never exceeds 50 cm in tidal range or one-half hour in phase.

Tidal amplitudes are predicted by harmonic analysis and correlation between the measured range at a given location and the moon-sun location with respect to the earth. Tidal component coefficients are associated with each periodic motion of celestial bodies such as:

		Hours	Coefficient
M <sub>2</sub>	Principal lunar period	12.42	0.908
S <sub>2</sub>	Principal solar period	12.00	0.422
N <sub>2</sub>	Larger lunar elliptic	12.66	0.174
K <sub>2</sub>	Lunar-solar semidiurnal	11.97	0.078/0.036
O <sub>1</sub>	Principal lunar diurnal	25.82	0.376
M <sub>f</sub>	Lunar fortnightly	327.86	0.156

As a result, shallow water tidal motions are one of the most predictable phenomena on earth.

### Extracting Energy From Tides

The relative potential of any given site as a source of tidal power is determined by calculating the natural

energy of the considered site.

Let A be the area of a basin, H the tidal range; then the total energy or natural energy per tide is

$$E = \rho g H^2 A_{av},$$

where  $\rho$  is the seawater density, and  $g$  the gravity acceleration.

This concept is used for comparison of sites. It is evident that only a fraction of the natural energy is recovered since turbines can only operate under a given range of head. Nevertheless, the concept is very useful for site assessment and comparison. Considering the shape of bays, one can measure with about 10 percent accuracy the following relationship:

$$E \cong 0.7 \rho g H^2 A_{max}/\text{tide},$$

where  $h$  is the mean high tide and

$A_{max}$  the area corresponding to the high tide level. Since each tide lasts about 12.45 hours, the power can be written as,

$$E_{kW} = \frac{0.7 \times 9.806 \times 10^6}{3600 \times 12.45} AH^2 = 1.53 \times 10^2 AH^2$$

where A is in square kilometers and H is meters.

The energy available on a yearly basis, using 705 tides per year, is thus,

$$E_{MkWh/year} = 8,760 \times 10^6 (E_{kW}).$$

Based on this concept it has been determined that the total tidal power potential in the entire world is 1240 billion kwh/year.<sup>1</sup> The amount of power which can be extracted varies substantially.

At the Rance, France, tidal power station the ratio of installed power to natural power is 55 percent.<sup>1</sup> The total energy produced there in 1973 was 560 million kwh or 15 percent of the natural energy available. The tidal amplitude varies from 5 meters at a low neap tide (coefficient 30), to 13.5 meters in the case of equinoctial spring tide (coefficient 155), which corresponds to a power variation of from 1 to 18 as shown in Table XX-1.

Tidal power can be used for peak power supply or for constant energy supply. In this latter case the peak power would be provided by other plants.

There exists a great number of schemes for extracting tidal power.<sup>2</sup> The determination of an optimum scheme is

<sup>1</sup> L. B. Bernshtein, "Kislaya Guba Experimental Tidal Power Plant and Problems of the Use of Tidal Energy," *Tidal Power*, T. J. Gray and O. K. Gashus (eds.) New York: Plenum Press, 1972.

<sup>2</sup> R. Gibrat, *L'Energie des Marées*, Presses Universitaires de France, 1966.



Table XX-1  
TIDAL POWER VARIATION

Tide	Seasonal coefficient	Power produced (million kwh)
Low neap tide	(30)	80
Medium neap tide	(45)	300
Medium tide	(71-72)	900
Medium spring tide	(95)	1,300
Equinoctial spring tide	(115)	1,450

a complex matter and the topography may impose a limit to what is economically feasible.

### Single-Pool, One-Way System

The single-pool, ebb-generation system shown in Figure XX-2 is the simplest system of power generation from tides. Water is admitted to a pool while the tide is high, and after an interval it is discharged through turbines to generate electricity, as shown in Figure XX-3. To obtain the most energy from the system, the pool should be emptied to about low-water level at low tide and should be almost completely refilled by the next high tide. However, rapid discharge and full replenishment require several turbines and sluices with each turbine and sluice performing only a fraction of the duty each would perform if fewer were used. Thus, a compromise must be reached between the total power that can be developed and the cost of the installation. As shown in Figure XX-3 these costs create the difference between the ideal goal (the solid line) and the practical compromise (the dashed line).

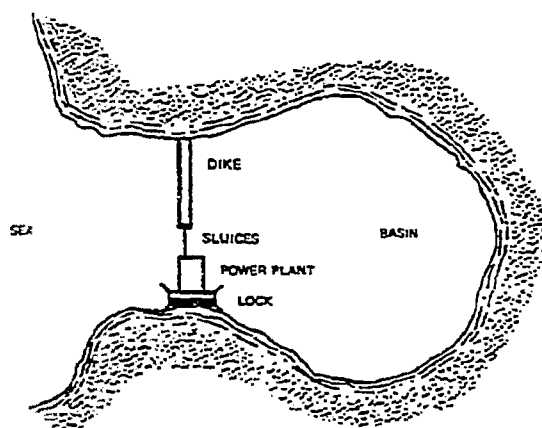


Figure XX-2. SINGLE-POOL SYSTEM

### Single-Pool, Two-Way System

In this system, power is generated by both inflow and outflow through the same powerhouse. (See Figures XX-7 and XX-4.) Previously, this method would have required switching the flow paths by means of a complex H-shaped arrangement of sluices controlling a forebay and tailbay. Major simplification of layout became possible with the advent of reversible-flow tubular turbines.

Theoretically, the energy available using this system is greater than for the one-way cycle. However, in practice this system involves discharging considerably more water in each direction, in every cycle, than does the one-way system. More turbines are required, and the generation periods must be curtailed in order to drain or refill the basin in preparation for the reverse-flow generation phase. This process requires a considerable emptying and refilling capacity, a portion of which may be provided by free discharge through the turbines. A typical operating regime is illustrated by the solid line in Figure XX-4. In comparison with the one-way system shown in Figure XX-3, there are twice as many generation periods.

More energy can be produced using this system than using the one-way system. However, it also costs more, generally more than proportionate to the increased power production.

The added refinement of the low-head pumping capability for boosting the emptying or refilling process at the turn of the tide may provide an increase in energy output with only a modest increase in cost. This capability is particularly valuable during below-average tides, when it would generally be impractical to increase the outputs from large tides to the same degree because of limited installed capacity. The dashed line in Figure XX-4 illustrates how pumping can be employed to increase energy output. An important aspect is that by such pumping, usually an hour or more before the demand peak, the next generating period can be advanced, or delayed.

### Multiple-Pool System

The classical two-pool system, called the DeCoeur system, is capable of generating power either at specified need periods or continuously (See Figure XX-5). The turbines work between two pools, one of which is regularly replenished by each high tide and the other is drained by each low tide. Output may be concentrated into selected periods within the limits of the installed turbine capacity, or continuously, as shown in Figure XX-6.

### Tidal Power Plants

Tidal power plants consist of three basic components: the power house or housing for the generating units; the

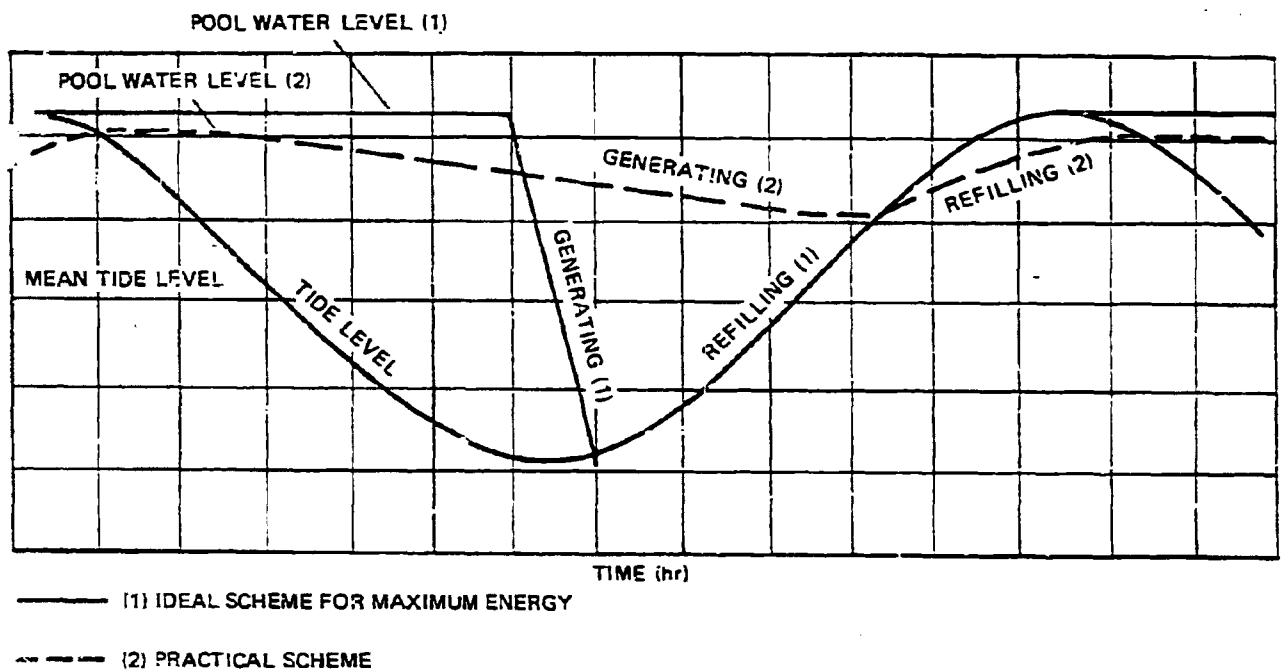


Figure XX-3. WATER LEVEL VARIATIONS FOR SINGLE-POOL, ONE-WAY SYSTEM

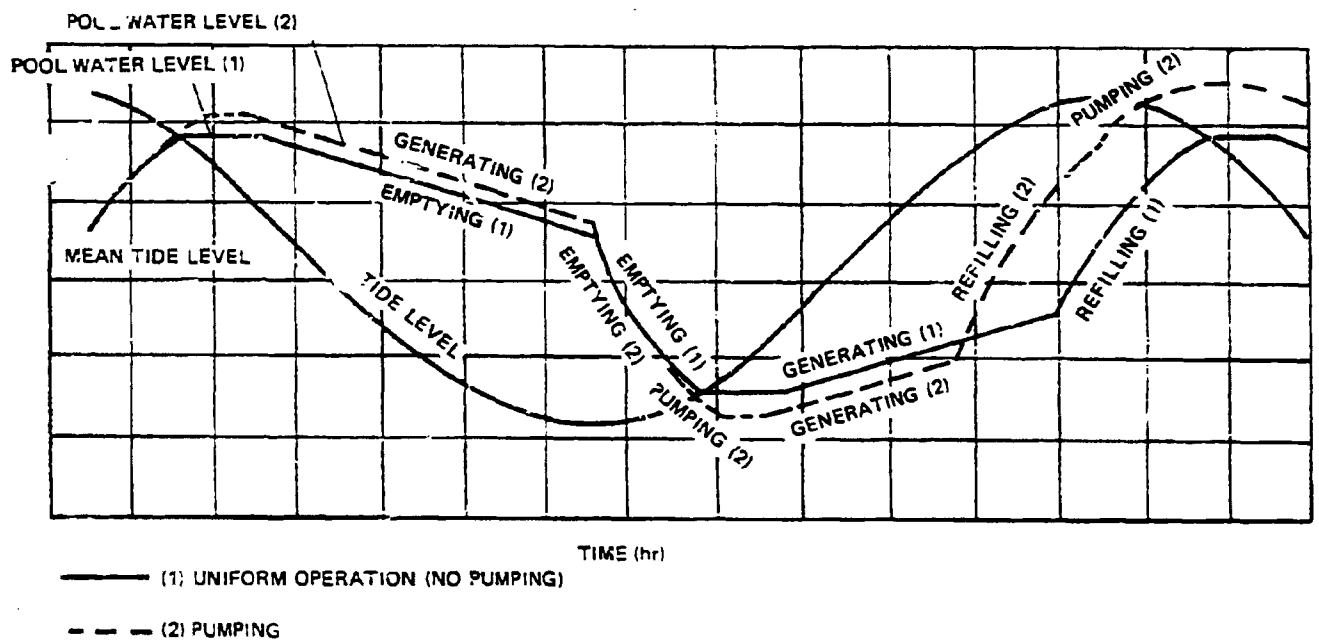


Figure XX-4. WATER LEVEL VARIATIONS FOR SINGLE-POOL, TWO-WAY SYSTEM

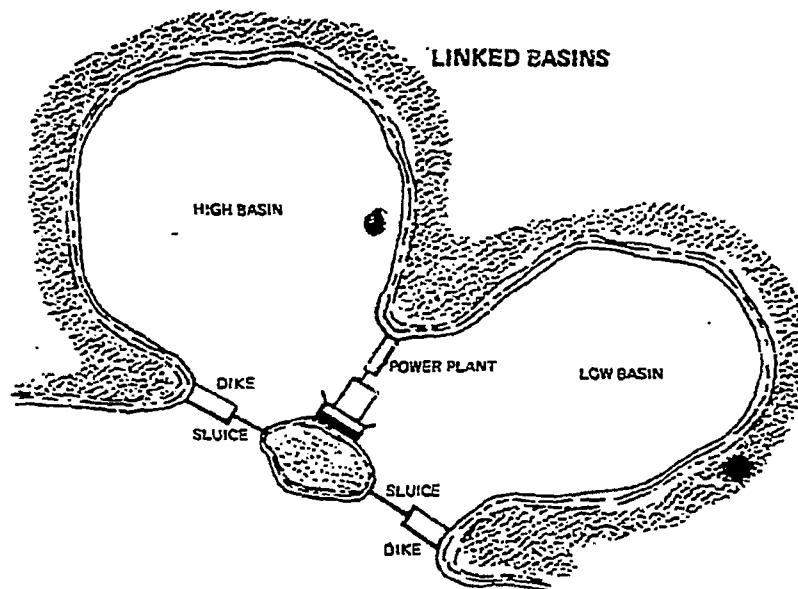


Figure XX-5. DOUBLE-POOL SYSTEM

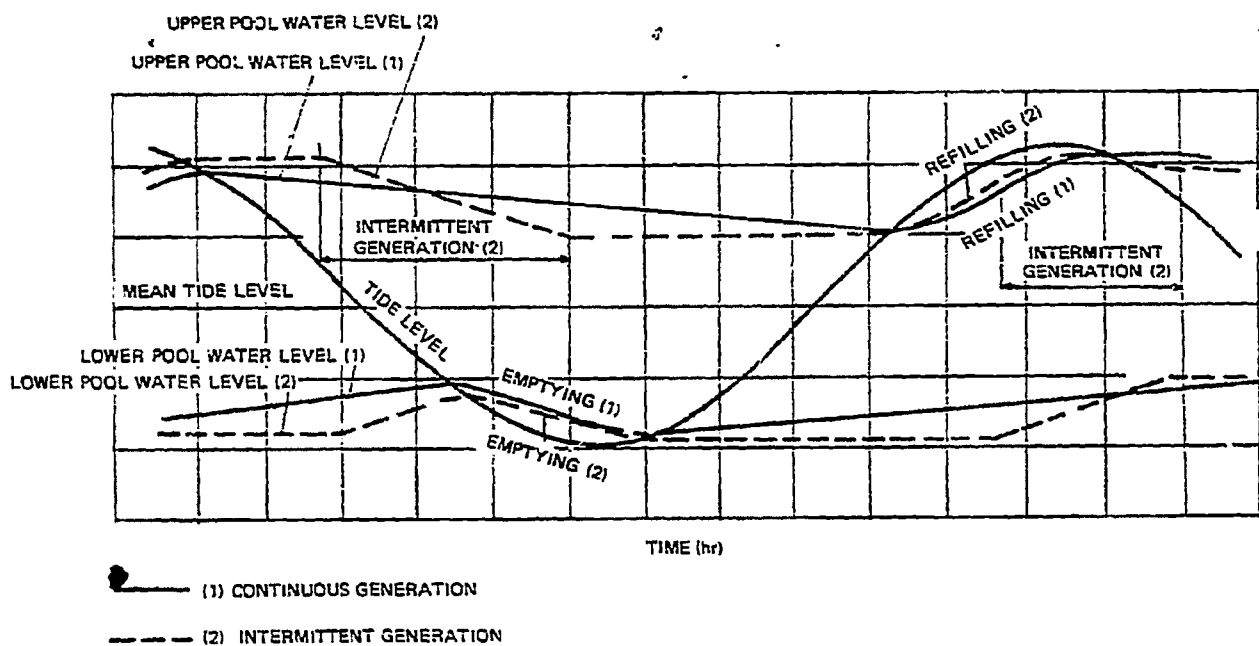


Figure XX-6. WATER LEVEL VARIATIONS FOR STEADY PRODUCTION  
IN DOUBLE-POOL SYSTEM

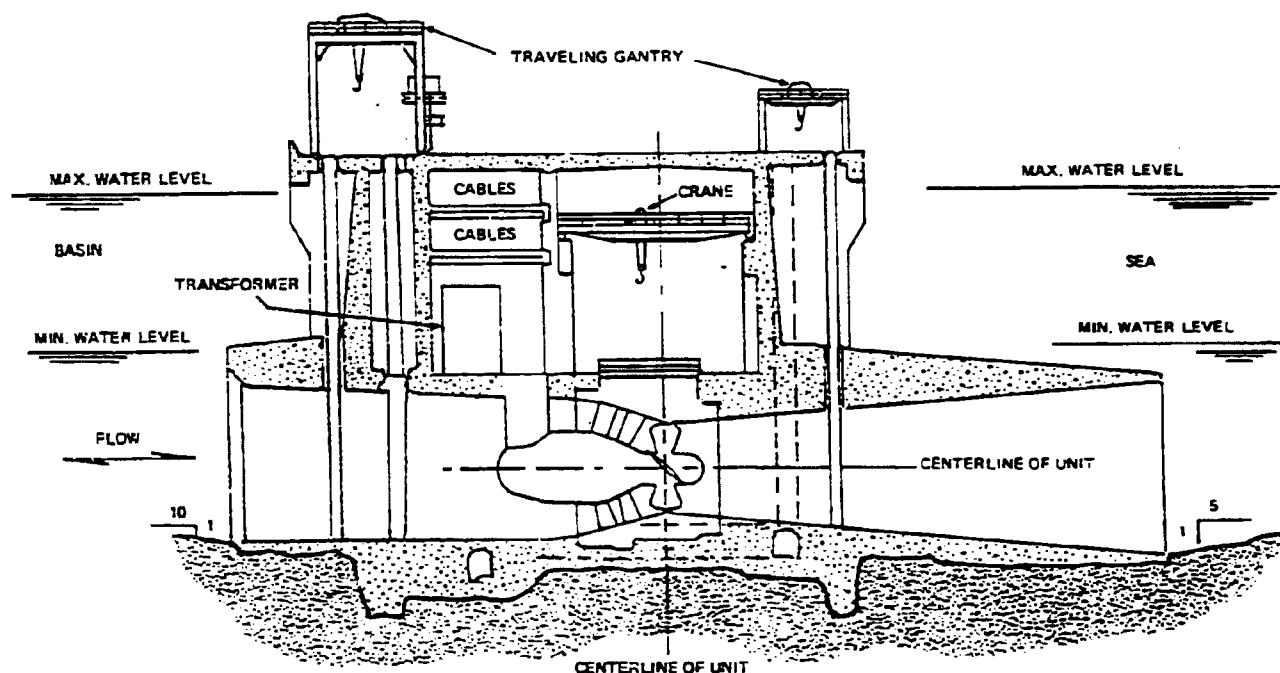


Figure XX-7. CROSS SECTION OF A POWER PLANT EQUIPPED WITH A BULB-TYPE TURBINE

sluiceways with their gates for filling or emptying the controlled basins; and the dikes, usually rockfill, constituting the closure between power houses and sluiceways and between either of these and the abutments of the development.

Figure XX-7 shows the cross section of a power plant equipped with a bulb-type turbine, constructed in situ behind temporary cofferdams. A prefabricated element or a caisson floated in place costs less to construct. The dike must be high enough so that no appreciable overtopping will occur under the most extreme combinations of high water and waves. The sluiceways must be equipped with gates that can be operated frequently, quickly, and reliably.

In a tidal power plant, power is developed at low to very low heads. The only turbines that are adaptable to such plants are the axial flow, high specific speed types including Kaplan bulb, straight-flow and tube designs.

There are very few reliable and detailed cost estimates on tidal power plants. The total cost of the Rance tidal power station in 1960 was \$100 million (1960 evaluation) for 240,000 kw of installed power and an annual production of 560 million kwh with a value of \$420/kw of equipped power based on the total estimated cost of production.<sup>1</sup> Later, the value was increased to \$500/kw of equipped power. The cost per kilowatt-hour produced is \$0.0026, based on 1973 calculations.

The total cost of the Passamaquoddy tidal power project as designed and evaluated in 1963 was \$759 million for 1 million kw of power installed. The estimated yearly production was to be 1000 kwh/yr, or \$759 per kw of equipped power. Canada believed this project to be uneconomical because the interest rates used were higher than those applied in the United States. The current cost of construction of the Passamaquoddy tidal power project is now being reassessed under the direction of ERDA and the New England Division of the U.S. Army Corps of Engineers.

### Operational Tidal Power Plants

There are only two tidal power plants in operation in the world: one is in the Rance Estuary in Brittany, France; the other is on the White Sea at Kislaya Guba in the USSR. Both installations have been marked by new technology developments.

The Rance installation, inaugurated in November 1966, demonstrated that varying power demand could be matched with tidal energy making the tidal plant a valuable component of a grid system regardless of season.

<sup>1</sup>G. Mauboussin, "L'Usine Maremotrice de la Rance," *Tidal Power*, T.J. Gray and O.K. Gashus (eds.), New York: Plenum Press, 1972.

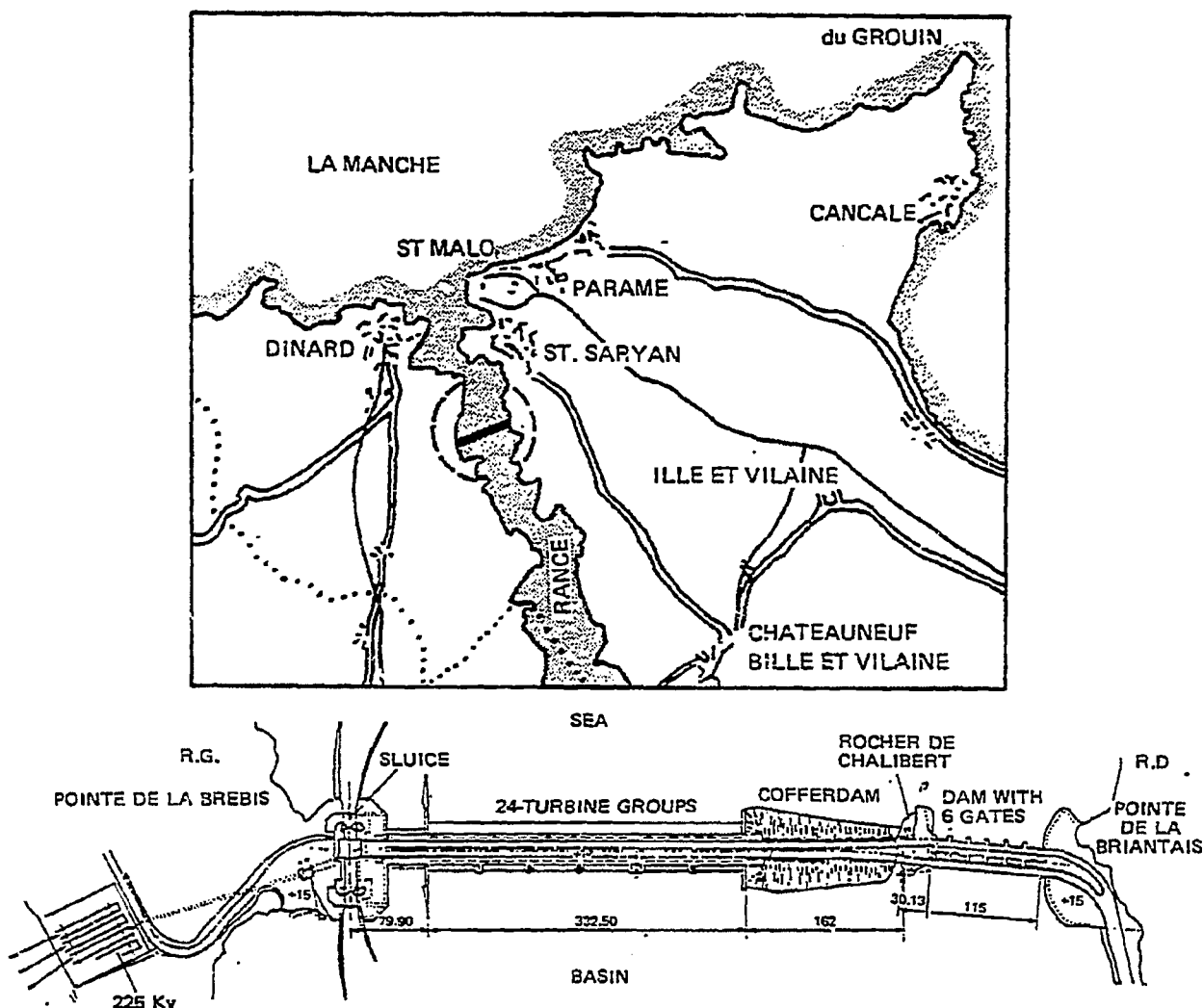


Figure XX-8. THE RANCE ESTUARY AND LOCATION OF THE TIDAL PLANT

This was achieved through the systematic use of the reversible bulb-housed turbine generator unit with variable pitch runner blades.

The Kislaya Guba plant, actually only a small experimental station, is significant for the method of its construction. Based on the Russian experience in construction of floating reinforced concrete docks, and similar work in Holland and West Germany, unit plants were built on land, and floated into place, thus avoiding the expensive, difficult and lengthy operation of building a cofferdam.

#### Rance Tidal Power Plant<sup>1</sup>

The Rance Estuary is located on the coast of Brittany in France (Figure XX-8) where the average tide is 11.40

meters. The Rance tidal power plant has been a pioneering achievement: it has demonstrated the effectiveness of the group-bulb turbine system, and has provided data for studies in physical oceanography, construction at sea, and corrosion and protective measures.

The plant has now been in operation for ten years and has required very little maintenance. As previously mentioned based on 1973 calculations, the cost per kwh produced is \$0.0026. It should be pointed out that if the float-in-place method of construction were to be used, a plant like Rance could be built at a much reduced cost.

Exploitation of tidal power would be much improved if we could produce energy not only during ebb tide, but also during the flow period leading to ebb. The new

<sup>1</sup> R. Gibrat, *L'Energie des Marées*, Presses Universitaires de France, Paris, 1966.

**Table XX-2**  
**RANCE GROUP-BULB TURBINE CHARACTERISTICS**

	<b>Turbine:</b> Kaplan type with 4 adjustable blades Diameter: 5.35 meters Power: 10 mw Speed: 94-380 rpm  <b>Generator:</b> Rotating in air at pressure 2 kg/cm <sup>2</sup> (absolute) Power: 10 mw at cos $\varphi$ = 1						
	Head (meters):						
	11	9	7	5	3	2	1
Discharge Basin - Sea m <sup>3</sup> /sec	110	130	175	260	200	—	—
Power, 1000 Kw	10	10	10	8	3.2	—	—
Turbine Discharge Sea - Basin m <sup>3</sup> /sec	130	155	230	195	135	—	—
Power, 1000 Kw	10	10	95	5.5	2	—	—
Pump Discharge Sea - Basin m <sup>3</sup> /sec	—	—	—	—	170	195	225

bulb-group concept was used at Rance allowing the turbine to work in both directions by reversing the blade. Furthermore, using the generator as a motor, the turbines were also able to work as pumps in either direction. Finally, by having the blades parallel to the axis of the turbine, group-bulb turbines could also operate as sluice gates. The flexibility of such a system considerably increases the efficiency of tidal power extraction, since the groups are able to work as turbines and pumps in both directions and as gates.

The great advantage of pumping becomes evident when one considers that if energy is expended to overfill or empty the pools behind the dam, this requires only a small amount of energy since the head is only one meter. This water however could be released later at a head of 7 meters, therefore giving a considerable gain in energy. Furthermore, this gain can be considerably increased if the pumping can be done during hours of low energy demand so that energy can be produced during the peak load. A group of 24 of these group-bulb turbine generators were installed at Rance tidal power station, each with a power of 10,000 kilowatts. The main characteristics of these groups are shown in Table XX-2.

#### Kislaya Guba Experimental Plant

The USSR has a tidal power potential of 210 billion kWh/year of the world's estimated 1240 billion kWh.<sup>1</sup> The use of the 40 billion kWh/year power resources of the White Sea could be incorporated into the integrated power system of the European part of the country.

The Kislaya Guba tidal power plant, 600 miles north of Murmansk, is located in a narrow neck 50 meters wide that connects the sea with the Ura-Guba Bay. The site was selected because of the relative simplicity of the installation and its proximity to a power system, although the height of the tide here only varies from 1.3 to 3.9 meters. The tidal power plant was built at an industrial center and was delivered to the site in a finished form with the equipment already assembled.

The power of this small experimental plant was determined only by the requirements of the experiment. Two units were installed, one Russian and one French. The French unit is a bulb-housed, reversible-flow turbine-generator with a capacity of 400 kW. The diameter of its runner is 3.3 meters; its speed is 72 rpm; and it is connected via a speed booster to a 600-rpm synchronous generator.

#### Future Tidal Power

Serious studies are underway at many points in the world where the tidal conditions indicate good potential for generating electric power. (See Figures XX-9, 10, and 11.) In some cases the distances of the tidal sites from users of electric power prevent their economic use until new techniques are discovered for long-distance power transmission. Major study projects are listed in Table XX-3 and some are compared with the existing plant at Rance in Table XX-4.

<sup>1</sup> L. B. Bernshrein, "Kislaya Guba Experimental Tidal Power Plant and Problems of the Use of Tidal Energy," *Tidal Power*, T. J. Gray and O. K. Gashus (eds.) New York: Plenum Press, 1972.

Table XX-3  
TIDAL POWER PROJECT STUDIES

Country	Location	Physical Characteristics	Tidal Range	Electric Power
United States	Cook Inlet, Alaska (near Anchorage) <sup>a</sup> (See Figure XX-9)	230 miles long, varying from 60-13 miles wide. Five possible sites.	15-24 feet	A. 75,000 Gwh/year B. 10-12,000 Gwh/year C. 60 Gwh/year D. 916 Gwh/year E. — (See Figure XX-9)
United States — Canada	Passamaquoddy, Bay of Fundy, Maine/New Brunswick <sup>b</sup> (See Figure XX-10)	Double-basin: Passamaquoddy Bay (101 square miles) and Cobscook Bay (41 square miles)	12-27 feet	1843 million kWh/year
Canada	Bay of Fundy	Double-basin (See Table XX-4)	23-54 feet	(See Table XX-4)
Argentina	Valdes Peninsula <sup>c</sup> (See Figure XX-11)	Single-basin with canal	—	75,000 Gwh/year
Great Britain	Severn River, Bristol Channel, <sup>d</sup> and Solway Firth	Single-basin, with locks for navigation, and pumped storage	—	4 billion Kwh/year 10,432 Gwh/year 3.2 billion Kwh/year
France	Bay of Mount-Saint- Miche <sup>e</sup>	Double-basin (See Table XX-4)	12-41 feet	(See Table XX-4)
Korea	Garorim Bay <sup>e</sup>	Unknown	Unknown	Unknown
USSR	Okhotsk Sea	Unknown	Unknown	10 million kw

Sources:

<sup>a</sup>E. M. Wilson and M.C. Swales, "Tidal Power from Cook Inlet, Alaska," *Tidal Power*, T. J. Gray and O. K. Gashus (eds.), New York: Plenum Press, 1972.

<sup>b</sup>F. L. Lawton, "Tidal Power in the Bay of Fundy," *Tidal Power*, T. J. Gray and O. K. Gashus (eds.), New York: Plenum Press, 1972. S. L. Udall, *The International Passamaquoddy Tidal Power Project and Upper Saint John River. Hydroelectric Power Development*. (Report to President John F. Kennedy), Department of Interior, July 1, 1963.

<sup>c</sup>H. E. Fentzleff, "The Tidal Power Plant San Jose, Argentina," *Tidal Power*, T. J. Gray and O. K. Gashus (eds.), New York: Plenum Press, 1972.

<sup>d</sup>E. M. Wilson, B. Severn, and M. C. Swales, *The Bristol Channel Barrage Project*, 11th Conference on Coastal Engineering, London, 1968.

<sup>e</sup>*Feasibility Study of Tidal Power Plan, R-74-51*, Korean Institute of Science and Technology, Ministry of Science and Technology, Seoul, Korea, 1974.

Table XX-4  
COMPARISON OF TIDAL PROJECTS

Characteristics of the Basins	U.S. -- Canada	Canada -- Bay of Fundy			France	
	Passamaquoddy	Petit Coirlec Memramcook	Cumberland Shepody	Minas Basin	Rance	Mont Saint-Michel
Scheme	2 basins	2 basins	2 basins	1 basin	1 basin	2 basins
Tidal range (ft)	12 to 27	24 to 54	23 to 51	24 to 53	11 to 38	12 to 41
High	101	12	45	300	8	200
Area (square miles)						
Low	41	9	28	—	—	—
Length of dam (miles)	6.8	2	6	4	—	—
Natural energy (M Gwh)	16,000	7,300	36,000	160,000	2,000	60,000
Installed power	300,000 kw	201,000 kw	450,000 to 1,000,000 kw	1 to 8 million kw	240,000 kw	3,000,000 kw
Number of sluice gates	160	51	38 to 78	—	6	—
Guaranteed power	95,000 kw	54,000 kw	160,000 to 300,000 kw	—	—	—
Annual production in M kwh	1,900	1,310	2,140 to 7-9,000	Up to 30 or 40,000	600	25,000



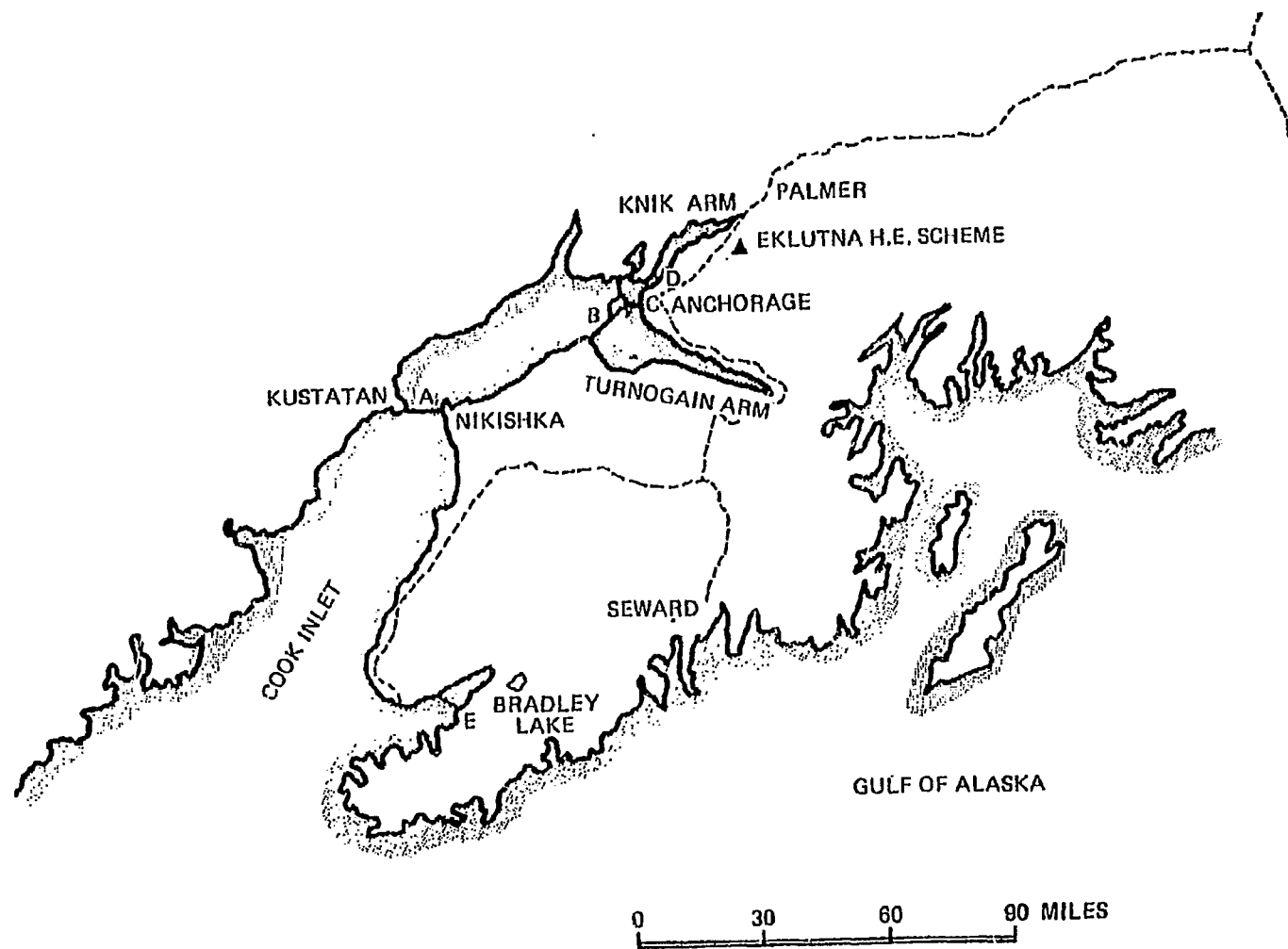


Figure XX-9. POTENTIAL SITES FOR TIDAL POWER DEVELOPMENT COOK INLET



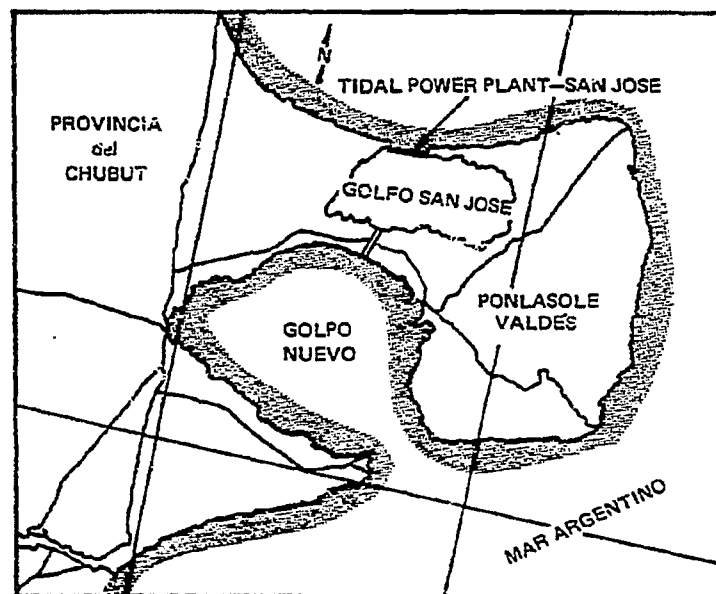


Figure XX-11. VALDES PENINSULA , ARGENTINA

## WAVE ENERGY

The recovery of energy from wave power has always fascinated investors. R. Dhaile<sup>1</sup> reports in 1956 to have examined more than 600 patents, some of them demonstrating a disarming ignorance of the laws of physics. He concluded that not even one was worth developing. More than 80 years ago, Albert Stahl<sup>2</sup> cited 20 proposals for harnessing wave power in the United States. The back and forth motion of breaking waves and at times their devastating effects may give the impression that a huge amount of energy could be tapped.

In fact, this power, though impressive, is rather diffused. The head is roughly the size of the wave height. The main economic problem arises because any structure has to be designed to withstand the largest storm waves, while the prevailing waves, which would provide most of the energy, are only about a tenth the size. Finally, wind-generated waves are not a dependable source of energy as a result of the large variation of sea states inherent to meteorological fluctuations.

However, wave power like tidal power has been used for centuries. The water which circulates in the basins of the oceanographic Museum of Monaco has been raised for decades by pumps activated by wave power. In Japan, wave-activated turbine-generators have also been used for

a long time to generate the power required on buoys. A "wave pump" is a gently-sloped, convergent channel, terminated by a sill over which the wave crests pour. It is sometimes used in coastal engineering to create circulation in large bodies of still water. An experimental station based on this principle was built in Algeria to recover wave energy on an industrial scale.

Although there is still some interest in wave power, it is generally held that it could only be a local source in those few areas where the sea state stays predominantly high. However, both British and Japanese projects envision the potential of generating power from waves on a commercial and industrial basis.

### Wave Climate

It has been estimated that the total amount of power which is dissipated along the shorelines of the world is

<sup>1</sup> R. Dhaile, *Harnessing the Mechanical Energy of the Waves—Energy of the Sea*. IVth Days of Hydraulics, S.H.F., published by La Houille Blanche, June 13-15, 1956.

<sup>2</sup> A. Stahl, "The Utilization of the Power Ocean Waves," *Transactions American Society of Mechanical Engineers*, 13 (1892) pp. 438-505.

2.5  $10^9$  kw, or about an average of 6.25 kw per m over 400,000 km.<sup>1</sup> The energy flux or power transmitted by periodic water waves in deepwater is

$$P \text{ kw/m} = 0.956 H^2 T$$

where T is the wave period.

A surface wave three meters high with constant period and amplitude transmits 100 kw for every meter of wave crest or 100 megawatts per kilometer (assuming that the wave period is 11.3 seconds). It could be compared to the power of a line of automobiles, side by side, at full throttle.

But waves occur in all sizes and periods. The irregular and random nature of wind-generated waves are better described by a wave spectrum or by an energy spectrum giving the amount of energy as a function of frequency.

Within a given sea state, corresponding to a meteorological and oceanographical event, the probability P of experiencing a wave equal to or greater than a definite value H is defined by an integrated Rayleigh distribution:

$$P(H) = \exp\left[-\frac{H^2}{2\sigma^2}\right]$$

where  $\sigma$  is a deviation parameter characterizing the sea state and defined by  $\sigma^2$  = mean value of the square of the free surface elevation.

Wave climate is defined by the probability distribution of sea states defined by the significant wave height  $H_s$ . The significant wave height is the average value of the highest one-third wave heights in a sea state and corresponds to a probability of 0.135 in that sea state.  $H_s$  and  $\sigma$  are related by:

$$H_s = 4\sigma$$

The average energy flux or wave power in terms of  $H_s$  is

$$P_{\text{kw/m}} \cong \frac{0.959}{2} H_{s,m}^2 T_{\text{av sec}}$$

The probability that the reported significant wave height exceeds the stated value of exceedance probability,  $p(H_s)$ , is commonly expressed by a Frechet distribution defined

$$p(H_s) = \exp\left[-(H_s/\sigma)^\nu\right]$$

Table XX-5

# SEA STATES AND COAST EXPOSURE

Zones	Areas	$\sigma$ (meters)	$\nu$
U.S. Pacific Coast	Astoria	1.96	1.62
	North Bend	1.94	1.61
	San Francisco	1.62	1.43
	Point Mugu	1.55	1.58
	San Diego	0.82	1.15
	Beja	1.20	1.28
U.S. Atlantic Coast	Quonset Point	1.02	1.24
	Norfolk	0.89	1.14
	Miami	0.92	1.19
U.S. Gulf of Mexico Coast	Corpus Christi	0.94	1.28
	Apalachicola	0.88	1.08
Atlantic Ocean	Bermuda (Area 2)	1.00	0.97

The value of  $\sigma$  and  $\nu$  are functions of the coast's exposure (see Table XX-5) and are approximately related by the Sonu formula:<sup>2</sup>

$$\sigma = 2.5\nu^{-2} \quad (\sigma \text{ in m})$$

The average wave periods are related to significant wave height by the formula:

$$T_{\text{av sec}} = a \sqrt{H_{s,m}}$$

where a is:

- 5.2 for the Pacific Coast
- 4.8 for the Atlantic Coast
- 4.4 for the Alaska Coast
- 4.5 for the Gulf of Mexico

The above equations combined with Table XX-5 immediately give probability distributions of availability of wave energy in non-protected areas along the United States coast. Figure XX-12 illustrates the wave height and energy flux exceedance probabilities at various locations along the United States Pacific Coast. It is important to notice that the 100 kw/m is exceeded 1 percent of the time at most locations, and 2.5 kw/m is exceeded 80 percent of the time.

<sup>1</sup> B. Kingsman, *Wind Waves*. Englewood Cliffs, New Jersey: Prentice Hall, 1965.

<sup>2</sup> C. Sonu, *Computer Prediction of Nearshore and Surf Zone Statistics*, ONR Geography Branch, Code 462, Tetra Tech Report TC-394, 1975.

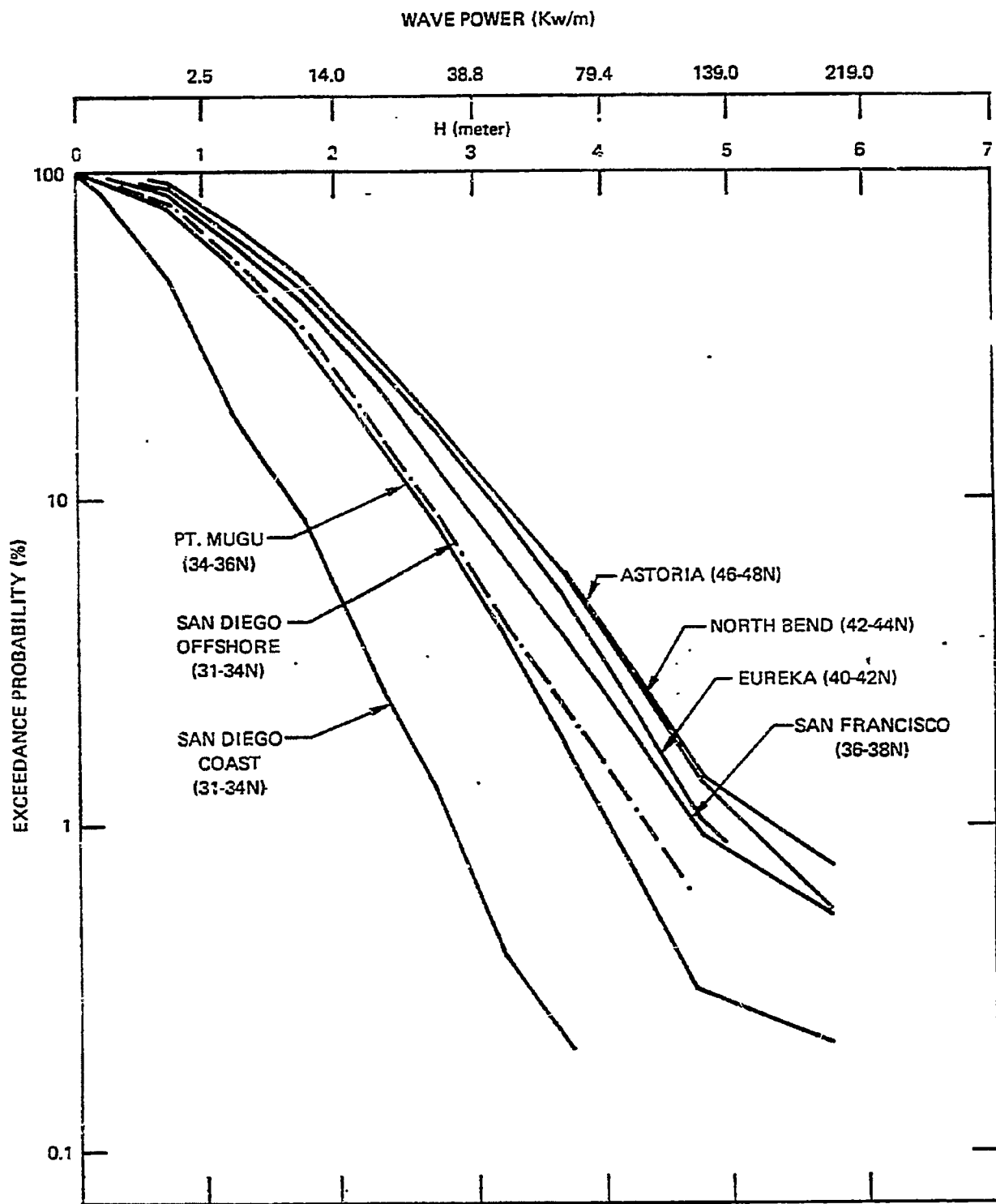


Figure XX-12. WAVE HEIGHT AND WAVE POWER EXCEEDANCE PROBABILITIES  
ALONG THE UNITED STATES PACIFIC COAST

## Wave-Powered Energy Generators

All wave power extracting systems could be classified as being based on three different basic principles or combinations:

- The wave energy converging channel (or wave pump or dihedron) creating a head above sea level,
- The resonance floating systems moved by buoyancy and activating a water or air turbine, or
- The mechanical vanes or cams which are activated by wave pressure fluctuations.

### Dihedron

One of the rare experiments made to recover wave energy on an industrial basis has been performed on the Algerian coast at Sidi Ferruch near Pointe Pescade. The system, patented in 1940 by Gianoni and Giry, consisted of vertical dihedrons terminated by a slot and a valve above sea level.<sup>1</sup>

The wave crests concentrating their energy in the dihedrons pour over a weir creating a mass of water above sea level (See Figure XX-13). The corresponding potential energy, retained by a flap vane, is then converted into useful work by conventional low-head water turbines. A resonance effect is obtained when the length of the dihedron is about one-fourth of a wave length. The following dimensions were considered for two locations:

Dimension	Mediterranean (meters)	Atlantic Ocean (meters)
Length	20	30
Opening	6	8 to 9
Depth	2 to 3	3 to 4
Valve width	0.15 to 0.20	0.20 to 0.30
Head (obtained with a 2-meter height wave)	4	5 to 6

Scale-model experiments using these proportions indicated that, at best, 35 percent of the wave energy could be recovered, the average efficiency being 20 percent.

A dihedron wave pump system was designed to be built on a breakwater at the harbor of Casablanca, but was not pursued for economic reasons.

### Wave Activated Turbine Generator

- The second category of wave energy generator has been best illustrated by Y. Masuda, J. P. Isaacs and D.

<sup>1</sup>R. Dhaile, *Harnessing the Mechanical Energy of the Waves—Energy of the Sea*, IVth Days of Hydraulics, S.H.F., published by La Houille Blanche, June 13-15, 1956.

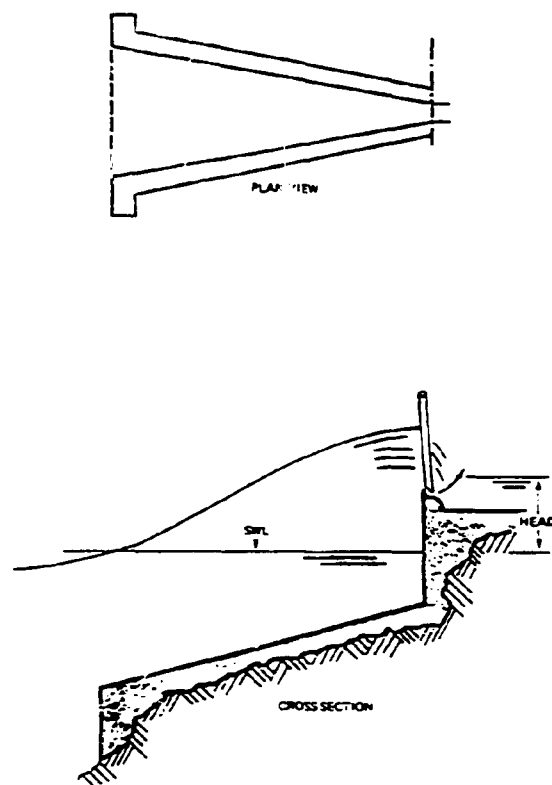


Figure XX-13. DIHEDRON WAVE PUMP

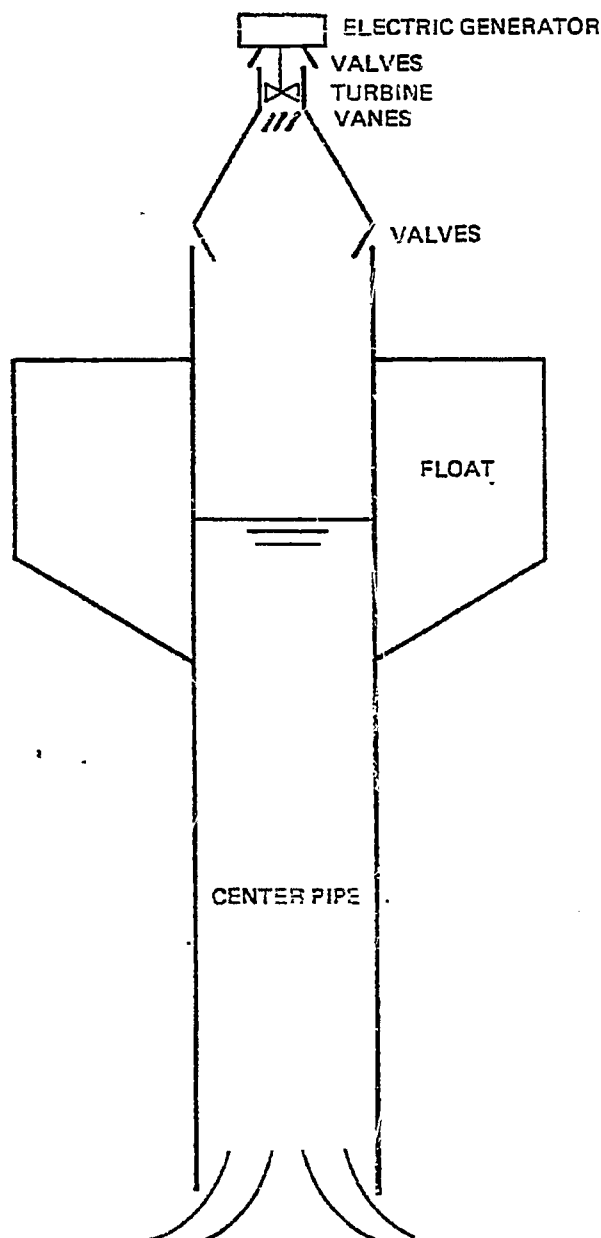


Figure XX-14. SCHEMATIC CROSS SECTION OF WAVE POWERED FLOATING BUOY

Castel.<sup>1</sup> These systems are conceived to provide a continuous source of power to floating buoys. They consist schematically of a long vertical pipe in which the water moves up and down and are kept buoyant by a float (see Figure XX-14). The pipe is designed to increase wave resonance effects.<sup>2</sup> A valve prevents the water from flowing back down and the potential energy which it generates activates a low-head water turbine.<sup>3</sup>

Another system, that reported by Masuda, acts on an air cushion; the air is compressed and processed through a system of valves and vanes to activate an air turbine.<sup>4</sup> This system is used on more than 300 mass-produced floating buoys with power outputs of 70 and 120 watts, which are now in service in Japan. A 500-watt unit has also been tested.

In 1947 much larger design projects based on the same principle were considered for use off the coast of Japan. Today 120-meter diameter buoys are being considered in order to generate 3 to 6 Mw at a cost of 2¢/kwh (1 m<sup>2</sup> of buoy generates 1 kw during 500 hours/year). In the United States the Coast Guard has operated wave activated turbine generators (WATG) to produce enough energy to operate navigational aid buoys. During testing at Chesapeake Light, the WATG generated an average power of 5.75 watts, well in excess of that required to power buoy lights.

#### Salter Cams

The most ambitious project now being considered for recovering wave power is located 10 miles west of the Hebrides Islands off the coast of Scotland, under the leadership of Dr. Andrew Salter, of the University of Edinburgh, and under sponsorship of the British Department of Trade and Industry.<sup>5</sup> The device Dr. Salter proposes would be a series of axles each with 20 to 40 huge swiveling cams. Each set would be as long as a super-tanker. The set of cams will then be a few hundred kilometers long (See Figure XX-15).

<sup>1</sup>Y. Masuda, *Wave Activated Generator for Robot Weather Buoy and Other Use*, Colloque International sur l'Exploration des Océans, Bordeaux, 1971, 5, pp. 1-18. J. D. Isaacs and D. Castel, *Wave-Powered Generator*, Scripps Institution of Oceanography, unpublished annual report, 1974.

<sup>2</sup>J. Valembois, "Wave Resonator," *Energy of the Sea*, IVth Days of Hydraulics, S.H.F., published by La Houille Blanche, June 13-15, 1956.

<sup>3</sup>J. D. Isaacs and D. Castel, *Wave-Powered Generator*, Scripps Institution of Oceanography, unpublished annual report, 1974.

<sup>4</sup>M. E. McCormick, R. L. Holt, and C. E. Bosworth, "A Pneumatic Wave-Energy Converter for Offshore Structures," *Offshore Technology Conference Proceedings*, 2, 1975, pp. 167-170.

<sup>5</sup>S. H. Salter, "Power from Sea Waves?," *Philosophical Transactions of the Royal Society of London, Series A*, 276, 1974, p. 492.

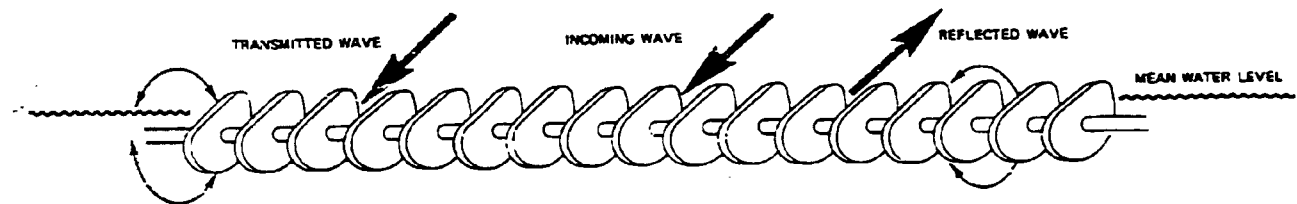


Figure XX-15. ROCKING WAVE-POWERED DEVICE

The up and down wave-induced motion pumps water to a high level. The corresponding potential energy is then processed through a turbine-generator or is used to generate hydrogen. Each cam unit would cost \$48 million and will produce 50 megawatts based on the severe nature of the sea states in this part of the world. Salter considers wave power as the ultimate clean solution to the electrical requirements of the United Kingdom. Whether this opti-

mistic assessment is substantiated remains to be seen. It is certainly the most efficient system ever devised. It seems that up to 80 percent of the wave energy, practically all the wave energy contained in the upper layer, can be extracted. A similar system with 2 degrees of freedom that would lead to an even more efficient system is under investigation at M.I.T.<sup>1</sup>

<sup>1</sup> Carmichael and Mei, 1976, private communications.

## OCEAN CURRENTS

The large amounts of power available from ocean currents are very impressive and have given rise to some interesting concepts for harnessing this power. For example, the currents of Gibraltar and Bab el Mandeb, at the south end of the Red Sea with a current power of  $10^9$  w, have attracted the interest of oceanographers.

In the United States, the attention focuses on the Gulf Stream.<sup>1</sup> Off Florida, this current sometimes reaches 2.5 m/sec with a volume flow of 30 million  $m^3$ /sec (See Figure XX-16). If only 4 percent of that energy were extracted, it would give approximately 1000–2000 megawatts of power. Apart from the land itself, the Gulf Stream is the greatest natural resource of the United States and perhaps the most neglected. The Gulf Stream increases in power five times from the Florida Keys to Cape Hatteras. A marine turbine submerged in the Gulf Stream would generate power equivalent to that generated by a wind turbine exposed continuously to a 43 mph wind stream. Even greater unit outputs can be obtained

from local sea currents along coasts all over the world.

Engineering ingenuity has been challenged for extracting this low-head power supply. A number of schemes have been devised, ranging from Kaplan type turbines with very large specific speeds<sup>2</sup> to Savonius rotors<sup>3</sup> (see also Figure XVIII-7 in Chapter XVIII) and a line of drags in form of a parachute attached to cables activating an energy converter.<sup>4</sup>

A very interesting marine turbine has been designed by

W. S. von Arx, H. B. Stewart, Jr., and J. R. Apel, "The Florida Current As a Potential Source of Useable Energy," *Proceedings of the MacArthur Workshop on the Feasibility of Extracting Useable Energy from the Florida Current*, H. B. Stewart (ed.), NOAA Atlantic Oceanographic and Meteorological Laboratories, Miami, 1974, pp. 91-105.

<sup>2</sup> J. A. Green, "Self-Contained Ocean Resources Base," *Marine Technology Society Journal*, 4(5), 1970, pp. 58-101.

<sup>3</sup> W. E. Heronemus, P. A. Mangarella, R. A. McPherson, and D. L. Ewing, "On the Extraction of Kinetic Energy from Oceanic and Tidal River Currents," *Proceedings of the MacArthur Workshop on the Feasibility of Extracting Useable Energy from the Florida Current*, H. B. Stewart (ed.), NOAA Atlantic Oceanographic and Meteorological Laboratories, Miami, 1974, pp. 138-201.

<sup>4</sup> G. E. Steelman, "An Invention Designed to Convert Ocean Currents Into Useable Power," *Proceedings of the MacArthur Workshop on the Feasibility of Extracting Useable Energy from the Florida Current*, H. B. Stewart (ed.), NOAA Atlantic Oceanographic and Meteorological Laboratories, Miami, 1974, pp. 258-277.



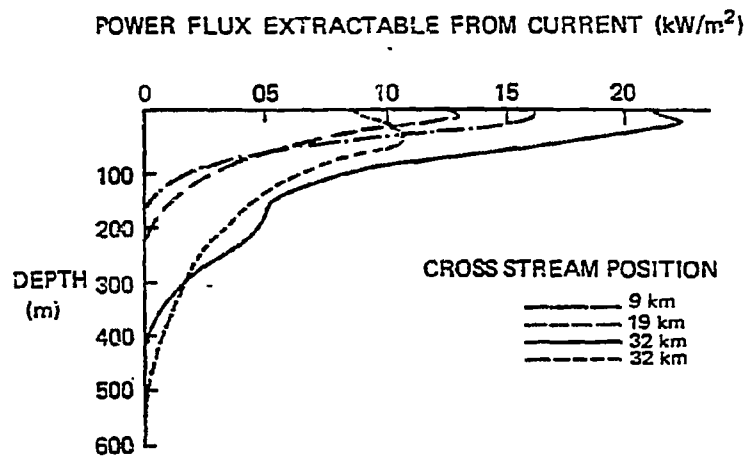


Figure XX-16. POWER FLUX FROM FLORIDA CURRENT

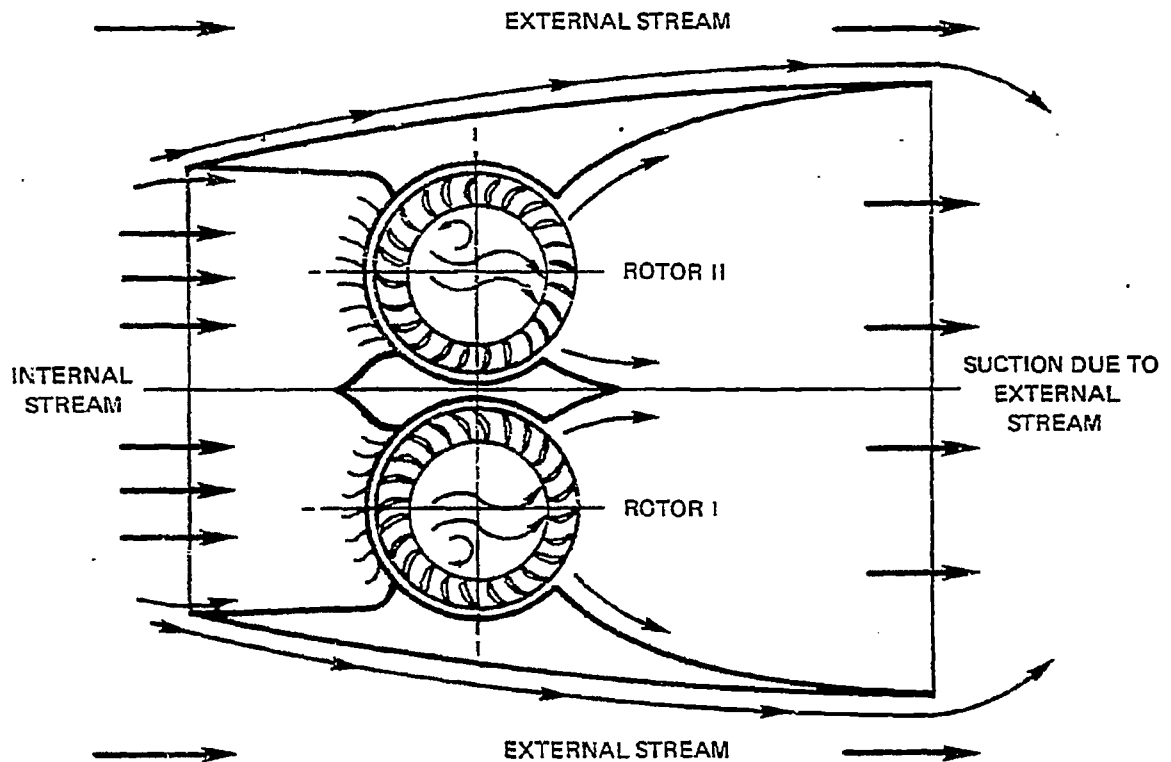


Figure XX-17. SCHEMATIC REPRESENTATION OF PAVLECKA'S MARINE TURBINE IN CROSS SECTION

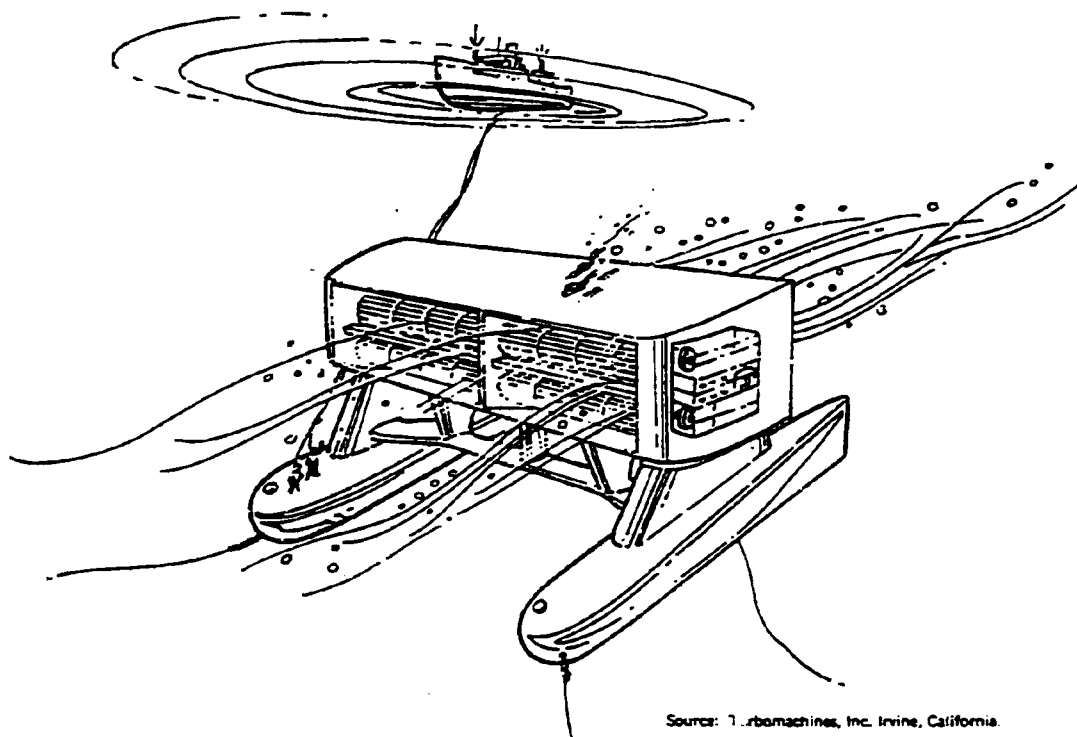


Figure XX-18. 10 Mw OUTPUT STREAM TURBINE 300 FEET WIDE

V. Pavlecka of Turbomachines, Inc.<sup>1</sup> This stream turbine features mechanical simplicity and is claimed to have a high efficiency of energy conversion. (See Figure XX-17.) The driving fluid approaches the rotor with a momentum, enters into the rotor peripheral cascade of blades, and imparts a driving force to it. The fluid inside the rotor imparts an additional incremental force on the blades because a core vortex is established. This core vortex regulates the flow through the turbine. As the flow exits from the blade configuration, it imparts another force to the blades, giving up an additional portion of its kinetic energy. Therefore, flow velocity is further reduced by entering the diffuser section of the apparatus, increasing the pressure at the diffuser exit. The free stream pressure that exists beyond the exit is significantly lower, and the resulting pressure differential draws large flows through the turbine to allow minimal dimensions for the housing. As a consequence of the housing and the hydromechanical effects it creates, the marine turbine has a power output increase for two significant reasons: a greater percentage of the kinetic energy of the current can be extracted because of the reduced exit velocity, and the turbine captures current flow from a stream tube considerably greater than the rotor area and, therefore, the stream enters the turbine rotor at speeds higher than the free stream speed. The result of this concept is that a housed marine turbine can deliver power several times

that of unhoused turbines of the same dimensions.

A. Seginer has demonstrated this performance improvement with shrouded windmills.<sup>2</sup> He obtained power increases four times that of unshrouded devices.

A marine turbine of this type appears to be a very promising method for extracting energy from the ocean currents. A 300-foot by 50-foot turbine of this type if placed in the Gulf Stream would develop 10 MW.

In the Sicily-Calabria current off Italy this same unit would develop 49.5 MW (1 MW = 1340 horsepower). Thirty-five such units can be deployed per square mile of ocean in a single tier. In Messina Straits there is available at least 16.873 square miles, with a high current of 7.83 mph, allowing a half-mile free margin along the coast. This high current could generate (350) (16.875) (49.5) = 29,200 MW. At least another 20,000 MW could be generated from lower speed currents further up and down the Messina Straits. There would thus be made available enough electrical power to satisfy all of Italy's requirements. All marine turbines would be submerged to allow for ample clearance for all ships. Figure XX-18 presents a drawing of such a proposed marine turbine.

<sup>1</sup>V. Pavlecka, *Sources of Energy*, Turbomachines, Inc., Irvine, California 92705, January 20, 1975.

<sup>2</sup>A. Seginer, "Flap Augmented Shrouds for Aerogenerators," *Los Angeles Council of Engineers, Scientific Proceedings Series, Volume 2*, Los Angeles Area Energy Symposium, 1976.

There are of course environmental problems that must be addressed before starting to implement such grand schemes for harnessing ocean currents. The technology seems to be available, but the perturbations to the ecosystem and their consequences must be carefully assessed

before tapping this source on a large scale. There is little doubt that a cost-effective marine turbine power plant can be developed since the cost of the fuel, water current, is free, and the machinery can be rather simple.

## OCEAN THERMAL ENERGY CONVERSION (OTEC)

The earth's oceans can be viewed as natural thermal collectors and storage devices. Approximately one-half of the solar energy intercepted by the earth falls between the tropics of Cancer and Capricorn, a region composed of 10 percent land surface and 90 percent ocean surface. As a result there is an ocean thermal difference between the solar-heated upper surfaces and the polar-chilled lower regions. At 1500 feet under the sea, the water temperature is close to the freezing point and on the surface the water temperature in these tropical regions ranges between 70-80° F. These temperature differences cause density stratification that retards fluid mixing and prevents the ocean from arriving at a uniform temperature. Warm surface water flows from the equatorial regions to the poles and the cooler subsurface waters flow toward the tropics establishing a global circulatory flow which prevents the oceans from becoming stagnant pools. The existence of the temperature gradient in principle can be tapped to run heat engines and to generate electricity.

The method for retrieving this thermal energy includes a single-fluid, open-cycle system and a secondary-fluid, closed-cycle system. The closed-cycle system uses a working fluid that boils with a high vapor pressure. The fluid continuously circulates inside a closed loop heat engine alternating between the liquid and vapor phases. The working liquid is compressed and passed through an evaporator on one side of a heat exchange surface. Warm water from the upper level of the ocean is pumped into the evaporator on the other side of the heat exchange surface where it gives up its heat to vaporize the working fluid. The vapor enters a turbine at high pressure and expands to drive the turbine which is connected to an electrical generator. The vapor is then condensed by the cold water pumped up from the ocean depths and the cycle is complete.

The open-cycle system uses sea water directly as the working fluid. The upper ocean waters represent a heat source and the deeper waters, a heat sink. Warm water is fed into an evaporator at reduced pressure where it is flash evaporated. Residual evaporator water is returned to the ocean below the surface. This saturated steam from the flash evaporation drives a turbine and generator. The

spent steam is condensed by cold ocean water. From the condenser the water is pumped up to the evaporator level and returned to the ocean.

### Characteristics of OTEC Plant

The thermodynamic efficiency of OTEC power plants is controlled by the available ocean water temperature differential, efficiency of the heat exchanges, fluid energy losses from pumping large amounts of water, and frictional losses incurred by the power plant machinery. An overall efficiency of between 2-3 percent, typical for such plants, is governed principally by the Carnot efficiency.

$$\eta = (T_2 - T_1)/T_2$$

where  $T_1$ ,  $T_2$  are temperatures in degrees absolute of the upper and lower water sources. The maximum value obtained is approximately 13 percent. We know from principles of thermodynamics that this value represents an upper efficiency bound for reversible heat engines. This astonishingly low efficiency does not preclude its viability, however, since the fuel in this case sea water, is free. The efficiency can be improved from the 2-3 percent range by making technological advances in the heat exchanger and pumping components. Fluid frictional losses can be reduced also by lining pipes with hydraulically smooth materials and reducing the potential of biofouling.

Figure XX-19 shows the closed loop system schematically; the open system is shown in Figure XX-20. The processes can be seen to be extremely simple in principle. The major components of a Rankine-cycle OTEC closed system power plant are:<sup>1</sup>

- A boiler or evaporator fueled by warm sea water to change the state of the working fluid from liquid to high-pressure gas.

<sup>1</sup>A. Levi (ed.), *Solar Sea Power Plant Conference and Workshop*, Carnegie-Mellon University, Pittsburgh, Pennsylvania, June 1973.

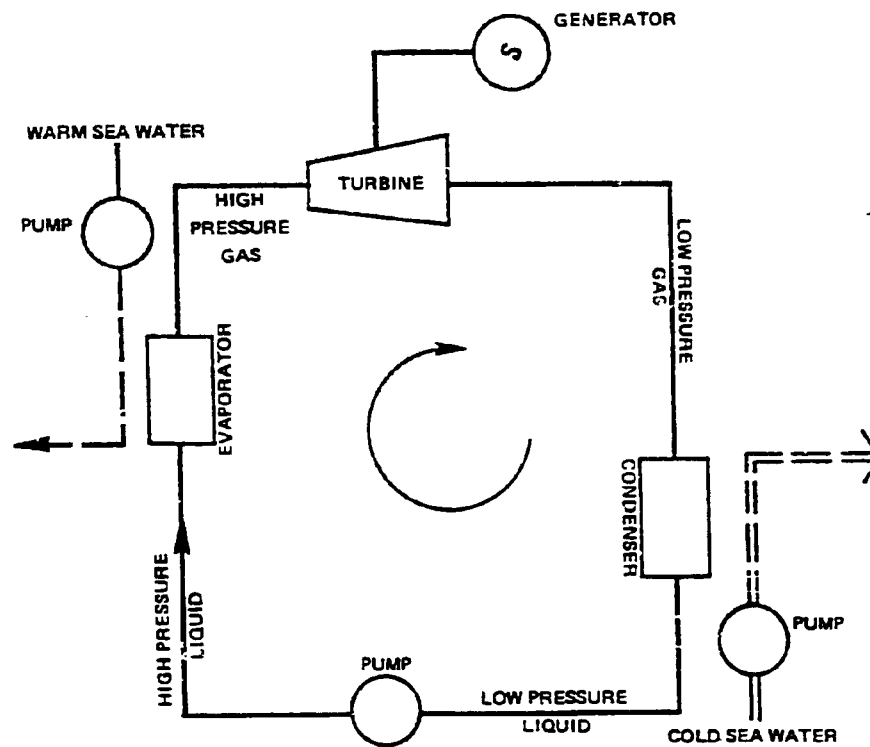


Figure XX-19. CLOSED-LOOP OTEC SYSTEM

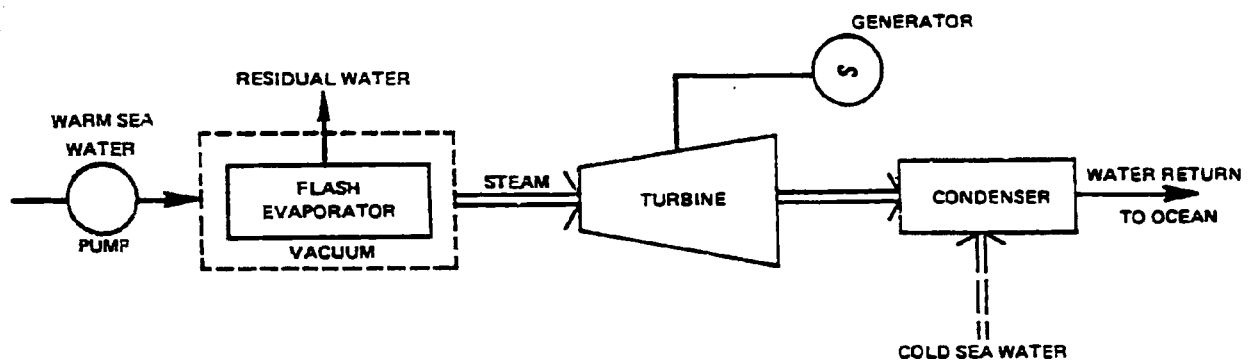


Figure XX-20. OPEN OTEC SYSTEM

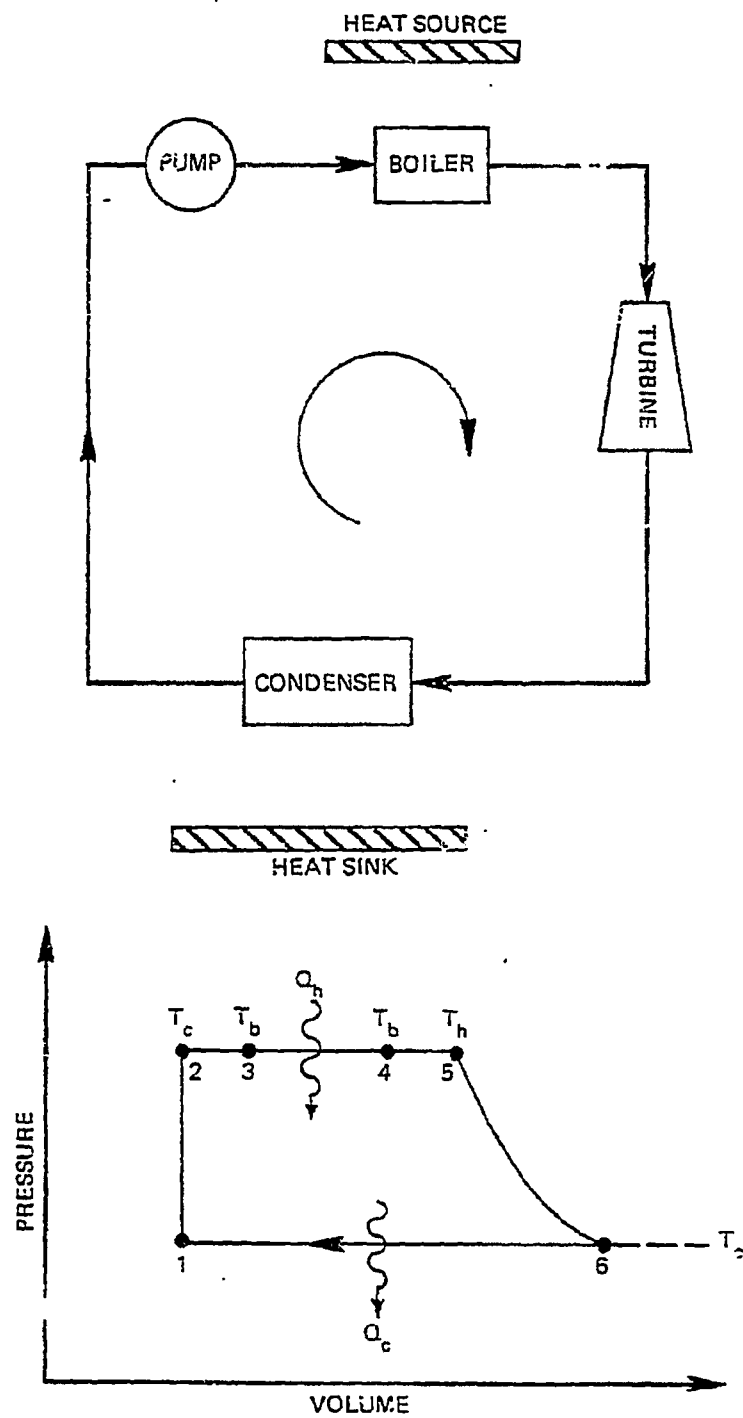


Figure XX-21. SCHEMATIC REPRESENTATION OF A RANKINE CYCLE STEAM ENGINE AND ITS PRESSURE-VOLUME DIAGRAM

- A turbine to convert the thermal energy stored in the working fluid into mechanical energy to drive an electric generator,
- A cold water pipe and pumping system to bring the cold water from the ocean bottom to feed into a condenser,
- A condenser which changes the state of the working fluid from low-pressure gas into liquid, and
- Pumps to circulate the working fluid from condenser to evaporator and to pressurize the liquid.

A Rankine cycle is shown schematically in Figure XX-21, together with its pressure-volume diagram. The diagram represents the pressure and volume changes of a given mass of water as it is moved from the condenser, through the boiler, into the expansion chamber, and back to the condenser. The water in the condenser is at a pressure less than atmospheric and at a temperature less than the normal boiling point. It is pumped into the boiler which is at a much higher pressure and temperature. In the boiler the water is heated to boiling and then vaporized at constant pressure. The steam is then superheated at the same pressure. It is then allowed to flow into a turbine where it expands approximately adiabatically (no net heat exchange) until its temperature and pressure drop to that of the condenser. Then the steam is condensed into water at the temperature and pressure as at the beginning, and the cycle repeats. The Rankine cycle is comprised of the following steps, as shown on Figure XX-21:

- 1→2 Adiabatic compression of water to boiler pressure
- 2→3 Isobaric (constant pressure) heating of water to boiling point
- 3→4 Isobaric, isothermal vaporization of water to saturated steam
- 4→5 Isobaric superheating of steam into superheated steam at temperature  $T_H$
- 5→6 Adiabatic expansion of steam into wet steam
- 6→1 Isobaric, isothermal condensation of steam into saturated water at  $T_C$ .

The open-cycle system can make use of direct contact heat transfer. This method is quite efficient and does not require the expensive heat transfer surfaces of a closed-cycle system. The open-cycle system using spray generators or falling films of water attached to passive surfaces offers an excellent means for increasing the heat transfer coefficients.<sup>1</sup> This approach results in a decrease in surface area required and thus material cost.<sup>2</sup> The

open-cycle plant requires vacuum enclosures which are necessary to flash-evaporate the incoming warm seawater and large steam turbines. The steam turbine represents a major cost element in the overall open-cycle design and great effort is being given to reducing its size while maintaining high efficiency.

Recent literature in the OTEC field is biased in favor of closed-cycle systems. This is no doubt the result of the adoption of the closed system for investigation by Lockheed and TRW.

The reason almost all OTEC conceptual designs deal with floating systems is that there are few shoreline locations where significant temperature gradients occur to make an on-shore plant location economically feasible.

### OTEC Working Fluids

Several working fluid candidates are being considered for OTEC powerplants. The characteristics of three of the most important working fluids are presented in Table XX-6.

### OTEC Siting

A generalized study of operational sea state and wave criteria is being undertaken for OTEC plants. There exists an acute shortage of sea state data for many areas of the world's oceans.<sup>3</sup> Such information, together with design wave criteria, is essential in planning of any marine structure. This project was conceived to help fill the void by acquiring environmental data on winds, waves, and currents for specified areas of interest for OTEC applications.

The zones of interest in the siting study include the Atlantic, Pacific, and Gulf Coasts of the United States, the Hawaiian Islands, and all oceanic areas located between 20° N and 20° S latitudes. The ideal site would be one where a temperature difference of approximately 40° occurs over a shallow bottom and is close to the consumer to minimize energy transmission problems and costs. The wind-wave-current-conditions should be mild and the environment relatively free from severe storms. The specific sites to be chosen for OTEC plants will be arrived at by weighing all these aspects.

### Major Design Components

The heat exchangers are the dominant cost elements in the closed-cycle OTEC design. Titanium, aluminum,

<sup>1</sup> C. Brown and L. Wechsler, *Engineering on Open Cycle Power Plant for Extracting Solar Energy from the Sea*, Paper Number OTC 2254, Presented at the Offshore Technology Conference, 1975.

<sup>2</sup> C. Zener, A. Levi, and C. C. Wu, *Solar Sea Power First Quarterly Report*, Carnegie-Mellon University, Pittsburgh, Pennsylvania, October 1973.

<sup>3</sup> G. Duggan (ed.), *Third Workshop on Ocean Thermal Energy Conversion*, Houston, Texas, May 1975.

Table XX-6  
COMPARISON OF OTEC WORKING FLUIDS

Criteria	Ammonia	Propane	R-12/31
Heat transfer characteristics (50-70° F) Thermal conductivity (Btu/hr-ft <sup>2</sup> -° F)	Liquid: 0.29 Vapor: 0.014	Liquid: 0.07 Vapor: 0.01	Liquid: 0.05 Vapor: 0.006
Materials compatibility	Ammonium hydroxide not compatible with materials containing copper	Excellent except for some plastics	Excellent
Thermodynamic properties (50-70° F): Heat of evaporation (Btu/lb) Heat capacity (Btu/lb-° F)	500 Liquid: 1.13 Vapor: 0.19	140 Liquid: 0.62 Vapor: 0.24	70 Liquid: 0.24 Vapor: 0.037
Cost (Heat engine related)	Base	+10.7M additional with CuNi tubes	+21M additional with CuNi tubes
Safety			
Toxicity	Severe but easily detected	Slight, difficult to detect	Slight, difficult to detect
Flammability	Moderate	Severe explosion hazard	Not flammable
Solubility in water	High	Low	Very low, hydrolyzes
Availability	Readily available	Readily available	Possible problem
Effect on external environment	Slight	Undesirable local effects	Potentially severe problems
Effect of contamination of working fluid	Moderate	Negligible	Negligible

Source: R. Douglass, J. Hoilett, and A. Karalis, *Ocean Thermal Energy: An Engineering Evaluation*, Offshore Technology Conference, Paper Number OTC 2252, 1975.

stainless steel and copper-nickel are possible materials for the heat exchange surfaces. The material will be selected based on its heat transfer quality, cost, availability, rate of production, life expectancy, resistance to biofouling and compatibility with the working fluid. Biofouling of the heat exchange surfaces is a potentially serious problem because very efficient heat transfer is necessary for OTEC operation.

A platform structure is conceived for most OTEC designs. This structure provides flotation or buoyancy; support for power modules and the cold water pipe; and provides space for the crew, auxiliary equipment, and controls.

In order to use the cold water in the ocean depths as a condenser fluid, a cold water pipe will be used which extends from 1000-4000 feet below the ocean surface and will have a diameter as large as 130 feet. Naturally, for this size pipe, the material density, weight, cost, strength, resistance to biofouling and corrosion, hydrodynamic smoothness, and life expectancy are all important aspects that must be considered before a selection is made.

The gas turbines, electrical generators, and pump required for the closed-cycle OTEC systems are considered to be standard items requiring no new technology. Only the questions of size and numbers required to meet the particular design criteria need to be addressed.

Mooring is a special problem for floating OTEC plants. Single- and multiple-point grounding with cables have been considered. An active thrust system using the water discharge from the hot and cold water loops to position and maneuver the OTEC plant seems promising.

#### Power Transmission

A study is being conducted to determine which electrical transmission system will be the most appropriate for transporting to shore the power generated by a OTEC plant.<sup>1</sup> Results of this study should provide info.

<sup>1</sup>C. Zener, A. Levi, and C. C. Wu, *Solar Sea Power First Quarterly Report*, Carnegie-Mellon University, Pittsburgh, Pennsylvania, October 1973.

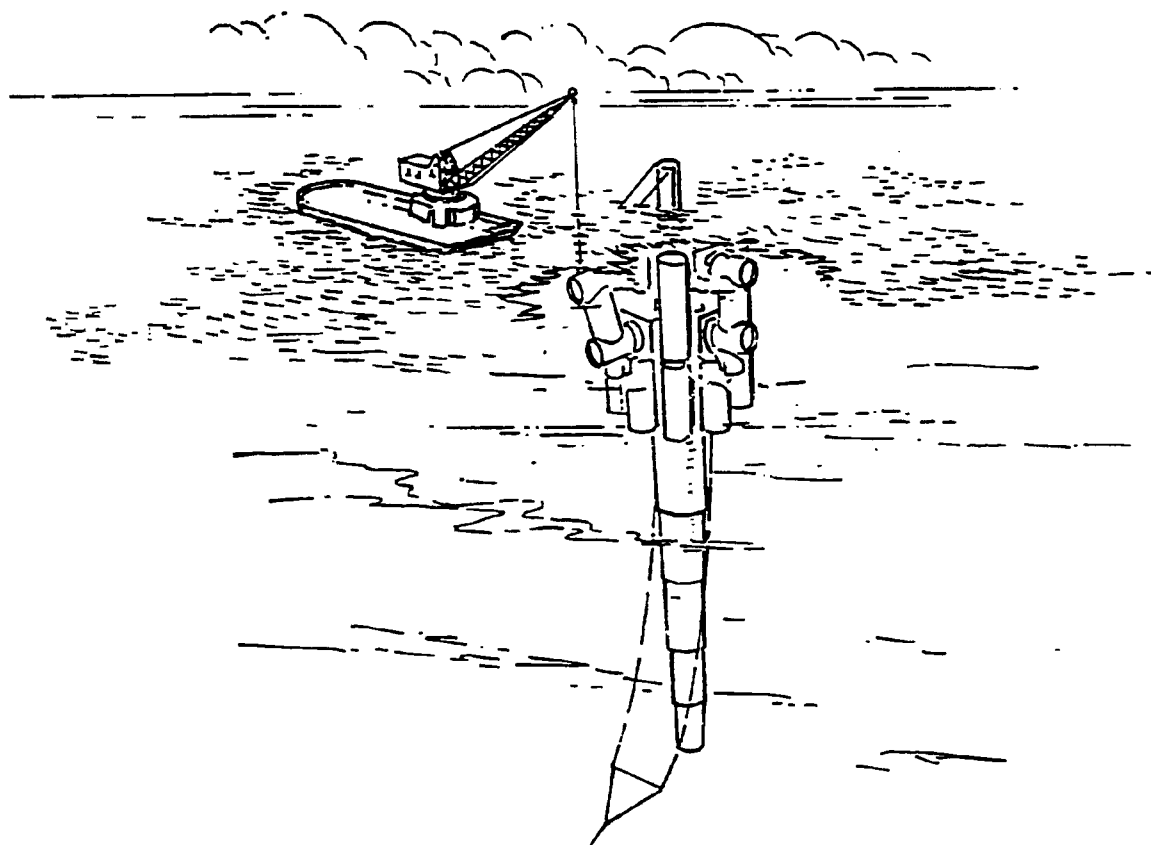


Figure XX-22. LOCKHEED OTEC POWER PLANT

mation regarding losses associated with electric transmission via submarine power cables and data on chemical energy transmission to arrive at the costs involved. Results of previous studies of electrical versus hydrogen transmission conducted by Arthur D. Little, Inc., indicate that if the final energy form produced is to be hydrogen, then it is most economical to pipe it as hydrogen. If the final energy use is to be electrical, then within a certain distance between plant and shore, electrical energy transmission is the most economical.

#### Current OTEC Projects

Studies of program alternatives and cost-benefit-risk tradeoffs are being made, and research and development on heat exchanger technology, biofouling, and high Reynolds number ( $10^6$ - $10^8$ ) hydrodynamic flows past circular cylinders are being conducted. Criteria will be developed for a possible test facility. With the test program, critical components and subsystems will be identified and prescreened so that the most promising candidates can be developed for future large-scale testing.

The remainder of this section will be devoted to a description of the current Lockheed and TRW baseline OTEC power plant designs. Lockheed's baseline design is configured as a number of power generating modules attached to a semisubmersible spar-type core structure<sup>1</sup> (See Figure XX-22). Each power module is self-contained having its own sea water circulating pumps, heat exchangers, turbine, generator, working fluid pumps, and auxiliary equipment. The semisubmersible spar was selected for its good stability, minimum air-water interface exposure and ability to translate vertically, via ballast transfer. Shown in Figure XX-23 is a typical OTEC sea water temperature profile vs water depth.

The Lockheed system is a Rankine closed-cycle plant using ammonia as the working fluid. The heat exchanger surfaces are constructed from titanium using a shell and tube configuration with sea water inside the tubes.

The baseline power module (60 MWe) is a steel structure having 9200 long tons displacement. This module is completely submerged in its normal operating

<sup>1</sup>L. Trimble and F. Naef, *Ocean Thermal Energy Conversion*, Paper Number OTC 2258, Presented at the Offshore Technology Conference, 1975.



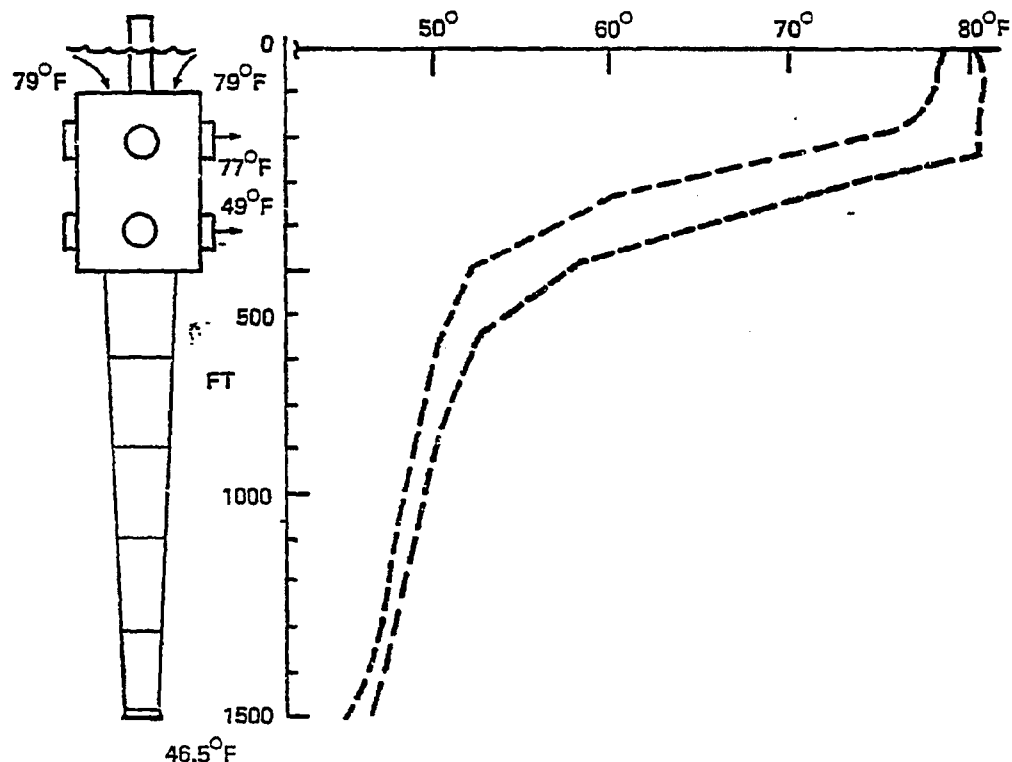


Figure XX-23. OTEC SEA WATER-EFFLUENT TEMPERATURE VS WATER DEPTH

position. The evaporator is located near the top of the module and the condenser is 138 feet below the evaporator. The turbines are axial flow units driven by ammonia vapor at 135 psi inlet and 92 psi exhaust.

Four axial-flow shrouded sea water circulation pumps are mounted inside each heat exchanger. The eight pumps move water at approximately 28,000 cfs.

The baseline cold water pipe consists of five telescoping sections of post-tensioned concrete pipe. Each has a nominal length of 200 feet resulting in a 1000-foot totally extended length. The outside diameter varies from 129 feet at the top to 105 feet at the bottom. The pipe thickness is 1.5 feet as shown in Figure XX-24.

The major elements of the mooring system consist of a trapeze, spreader, bridle, swivel, mooring line, structural link and weight anchor (See Figure XX-25).

Lockheed's OTEC unit is scheduled to be undergoing tests at sea beginning in 1982.

TRW's baseline OTEC configuration features a binary closed Rankine cycle operating on an overall temperature difference of 39.3° F using ammonia as the working fluid.<sup>1</sup> Heat exchanger tubes are of titanium; the cold

water pipe (50 foot diameter, 4000 foot length) is of fiber reinforced plastic. The system is designed to deliver 100 MW electric power. Figure XX-26 illustrates its baseline configuration.

#### Cost

A detailed cost estimate of a 100 MW capacity OTEC power plant based on 1972-73 costs shows that OTEC power from the improved version will be competitive with nuclear power and coal.<sup>2</sup> Table XX-7 displays results from this analysis. Due to significant improvements in the heat transfer surface technology, the OTEC concept appears in even a more favorable light. The estimates presented in the table take into account the cost in electrolyzing ocean water to produce hydrogen as well as handling and distributing the hydrogen fuel.

<sup>1</sup>R. Douglass, J. Hollett, and A. Karalis, *Ocean Thermal Energy: An Engineering Evaluation*, Paper Number OTC 2252, Presented at the Offshore Technology Conference, 1975.

<sup>2</sup>O.M. Griffin, *Energy from the Sea: An Appraisal*, Naval Research Laboratory, May 1974.

Table XX-7

## POWER PLANT COST COMPARISONS

	Fossil Fuel <sup>a</sup>		Nuclear <sup>b</sup>	OTEC Baseline	OTEC Improved
	Oil	Coal			
Investment, \$/kWe	465	450	500	2,660	2,070
Use Factor	0.75	0.75	0.6	0.9 <sup>c</sup>	0.9
Fixed charges mills/kWh	11	10	14	35 <sup>d</sup>	20 <sup>d</sup>
Operating cost, mills/kWh	1	1	1	1	1
Fuel cost, mills/kWh	20	7 <sup>b</sup>	11	0	0
Total power cost, mills/kWh	32	18	26	36	21

<sup>a</sup>Except as noted, values are taken from Solar Energy Task Force, Project Independence Blueprint Final Report, Oct. 4, 1974. Investment costs include \$100/kWe for pollution and safety control costs, and costs for fossil-fuel plants include 30-day fuel storage facilities.

<sup>b</sup>Coal at \$18/ton, *Energy From Coal*, Energy Research and Development Administration, ERDA 76-67.

<sup>c</sup>OTEC is assumed to be base-loaded because there is no fuel consumption.

<sup>d</sup>Includes consideration for longer life of OTEC plant because of lower operating temperatures and more uniform environment.

TRW's cost estimate for their 100 MW baseline plant construction is \$210,000,000 (34 mills/KW hr at 90 percent plant factor, 25 year plant life).

### Needed Technology

The critical components of an OTEC power plant are the heat exchangers, turbines, and pumps. There is a need

to improve the performance and efficiency of these components and to eliminate the corrosion and bio-fouling which result from contact with ocean water.

The effects of locally altering the ocean temperature gradient by pumping large quantities of warm and cold water requires careful investigation. It is conceivable but perhaps quite unlikely, for example, that the redistribution of these thermal differentiated waters can, when

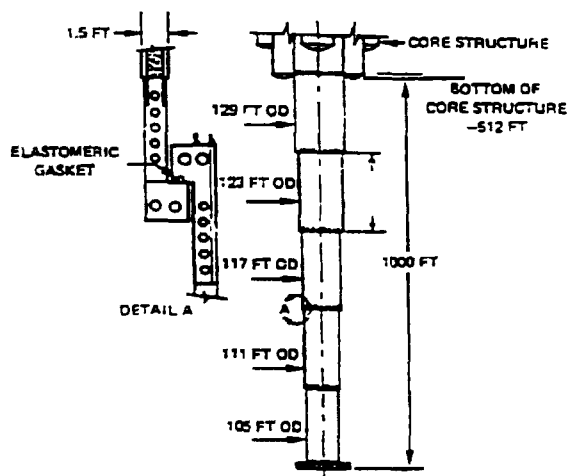


Figure XX-24. LOCKHEED COLD-WATER PIPE ARRANGEMENT

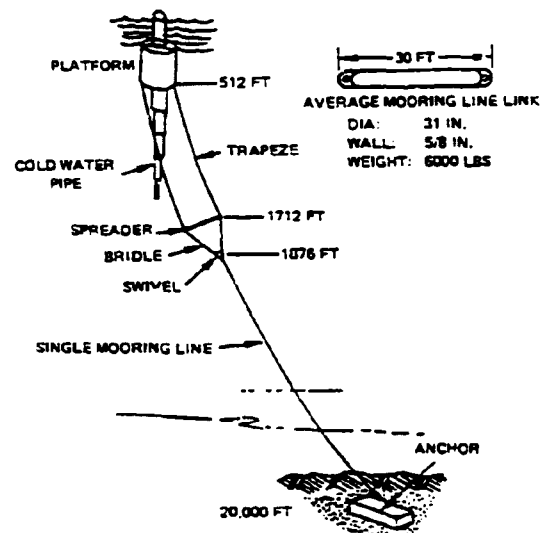


Figure XX-25. LOCKHEED MOORING SYSTEM

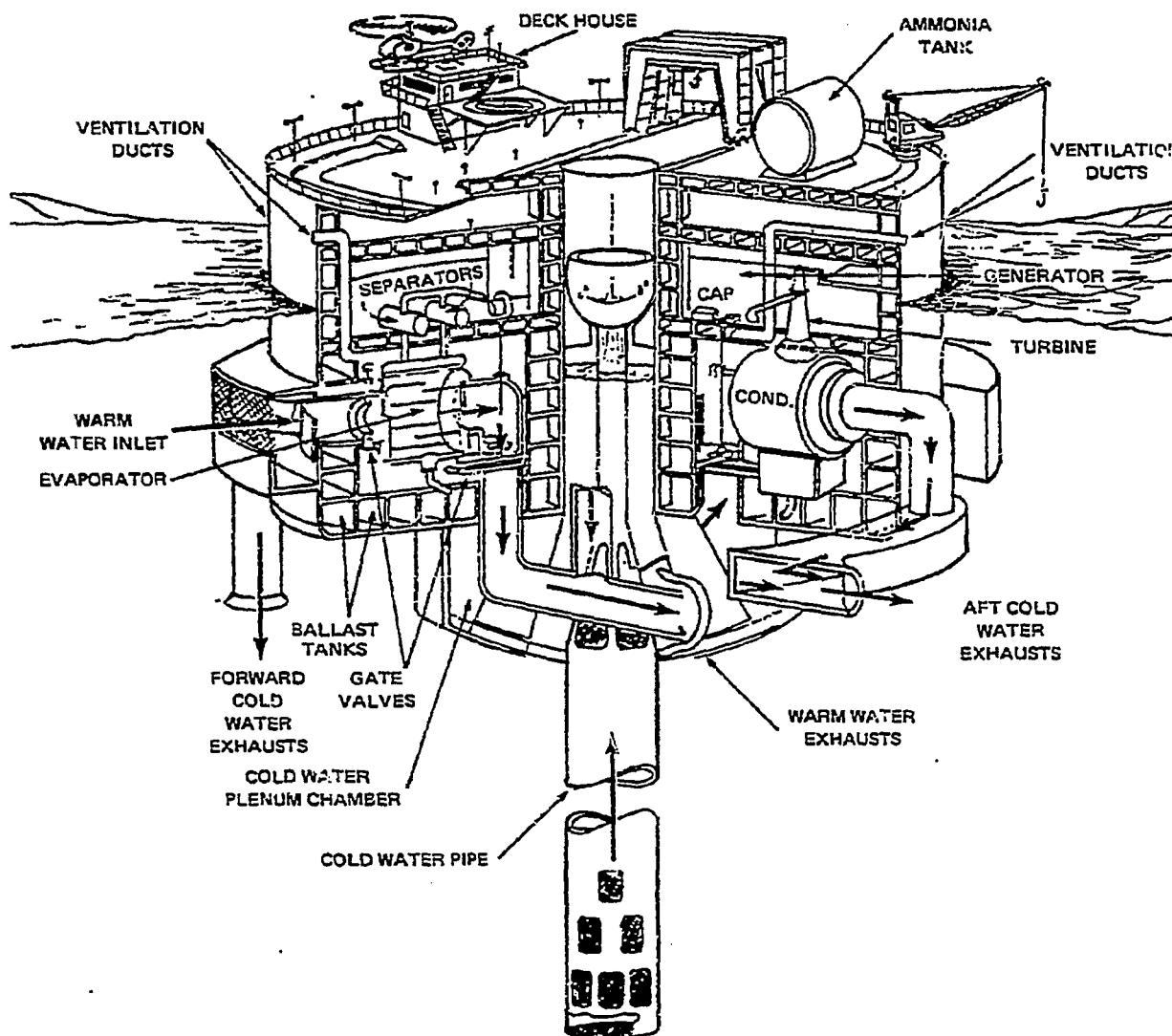


Figure XX-26. CUTAWAY VIEW OF THE TRW OTEC PLANT

mixed upon discharge, alter the temperature gradient and nullify the efficiency of the OTEC plant. A proper design of course will avoid such a catastrophe.

The effect of ingestion of fish and other marine life into the water transfer system of an OTEC can have a potentially adverse effect on such life. These problems need be considered and measures taken to eliminate or greatly reduce the ingestion of biota. It has also been recognized and positively displayed that the dispersion of nutrients from depths into the upper warm strata of the ocean can have a profound beneficial effect, giving rise to a potentially large and important maricultural industry. This possibility requires further evaluation especially in terms of potentially offsetting adverse effects on the environment such as the disturbance of the ecosystem.

Further investigation is needed to examine the chemical-industrial processing operations and electrical distribution systems in connection with OTEC plants.

### OTEC Potential

OTEC technology has moved quickly from laboratory status to the current initial engineering development phase. Currently, a land test facility requiring a tremendous water and heat supply and an off-shore pilot plant will be established. Testing and evaluating components, modules, and heat exchanger surfaces will begin by 1980-1981. It is believed that current development work can provide a low-risk design.

The ERDA OTEC program is aimed at demonstrating

that an OTEC plant is feasible, economical, and can be operative in the late 1980s. The present demonstration plants are envisioned as producing electricity transmitted to shore by cable. It is ERDA's hope to stimulate the

commercial use of OTEC to supply over  $1.5 \times 10^{12}$  kwh annually, resulting in a savings of approximately 2.5 billion barrels of oil per year.

### SALINITY GRADIENT ENERGY

The energy available from the osmotic pressure generated by the mixing of fresh water with seawater is extensive. The head, or pressure differential, between the fresh water flowing into the sea at a river's mouth, can be as great 780 feet.

The recovery of this energy is simple to conceive. It would require an underground water power plant at the

mouth of the river with the tailgate tunnel connected to a network of underwater osmotic membranes spreading around the fresh water in the ocean.

Actual construction of such a power plant is not considered technically feasible because the area of the membranes per unit of fluid discharge would be too large.

**CHAPTER XXI**  
**BIOMASS CONVERSION**

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## INTRODUCTION

Biomass conversion, or bioconversion, is the process of utilizing solar energy captured by photosynthesis. On a moisture-free basis, organic materials from algae to wood wastes have a remarkably uniform heat content of 7000-9000 Btu/lb. To utilize the solar energy captured in the biomass, several systems have been developed. Re-

search to expand the capability of bioconversion processes is underway. The most readily available source of biomass energy is the waste generated daily by industrialized society. In addition to the many schemes for utilizing this waste, there are proposals for both land and ocean farms to produce bioenergy crops.

## BIOMASS SOURCES

Biomass suitable for conversion into energy comes from a variety of sources: some originates from urban and industrial wastes, some from agricultural and forestry wastes. In addition to these sources, there is the possibility of growing organic matter specifically for energy production by land, fresh water, and ocean farming. At this time the most readily available biomass resource is in the form of wastes. Estimates of the quantity of usable waste vary greatly, and definitive figures are not available. One source estimates that the solid wastes generated in the United States in 1970 totaled 4.5 billion tons, of which about 13 percent represented the dry combustible fraction. Table XXI-1 lists the material content of the moisture-free fraction. Not all of this is collectable or usable, and there is considerable seasonal variation, particularly for crop residues.

Municipal solid waste (MSW) represents the most collectable portion of the usable resources and many energy waste recovery systems have been designed to utilize MSW. Table XXI-2 gives the breakdown of typical MSW on a percentage basis. The composition and quantity vary from season to season and from location to location. The high heating value of the composite MSW shown in the table is about 4500 Btu/lb. On a moisture- and ash-free basis, the heating value is about 8000-9000 Btu/lb.

Agricultural and forestry wastes are available in far greater quantities than MSW. However, these wastes are generally dispersed and low in heat content in their moist form. Collection and transportation of these wastes to central locations is not economically attractive.

The current disposition of agricultural and forestry wastes is shown in Table XXI-3. Of the total residues of 74 million dry tons, 418 million tons are considered available for use. The seasonal nature of farming makes 35 million tons of the agricultural and forestry residues available in the first quarter of the year, 50 million in the second, 174 million in the third, and 159 million in the fourth quarter.

Table XXI-1

### QUANTITY AND FUEL VALUE OF DRY COMBUSTIBLE SOLID WASTE DISCARDED IN 1970

Waste Source	Quantity (10 <sup>9</sup> lb)	Fuel Value (10 <sup>15</sup> Btu)
Urban and Industrial		
Household and municipal	168.4	1.348
Commercial and institutional	62.1	0.496
Manufacturing plant	23.5	0.188
Demoition	7.7	0.062
Wood related	51.3	0.411
Textile and fabric	0.6	0.005
Non-fabric synthetic materials	0.9	0.011
Food processing	1.5	0.008
Miscellaneous manufacturing	0.2	0.001
Sewage solids	13.8	0.083
Agricultural and Forestry		
Crop residues	644.0	5.152
Animal waste	72.0	0.482
Forestry residue	232.0	1.856
Total	1278.0	10.103

Sources: George L. Huffman, "Processes for Conversion of Solid Wastes and Biomass Fuels to Clean Energy Forms," *Conference on Capturing the Sun Through Bioconversion*, Washington, D.C., March 10-12, 1976.

John Alich, Jr., "Agriculture and Forestry Wastes," *Conference on Capturing the Sun Through Bioconversion*, Washington, D.C., March 10-12, 1976.

Energy plantations have been proposed as possible sources of biomass material for conversion into energy, such as synthetic natural gas. The matrix in Table XXI-4 indicates the areas of land mass that would be required to meet various amounts of the current U.S. demand for

Table XXI-2

## SAMPLE MSW COMPOSITION IN THE UNITED STATES

Component	Percent by Weight	Percent Moisture by Weight	Btu/Pound <sup>a</sup>
Food Waste			
Garbage	10.0	72.0	6,484
Fats	2.0	0	16,700
Rubbish			
Paper	42.0	10.2	7,572
Leaves	5.0	50.0	7,096
Grass	4.0	65.0	7,893
Street sweepings	3.0	20.0	6,000
Wood	2.4	20.0	8,613
Brush	1.5	40.0	7,900
Greens	1.5	62.0	7,077
Dirt	1.0	3.2	3,790
Oils, paints	0.8	0	13,400
Plastics	0.7	2.0	14,368
Rubber	0.6	1.2	11,330
Rags	0.6	10.0	7,652
Leather	0.3	10.0	8,850
Unclassified	0.6	4.0	3,000
Noncombustibles			
Ashes	10.0	10.0	
Metals	8.0	3.0	
Glass and ceramics	6.0	2.0	

<sup>a</sup>On a moisture- and ash-free basis.Source: *The Problem of Waste Disposal*, College of Engineering, University of Michigan, 1972.

natural gas if it were to be produced from an energy crop; 169,000 square miles is about 5.6 percent of the land mass of the conterminous states. Table XXI-5 summarizes observed yields for selected plant species. The rate of plant growth is in part determined by the availability of water. As a general rule, about 500 tons of water are required to produce a single ton of dry plant matter. To obtain a yield of 10 (dry) tons/acre-year, 44 inches of rain (or its equivalent as irrigation) must be provided. For comparison, rainfall over the southeastern United States averages 48 inches per year.

Table XXI-3

## AGRICULTURAL AND FORESTRY WASTES

	Crop (10 <sup>9</sup> lb)	Animal (10 <sup>9</sup> lb)	Forestry (10 <sup>9</sup> lb)
Total residue	644	72	232
Collected	14	52	150
Returned to soil	10	35	
Fed without sale	3		
Sold	1	8	50
Wasted		9	75
Used as fuel			25

Adapted from: John Alich, Jr., "Agriculture and Forestry Wastes," *Conference on Capturing the Sun Through Bioconversion*, Washington, D.C., March 10-12, 1976.

Table XXI-4

## POTENTIAL SNG PRODUCTION BY LAND FARM

Percent of Present Demand <sup>a</sup>	Area Required (square miles)		
	10 Tons/Acre-Year	25 Tons/Acre-Year	50 Tons/Acre-Year
1.66	12,000	5,000	2,800
10	72,000	30,100	17,000
50	361,000	150,500	84,500
100	723,000	301,000	169,000

<sup>a</sup>Approximately  $22 \times 10^{12}$  SCF/year.Source: George L. Huffman, "Processes for Conversion of Solid Wastes and Biomass Fuels to Clean Energy Forms," *Conference on Capturing the Sun Through Bioconversion*, Washington, D.C., March 10-12, 1976.

Because of the demand for water in biomass production, fresh water and ocean farming concepts have been proposed. Single-cell algae in nutrient-rich fresh waters exhibit growth rates as high as 70 (dry) tons/acre-year with 16-32 (dry) tons/acre-year reasonable for a 365-day growing season. Water hyacinth in the southeastern states can grow as rapidly as 60 (dry) tons/acre-year. A methane production fresh water farm with a capacity of 72 billion SCF/year would require 16,000 miles of canals on 348 square miles of land if water hyacinth were to be cultivated.<sup>1</sup>

Because of the limited availability of land area suitable for land or fresh water farming, studies are being conducted on ocean farming. The principal algae under consideration is the giant California kelp, which converts solar energy to biomass energy with a 2 percent efficiency under proper growing conditions. Because the surface waters in which the kelp would be grown are nutrient-deficient, the necessary nutrients would be supplied by the upwelling of enriched waters from 500- to 1000-foot depths. Plans call for a 100,000 acre farm by 1985-1990. The kelp will be anchored to a submerged raft of polypropylene lines. If anaerobic digestion is used to extract methane from the harvested kelp, the productivity of the ocean farm will be about 160,000 SCF/acre-year. A farm 470 miles on a side could supply the U.S. demand for natural gas. The American Gas Association is particularly interested in ocean farming of kelp. Considerable basic research has been done and indications are that the concept is reasonable.

<sup>1</sup> Richard S. Greeley and Peter C. Spewak, "Land and Fresh Water Farming," *Conference on Capturing the Sun Through Bioconversion*, Washington, D.C., March 10-12, 1976.



Table XXI-5

**ABOVEGROUND, DRY BIOMASS YIELDS OF  
SELECTED PLANT SPECIES**

Species	Location	Yield (tons/acre-year)
<b>Annuals</b>		
Exotic forage sorghum	Puerto Rico	30.6
Forage sorghum (irrigated)	New Mexico	7-10
Forage sorghum (irrigated)	Kansas	12
Sweet sorghum	Mississippi	7.5-9
Exotic corn (137-day season)	North Carolina	7.5
Silage corn	Georgia	6-7
Hybrid corn	Mississippi	6
Kenaf	Florida	20
Kenaf	Georgia	8
<b>Perennials</b>		
Sugarcane	Mississippi	20
Sugarcane (state average)	Florida	17.5
Sugarcane (best case)	Texas (south)	50
Sugarcane (10-year average)	Hawaii	26
Sugarcane (5-year average)	Louisiana	12.5
Sugarcane (5-year average)	Puerto Rico	15.3
Sugarcane (6-year average)	Philippines	12.1
Sugarcane (experimental)	California	32
Sugarcane (experimental)	California	30.5
Alfalfa (surface irrigated)	New Mexico	6.5
Alfalfa	New Mexico	8
Bamboo	Southeast Asia	5
Bamboo (4-year stand)	Alabama	7
Black cottonwood (2-year old)	Washington	4.5
Red alder (1- to 14-year old)	Washington	10

Source: John Alich, Jr. and Robert Inman, "Energy from Agriculture," at *Clean Fuels from Biomass, Sewage, Urban Refuse, and Agricultural Wastes*, Orlando, Florida, January 26-30, 1976.

### BIOCONVERSION PROCESSES

A number of technologies are available for converting biomass into useful energy forms. The basic energy recovery processes can be classified as thermal oxidation, pyrolysis, anaerobic digestion, and fermentation. There are a number of variations on each of these competing technologies. Tables XXI-6 and XXI-7 provide some perspectives on systems designed for MSW processing. Some of these systems are less than optimal for extracting energy from agricultural and forestry wastes. The high moisture content of land and water energy crops may favor bacterial systems for energy production from these sources.

#### Solid Fuel From Municipal Solid Wastes

In 1972, the Union Electric Company and St. Louis began operation of the Horner and Shifrin process for producing refuse derived fuel (RDF) for supplemental

firing (cofiring) with coal at the Meramac power plant. Initially, the refuse was shredded in a hammermill and the ferrous metals separated electromagnetically. The resulting mixture then supplied 10-20 percent of the fuel value for the Meramac plant. Figure XXI-1 shows a generic process for producing solid fuel from MSW for supplemental firing in a utility boiler. The air classifier separates the light and heavy fractions of the incoming shredded waste stream. The heavy fraction (about 25 percent by weight) consists of metals, glass, wood, ceramics, heavy plastics, food matter and yard wastes. After passing through a secondary shredder, the light fraction is compacted to 30 lb/cu ft for transport to the utility. Table XII-8 gives the typical composition of the light fraction of refuse-derived fuel. The heat content is 5000-6000 Btu/lb. A significant advantage of this form of RDF is the low sulfur content. On a Btu basis, the RDF has about 5 percent of the sulfur of utility grade coal.

Table XXI-6

## PERSPECTIVES ON MSW FUEL PROCESSES

Process	Positive Aspects	Negative Aspects
Solid fuel from MSW	<ul style="list-style-type: none"> <li>• Low investment requirement</li> <li>• High efficiency of energy recovery from MSW</li> <li>• Low net amortized disposal cost</li> <li>• Use of existing facilities</li> <li>• Revenues from recovered materials</li> <li>• Low sulfur content of RDF</li> </ul>	<ul style="list-style-type: none"> <li>• Co-firing of prepared MSW fuel limited to 20 percent of fuel requirement</li> <li>• Practical only in boilers equipped with ash-handling equipment and particulate emission controls</li> <li>• Possible corrosive effects on boilers</li> <li>• Low bulk density of RDF makes storage difficult</li> </ul>
Pyrolysis to a fuel gas	<ul style="list-style-type: none"> <li>• Clean, versatile low-Btu gas</li> <li>• Minimal feed preparation</li> <li>• Existing facilities can use product</li> <li>• Relatively high efficiency of energy recovery from MSW</li> </ul>	<ul style="list-style-type: none"> <li>• Storage of fuel produced not feasible</li> <li>• Cryogenic oxygen plant required</li> <li>• Capital-intensive</li> </ul>
Pyrolysis to a fuel oil	<ul style="list-style-type: none"> <li>• Final product is easily transported and stored temporarily</li> <li>• Existing facilities can use product</li> <li>• Full spectrum of secondary materials recovered for recycling</li> <li>• Low sulfur content of product</li> </ul>	<ul style="list-style-type: none"> <li>• Low energy recovery efficiency</li> <li>• Process requires large amount of purchased power</li> <li>• Corrosive nature of product</li> <li>• Possible corrosive effect on boilers</li> <li>• Capital-intensive</li> </ul>
Direct thermal conversion	<ul style="list-style-type: none"> <li>• Total electric power production package</li> <li>• Materials recovery for recycling</li> </ul>	<ul style="list-style-type: none"> <li>• Low energy recovery efficiency</li> <li>• Capital-intensive</li> <li>• Gas cleanup system required before gas turbine</li> </ul>
Incineration of MSW	<ul style="list-style-type: none"> <li>• Extensive history of operation</li> <li>• High energy efficiency</li> <li>• Adaptable to electric power generation</li> </ul>	<ul style="list-style-type: none"> <li>• Capital-intensive</li> <li>• Corrosion of boiler tubes</li> <li>• Requires market for steam produced</li> <li>• Landfill requirement for residues</li> </ul>
Anaerobic digestion	<ul style="list-style-type: none"> <li>• Clean, high-Btu gas produced</li> </ul>	<ul style="list-style-type: none"> <li>• Low overall system efficiency</li> <li>• Residual solids produced which require disposal</li> <li>• Increases burden on sewage treatment facilities</li> <li>• Large acreage required for facility</li> </ul>

Sources: *Fuels from Municipal Refuse for Utilities: Technology Assessment*, Bechtel Corporation, March 1975, p.v.  
*Resource Recovery Technology for Urban Decision Makers*, Urban Technology Center, School of Engineering and Applied Science, Columbia University, January 1976.

A second method for producing RDF is the Combustion Equipment Associates hydrolytic chemical treatment of the air-classified organic fraction. In this process, a proprietary chemical is added to the shredded fraction in a ball mill to break down the cellulosic structures in the prepared MSW. The end product is a fine powder called *Eco-Fuel II* with a density of 30 lb/cu ft and a heating value of 7500-8000 Btu/lb. For ease of handling, *Eco-Fuel II* can be briquetted. In addition to the fuel produced, ferrous metals are recovered for recycling.

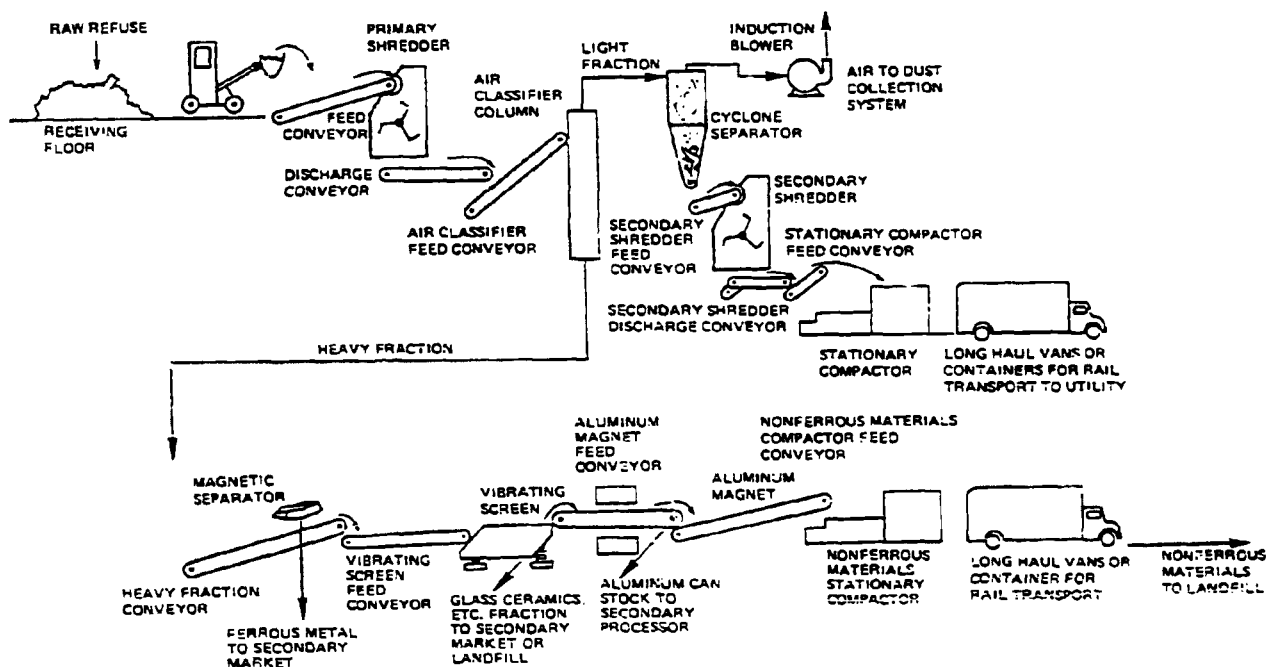
Black Clawson has developed a hydropulping process for the production of two grades of RDF. Product No. 1 has a moisture content of 50 percent and product No. 2 has a moisture content of 5-20 percent and can be briquetted for convenience. The process provides for the recovery of ferrous metals, aluminum and color-sorted glass cullet. The hydropulper process allows the production of a homogenized form of RDF that can be easily transported and stored.

Table XXI-7

**COMPARISON OF ENERGY RECOVERY PROCESSES**  
(Plant capacity 1,000 tons per day)

	Dollars Per Ton									
	Wheelabrator-Frye Waterwall Incinerator	Combustion Power Incinerator Turbine	Horner & Shirlin Co-combustion of Shredded Refuse	Combustion Equipment Associates Eco-Fuel II	Black Clawson Wet Pulped Fibrous Fuel No. 2	Monsanto Environ-Chem Landgard System	Occidental Research Flash Pyrolysis	Carborundum Torrax System	Union Carbide Purox System	Dynatech R/D Anaerobic Digestion to Methane
Investment (dollars per daily ton)	30,800	22,500	10,400	17,700	13,600	21,500	21,900	10,500	22,900	19,000
Capital cost <sup>a</sup>	10.24	7.49	3.46	6.00	4.49	7.17	7.28	5.48	7.60	6.63
Operating Cost										
Labor and supervision	3.40	3.10	2.59	3.10	2.69	3.10	3.04	3.10	3.40	3.10
Power	2.10	<sup>b</sup>	1.62	1.05	2.55	2.31	3.72	3.75	5.34	1.66
Other utilities and supplies	0.20	0.11	0.08	0.76	4.58	2.97	0.38	1.07	0.24	4.40
Maintenance	3.42	4.09	0.85	1.92	1.40	2.40	2.40	1.89	2.25	2.40
Miscellaneous	0.93	0.68	0.32	0.54	0.41	0.65	0.66	0.50	0.59	0.59
Disposal costs	1.08	1.50	0.00	0.72	0.60	0.48	1.14	...	...	6.28
Total operating cost	11.13	9.48	6.30	8.69	12.11	12.09	12.31	10.91	11.92	18.42
Total operating cost including amortization	21.37	18.97	9.82	14.59	18.60	18.17	19.59	16.39	19.62	24.95
Credits										
Energy	13.80	6.88	8.61	9.36	8.00	11.04	5.70	6.30	13.50	7.86
Materials	1.68	2.01	1.00	1.00	3.51	2.06	3.52	0.60 <sup>d</sup>	2.06	3.56
Total credits	15.48	9.70	8.20	11.04	12.11	13.10	9.28	6.90	15.56	11.42
Net disposal cost including amortization	5.89	7.10	1.63	3.65	4.40	6.07	10.31	9.49	3.06	13.53
Energy recovery efficiency	67% <sup>e</sup>	36% <sup>f</sup>	60% <sup>g</sup>	64% <sup>h</sup>	62% <sup>h</sup>	44% <sup>c</sup>	37%	45% <sup>i</sup>	62%	26%

<sup>a</sup>15 year amortization, 7 percent interest.<sup>b</sup>Self generated<sup>c</sup>Includes conversion to steam<sup>d</sup>Overall conversion to electricity.<sup>e</sup>Reflects allowance for less efficient combustion as compared with oil/gas.<sup>f</sup>Does not include fuel value of charSource: *Resource Recovery Technology for Urban Decision Makers*, Urban Technology Center, School of Engineering and Applied Sciences, Columbia University, January 1978



Adapted from: *Fuels from Municipal Refuse for Utilities: Technology Assessment*, Bechtel Corporation, March 1975, pp. 2-12.

Figure XXI-1. SOLID FUEL FROM MSW

### Pyrolysis to a Fuel Gas

Pyrolysis is the thermal decomposition of materials in the absence or near absence of oxygen. In general, fuel gases, liquids and chars can be produced by pyrolysis with the quantities of each determined by the pressure, temperature, residence time, catalysts and reactor charge mixture. Several companies have developed variations of

the pyrolysis process.

Union Carbide has developed the oxygen refuse converter system (Purox system) to produce medium-Btu fuel gas. The key element in the system is the reactor, which is a vertical shaft furnace with oxygen feed ports at the furnace base. The entering oxygen reacts with the char, which is one of the end products formed from the refuse. The heat of this reaction melts and fuses the ash, mer-

Table XXI-8

MSW LIGHT FRACTION SOLID FUEL

Component	Weight (percent)
Paper	55.0
Food wastes	16.0
Yard wastes	13.7
Ferrous metals	—
Non-ferrous metals	—
Glass, ceramics	2.7
Plastics	1.8
Textiles	2.5
Wood	2.6
Leather and rubber	1.8
Miscellaneous	3.9

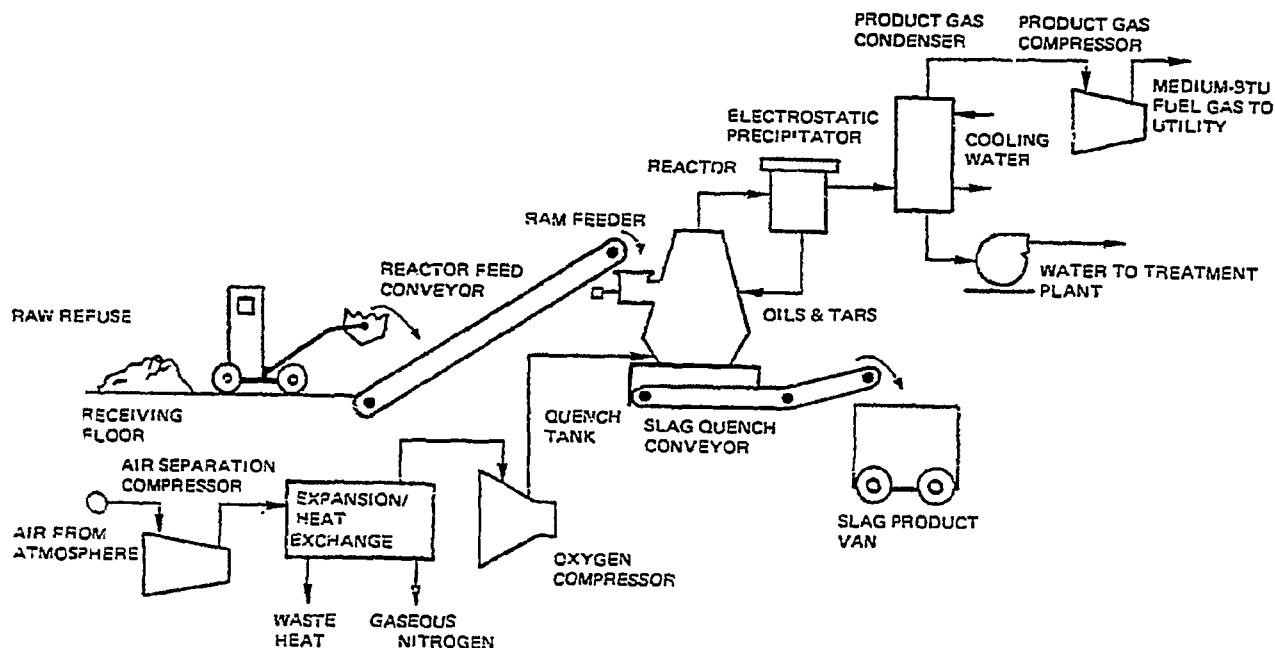
Source: *Fuels from Municipal Waste for Utilities: Technology Assessment*, Bechtel Corporation, March 1975, pp. 3-9.

Table XXI-9

COMPOSITION OF PYROLYSIS FUEL GAS

Component	Volume (percent)	Weight (percent)
CO	44.2	58.9
H <sub>2</sub>	31.0	2.9
CO <sub>2</sub>	13.2	27.6
CH <sub>4</sub>	3.8	2.9
C <sub>2</sub> H <sub>4</sub>	0.9	1.4
N <sub>2</sub>	0.9	1.2
H <sub>2</sub> O	6.0	5.1

Source: *Fuels from Municipal Waste for Utilities: Technology Assessment*, Bechtel Corporation, March 1975, pp. 3-29.



Adapted from: *Fuels from Municipal Refuse for Utilities: Technology Assessment*, Bechtel Corporation, March 1975, pp. 2-15.

Figure XXI-2. PYROLYSIS OF MSW TO A FUEL GAS

and glass in the input refuse stream and decomposes the organic fraction of the refuse charge in the upper, oxygen-deficient, portion of the furnace. The molten slag drains continuously from the furnace into a water-filled quench tank where a hard granular material is formed. The hot gases formed rise through the furnace drying the incoming refuse before exiting the furnace at about 200° F. Figure XXI-2 is a diagram of the basic pyrolysis of MSW to a fuel gas. The composition of the product gas is shown in Table XXI-9. It has a heating value of approximately 300 Btu/SCF with properties very similar to medium-Btu, coal-derived gas.

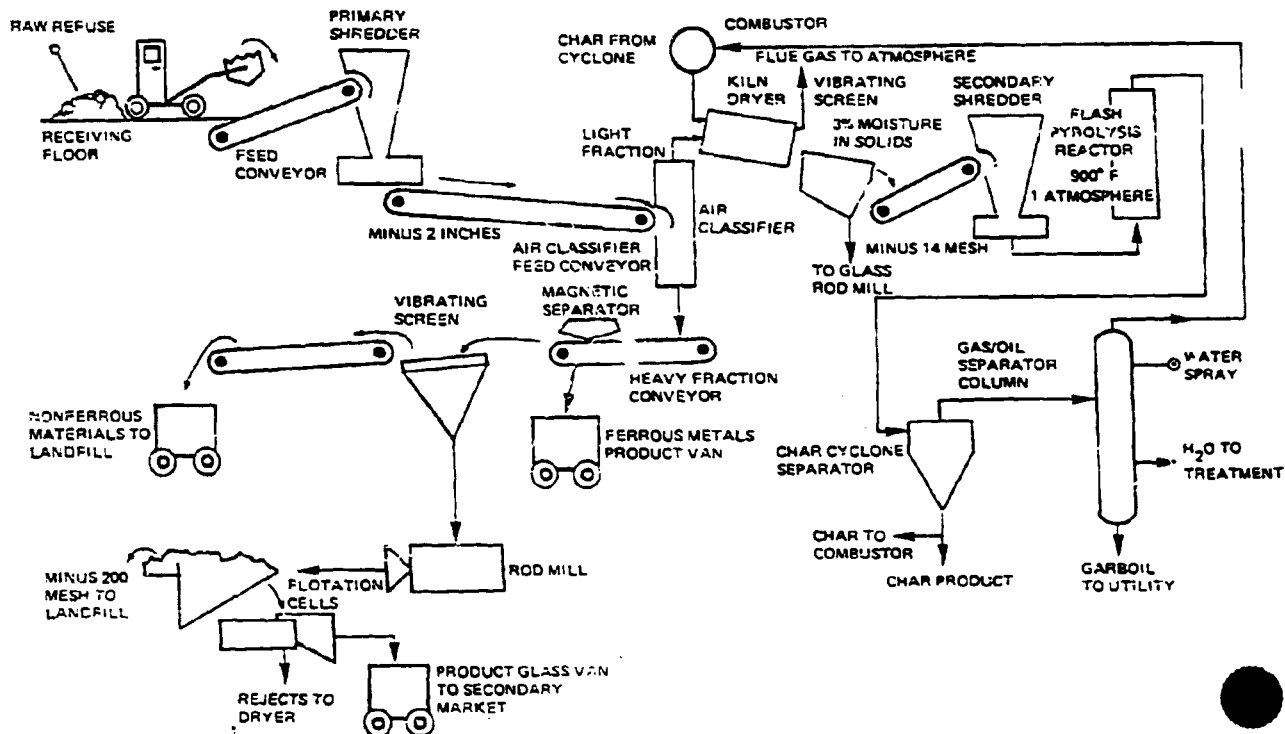
A process similar to the Purox system is Carborundum's Torrax system. Rather than oxygen, superheated air supplies the thermal driving force to maintain high enough temperatures to fuse the inert portion of the MSW.

The Monsanto Landgard system is another variation of the pyrolysis of MSW to low-Btu gas. In this case, partial incineration of MSW supplies the heat to pyrolyze the MSW in a rotary kiln at 40 percent of the stoichiometric air requirement. The result is a low-Btu gas (100 Btu/SCF), which is burned on site to generate steam for space heating and cooling.

### Pyrolysis to Fuel Oil

Occidental Petroleum has developed a flash pyrolysis process for the conversion of MSW to fuel oil with the recovery of ferrous metals, aluminum, and glass. Figure XXI-3 diagrams the Occidental Petroleum pyrolysis process. Details of the flash pyrolysis reactor design and method of operation are proprietary. Yields of one barrel of oil per ton of raw MSW feed have been confirmed. The oil is a highly oxygenated acidic tar that is viscous, corrosive and has a tendency to thicken on storage. It has a heating value of 10,500 Btu/lb and a low sulfur content. Table XXI-10 provides a comparison of pyrolytic oil with No. 6 fuel oil.

The Occidental process can be modified to produce a finely shredded and dried RDF by simply eliminating the pyrolysis step. The properties of the Occidental RDF are listed in Table XXI-11. For each 1000 tons of MSW processed, approximately 750 tons of RDF can be obtained. However, the energy requirements of the fine shredding and drying operations and the extra processing for the extensive materials recovery increases the cost of the Occidental RDF above that of the simpler Union Electric-St. Louis process.



Adapted from: *Fuels from Municipal Refuse for Utilities: Technology Assessment*, Bechtel Corporation, March 1975, pp. 2-19.

Figure XXI-3. PYROLYSIS OF MSW TO FUEL OIL

Table XXI-10

COMPARISON OF OCCIDENTAL PYROLYSIS OIL AND NO. 6 FUEL OIL

	No. 6	Pyrolysis Oil
Carbon (weight percent)	85.7	57.5
Hydrogen (weight percent)	10.5	7.6
Sulfur (weight percent)	0.7-3.5	0.1-0.3
Chlorine (weight percent)	—	7.3
Ash (weight percent)	0.05	0.2-0.4
Nitrogen (weight percent)	—	0.9
Oxygen (weight percent)	2.0	33.4
Btu/lb	19,200	10,500
Specific gravity	0.98	1.30
Lb/gal	8.18	10.85
Btu/gal	148,840	113,910
Pour point (° F)	65-85	90
Flash point (° F)	150	133
Viscosity (standard Saybolt units at 150° F)	340	1150
Pumping temperature (° F)	115	160
Atomization temperature (° F)	220	240

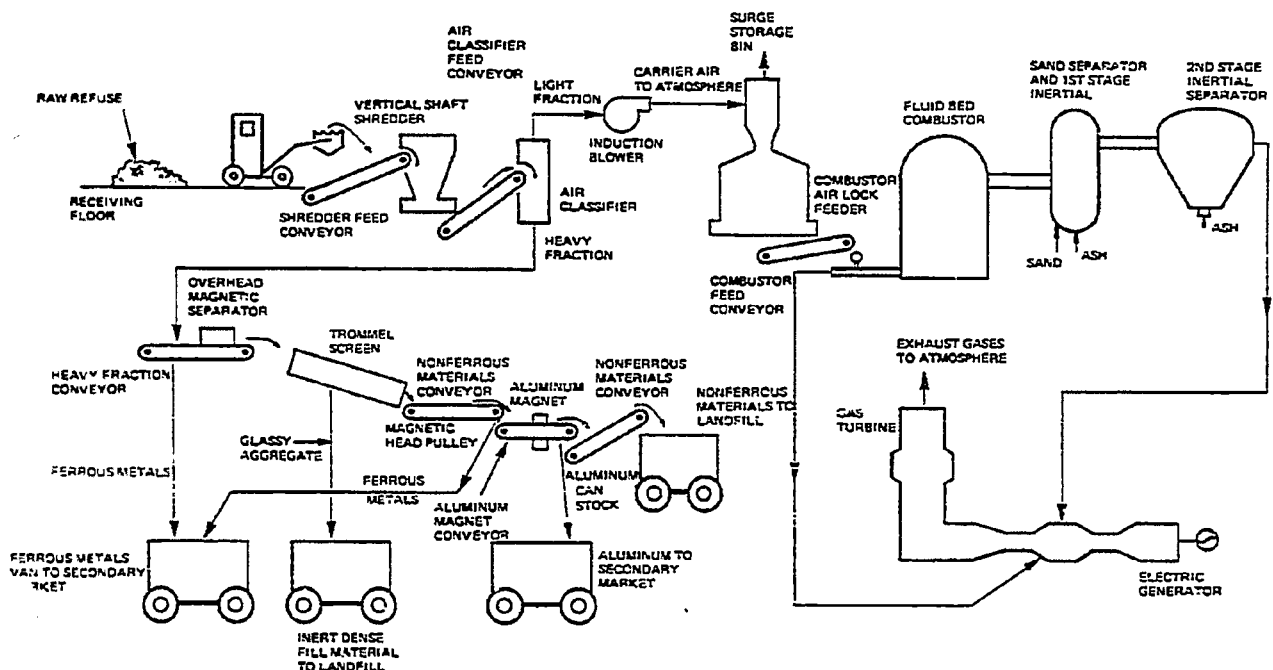
Source: *Resource Recovery Technology for Urban Decision Makers*, Urban Technology Center, School of Engineering and Applied Science, Columbia University, January 1976, p. 46.

Table XXI-11

CHARACTERISTICS OF OCCIDENTAL RDF

Heat content	6300 Btu/lb
Particle size	90 percent through 3/4 inch
Density	5 lb/cu ft
Moisture content	10 percent
Inert content	4-6 percent
Total ash content	8-14 percent
Sulfur content	0.2 percent
Chlorine content	0.3 percent

Source: *Resource Recovery Technology for Urban Decision Makers*, Urban Technology Center, School of Engineering and Applied Science, Columbia University, January 1976, p. 49.



Adapted from: *Fuels from Municipal Refuse for Utilities: Technology Assessment*, Bechtel Corporation, March 1975, pp. 2-25.

Figure XXI-4. THE CPU-400 SYSTEM

### Direct Thermal Conversion

The Combustion Power Company, Inc., has designed an incinerator turbine, the CPU-400 system, in which air-classified MSW is burned in a fluidized sandbed under pressure with the exhaust gases directed through a gas turbine for conversion of heat energy to electrical power. To some extent, the process is the same as the Union Electric-St. Louis process, which generates RDF for co-firing with coal. The CPU-400 process differs because the RDF is consumed immediately with no supplemental firing. An advantage of the process is reduction of noxious gas emissions, but cleaning the exhaust gas before passage through the turbine is a major problem. From a 1000 ton/day MSW plant, 340 MWh of electrical energy can be generated. Figure XXI-4 shows the energy and resource recovery aspects of this process.

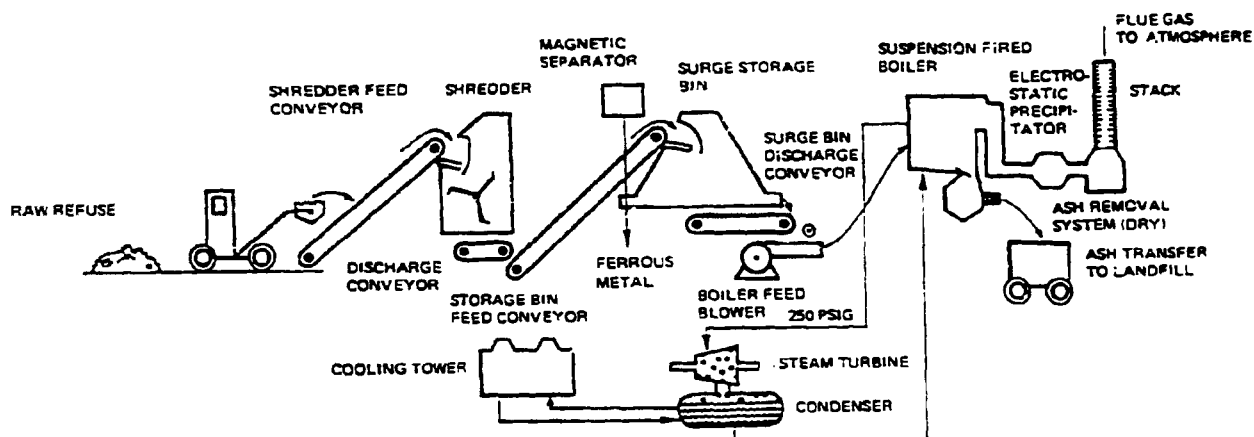
### Incineration of Municipal Solid Waste

One of the simplest energy recovery systems is the incinerator with heat recovery. Figure XXI-5 illustrates

such a recovery system. The Navy has operated a water-wall incinerator at Norfolk, Virginia, since 1967 with no shredding capability. Waterwall refuse incinerators are common in Europe; Wheelabrator-Frye has exclusive rights for developing the process in the United States. In late 1975, Refuse Energy Systems, Inc., started operation of a Wheelabrator-Frye steam generating plant in Saugus, Massachusetts, that processes 1200 tons/day of MSW. The steam is sold to a nearby General Electric plant for power generation and process heat applications.

### Anaerobic Digestion

Anaerobic digestion is a complex biochemical process in which organic matter is fermented in the absence of oxygen by a mixed culture of micro-organisms that produce methane, carbon dioxide, and residues. It is a two-stage process in which organic materials are first converted to acids, alcohols, and aldehydes by acid-forming bacteria. The second stage consists of conversion of the



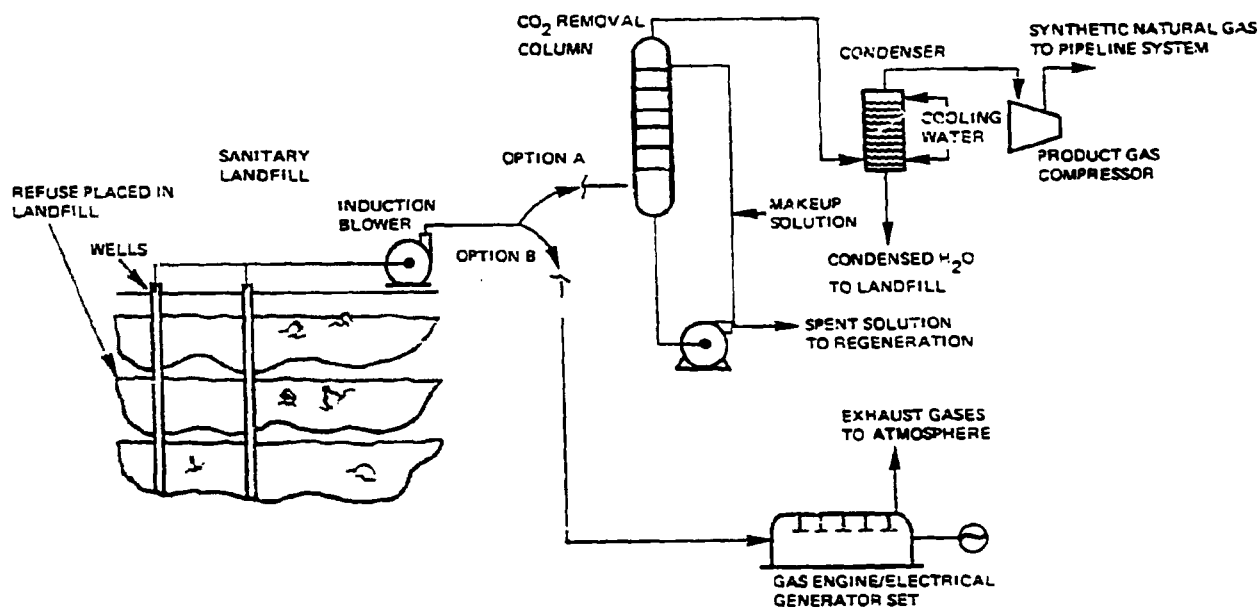
Adapted from: *Fuels from Municipal Refuse for Utilities: Technology Assessment*, Bechtel Corporation, March 1975, pp. 2-27.

Figure XXI-5. INCINERATION OF MSW

acids to methane and carbon dioxide by a second type of bacteria. This type of decomposition occurs in landfills and is possible in large concrete cells. Figure XXI-6 shows a typical energy recovery process for landfill applications. This process is in use at several sites in Southern California. The composition of the raw landfill gas is presented in Table XXI-12; it has a heating value of approximately 600 Btu/cu ft and can be upgraded to pipeline

quality gas. From a steady-state operation in which 100<sup>7</sup> tons of MSW are placed in a landfill each day, 14 tons of dry upgraded gas can be obtained daily.

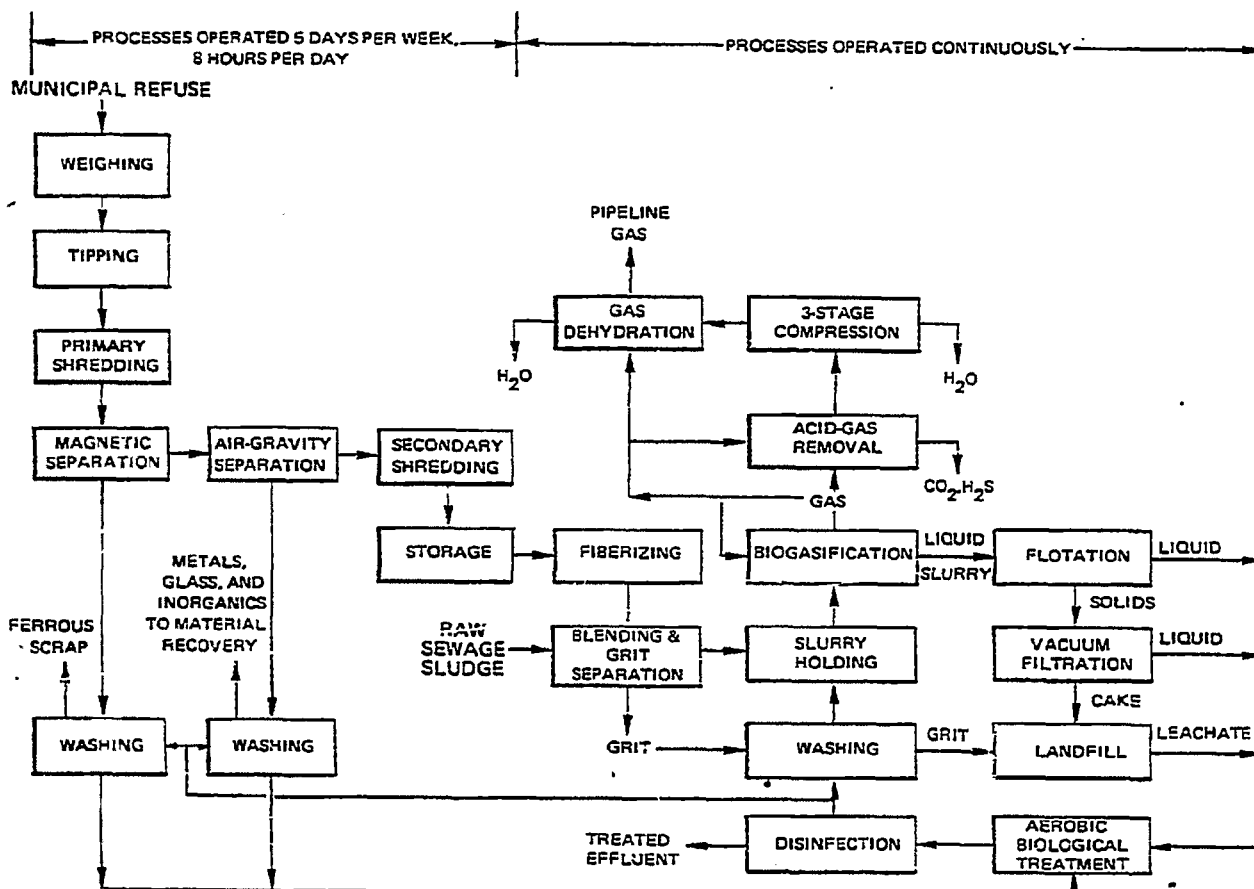
The Institute for Gas Technology has developed a Bio-gas process for the conversion of solid wastes and raw sewage sludge to pipeline quality gas. Figure XXI-7 outlines the proposed process. It is particularly applicable to organic matter with high moisture content, since anaer-



Adapted from: *Fuels from Municipal Refuse for Utilities: Technology Assessment*, Bechtel Corporation, March 1975, pp. 2-22.

Figure XXI-6. METHANE FROM LANDFILL MSW





Source: *Gas Scope*, Institute for Gas Technology, Spring 1975, p. 4.

Figure XXI-7. IGT BIOGAS PROCESS

robic digestion proceeds most rapidly when the solids content in the digester tank is less than 10 percent. Residence time in the digester is 15-30 days, which is a limiting factor for the application of biogasification.

Dynatech R/D has developed a process similar to IGT's Biogas process. The product gas is about 50 percent carbon dioxide by volume and requires processing to remove both the carbon dioxide and water vapor. Approximately 3700 SCF of methane are produced for each ton of MSW, which is processed with an additional 0.94 ton of sewage sludge.

### Biochemical Fractionation

In addition to anaerobic digestion, a number of other biochemical processes exist for producing fuels from biomass. Yeast fermentation of sugars to produce ethanol is a well-known example. Cellulose (wood, paper and plant materials) can be hydrolyzed to sugars. This process may

be catalyzed by mineral acids or enzymes. The Georgia-Pacific plant in Bellingham, Washington, produces 4 million gallons of ethanol per year from spent sulfite liquors by yeast fermentation.

Table XXI-12

### PROPERTIES OF RAW LANDFILL GAS

Component	Volume (percent)
CH <sub>4</sub>	44.6
CO <sub>2</sub>	39.6
H <sub>2</sub> O	14.0
O <sub>2</sub>	0.9
N <sub>2</sub>	0.9

Source: *Fuels from Municipal Refuse for Utilities: Technology Assessment*, Bechtel Corporation, March 1975, pp. 3-29.

## FACILITIES AND RESEARCH

Table XXI-13 lists some of the major energy and resource recovery facilities in operation or planned. In addition to these, there are numerous smaller facilities in operation for waste processing and energy generation. A glance at the table reveals considerable interest in energy recovery systems by industry, municipalities, and government.

Not listed in Table XXI-13 are two facilities planned for the processing of animal wastes into pipeline quality gas. Calorific Recovery Anaerobic Processes of Oklahoma City and ERA, Inc., of Lubbock, Texas, plan on using feedlot wastes to produce a primary product to be used as either a feed supplement or a fertilizer. Calorific will process 70,000 tons/year of manure and generate 641 million SCF of methane; ERA will process 80,000 tons/year of manure to obtain 438 million SCF of methane.

In addition to the research conducted by industry, ERDA and EPA have funds allocated for the development

of the biomass resource. ERDA funds \$3,830,000 research in fuels from biomass as part of its solar energy program. The ERDA FY 77 request for biomass research was \$3,000,000. These funds support programs in biomass sources (agriculture, silviculture and marine), conversion technologies (anaerobic digestion, enzymatic hydrolysis, fermentation, pyrolysis, hydrogenation and direct combustion), and advanced concepts such as the direct photosynthetic production of hydrogen.

Four major waste conversion processes have been under long-term EPA development: Combustion Engineering's CPU-400 Process, the St. Louis waste as a supplementary fuel, the Occidental (formerly Garrett) Pyrolysis Process, and the Monsanto Landgard System. Table XXI-14 lists major EPA research projects. EPA currently allocates \$4,066,000 for solid waste research and development. The same amount has been requested for FY 77.

## ENVIRONMENTAL CONSIDERATIONS

Many of the bioconversion schemes have beneficial impacts on the environment. The resource recovery and reduced demand on landfill sites favor MSW energy recovery systems for urban areas. In addition, the fuels derived from MSW are generally low in sulfur, making them attractive to the utility industry.

Negative environmental impacts are possible from land and ocean farming. The removal of agricultural wastes

from the fields could, in the long run, adversely affect soil productivity. Development of monocultures for land and ocean farming could open the way for serious blights. Extensive irrigation could have regional effects. Also there is a possibility that the use of deep waters for supplying nutrients in ocean farms could release large quantities of carbon dioxide to the atmosphere with possible global impacts.

Table XXI-13

MSW ENERGY RECOVERY SYSTEMS<sup>a</sup>

Location	Key Participants	Process <sup>b</sup>	Capacity (ton/day)	Description
<b>Existing Facilities—Electrical Generation</b>				
Amos, IA	City of Amos; Hanningson, Durham, and Richardson, Inc.	Cofiring with coal	200	Baling, shredding, magnetic separation, air classification, screening, other mechanical separation; 8 MW equivalent power
Menlo Park, CA	Combustion Power Corp.	Fluidized-bed combustor	75	Direct power generation from exhaust gases of combustor; 1 MW equivalent power
So. Charleston, WV	Linde Div., Union Carbide Corp.	Pyrolysis	200	Medium-Btu gas produced by Purox oxygen converter, shredding, 6 MW equivalent power
St. Louis, MO	City of St. Louis; EPA; Union Electric	Cofiring with coal	300	Prepared MSW fuel; 12 MW equivalent power
<b>Existing Facilities—Steam Generation</b>				
Baltimore, MD	City of Baltimore; Monsanto Envirochem Systems, Inc.; EPA	Pyrolysis	1000	Langford process: shredding, pyrolysis, water quenching, magnetic separation; steam at 200,000 lb/hr, 430° F, 330 psig
Baltimore County, MD	Baltimore County, Md., Environmental Services, Teledyne National	RDF	600-1600	Shredding, air-classification, magnetic separation
Braintree, MA	City of Braintree	Incineration	240	Steam at 60,000 lb/hr, 250 psig, saturated
Chicago, IL	City of Chicago	Incineration	1600	Steam at 440,000 lb/hr, 275 psig, saturated
East Bridgewater, MA	City of Brockton and nearby towns; Combustion Equipment Assoc.; East Bridgewater Association	RDF	400	Shredding, drying, air classification, magnetic separation, mechanical separation, sterilization; used in industrial boiler
Franklin, OH	City of Franklin, EPA, Bleck-Clawson	Paper fibers	160	Wet pulping, magnetic separation by a proprietary process.
Harrisburg, PA	City of Harrisburg	Incineration	600	Steam at 135,000 lb/hr, 455° F, 250 psig
Nashville, TN	Nashville Thermal Transfer Corp.; I. C. Thomasson and Assoc., Inc.	Incineration	720	Steam at 220,000 lb/hr, 620° F, 400 psig
New Orleans, LA	City of New Orleans, Waste Management, WCRH	Incineration	650	Shredding, air-classification, magnetic separation
Norfolk, VA	U.S. Navy	Incineration	360	Steam at 100,000 lb/hr, 275 psig, saturated

<sup>a</sup>This is a status summary of some of the energy and resource projects in the United States.<sup>b</sup>(RDF (refuse derived fuel) is listed when the method of combustion is not specified.Sources: *Fuels from Municipal Refuse for Utilities*, Bechtel Corporation, March 1975.NCRH Solid Waste Management Briefs, June 1976, *Pollution Engineering*, May 1976.

Table XXI-13 (Cont'd)

Location	Key Participants	Process	Capacity (ton/day)	Description
Orchard Park, NY	Torrax, Inc.	Pyrolysis	75	Aggregate, crude metal, glass wool recovery; steam at 18,000 lb/hr, 470° F, 500 psig
Saugus, MA	Ten communities including Saugus and part of northern Boston; Refuse Energy Systems Corp.	Incineration	1200	Waterwall incineration, magnetic separation; steam at 370,000 lb/hr, 875° F, 880 psig sold to General Electric
Facilities Committed Akron, OH	City of Akron; Glaus, Fyle, Schomer, Bruns and DeHaven; Ruhlman Construction Co.; Babcock and Wilcox	RDF	1000	Shredding, air classification, magnetic separation
Bridgeport, CT	Connecticut Resources Recovery Authority; Occidental Petroleum; Combustion Equipment Assoc.	Cofiring with coal	2200	Shredding, magnetic separation, air classification, mechanical separation; 25 MW equivalent power
Chicago, IL	City of Chicago; Ralph M. Parsons Co.; Consoar, Townsend and Assoc.	Cofiring with coal	1000	Shredding, air classification, magnetic separation; 23 MW equivalent power
Danvers, MA	Clean Community Corp.	RDF	2000	Prepare RDF as primary fuel for new boilers; sell steam and electricity; 50 MW equivalent power
Palmer Township, PA	Palmer Township, Eto and Rhodes, Pennsylvania Dept. of Environmental Resources	RDF	160	Shredding, air classification, magnetic separation
Hempstead, NY	City of Hempstead; Hempstead Resource Recovery Corp.	Incineration	2000	Wet pulping, magnetic and mechanical separation; 40 MW equivalent power
Milwaukee, WI	City of Milwaukee; Americology Div. of American Can Co.; Bechtel, Inc.	Cofiring with coal	1300	Shredding, air classification, magnetic separation; 31 MW equivalent power
Monroe County, NY (Rochester)	Monroe County; Raytheon Service Co.	Cofiring with coal	2000	Shredding, air classification, magnetic separation, mechanical separation
Pompano Beach, FL	Waste Management, Inc.; ERDA; Jacobs Engineering Co.	Anaerobic digestion	50-100	Sewage sludge to be mixed with MSW for methane production
San Diego County, CA	San Diego County; EPA; Occidental Petroleum	Pyrolysis	200	Shredding, air classification, magnetic, mechanical separation, froth flotation; pyrolysis oil for cofiring with oil; 4 MW equivalent power

Table XXI-13 (Cont'd)

Location	Key Participants	Process	Capacity (ton/day)	Description
St. Louis, MO	Union Colliery Co.	Cofiring with coal	8000	Shredding, air classification, magnetic separation, nuggetizing; 200 MW equivalent power
<b>Facilities Planned</b>				
Cleveland, OH	City of Cleveland	Undetermined	2000	Steam for use in utility; magnetic metals
Cuyahoga Valley, OH	Cuyahoga County Commissioners	Incineration	2000	Steam for industrial use, magnetic metals
State of Delaware	State of Delaware; EPA	Pyrolysis and anaerobic digestion	500 1230 sewage sludge	Shredding, air classification, magnetic and mechanical separation; produce RDF and agricultural products
Hartford, CT	United Illuminating; Connecticut Resources Recovery Authority; Combustion Equipment Corp.	Cofiring with coal	800	RDF used as primary fuel; 12 MW equivalent power
Knoxville, TN	Tennessee Valley Authority	Undetermined	3000	Energy for use in utility, magnetic metals, aluminum
Lyndhurst, NJ	Combustion Equipment Assoc.; N.J. Public Service Electric and Gas	Cofiring with coal	200	5 MW equivalent power
Seattle, WA	City of Seattle	Pyrolysis	1500	Gas produced with possible methanol or ammonia production; 30 MW equivalent power
Scranton, PA	Research-Cottrell, Inc.; Community Control Energy Corp.	RDF	600	Shredding, air classification, drying, magnetic separation; aluminum separation; steam production from RDF
Westminster, CO	Energy Conversion Systems; Public Service Co. of Colorado	Incineration	450	11 MW equivalent power
<b>Projects Under Study</b>				
Berlin, CT	Cities of Berlin, Hartford, New Haven; Connecticut Resources Recovery Authority	Undetermined	2200	Energy and materials
Beverly, MA	Cities of Beverly and Salem	Undetermined	1000	RDF or steam for use in industry and utility
Eugene, OR	Lane County	Undetermined	1000	24 MW equivalent power

Table XXI-13 (Cont'd)

Location	Key Participating	Process	Capacity (ton/day)	Description
<b>Facilities Planned—cont'd</b>				
Honolulu, HI	City of Honolulu; Hawaiian Electric Co.	Incineration	2000	Steam-electric unit; 48 MW equivalent power
Miami, FL	Dade County	Undetermined	3000	75 MW equivalent power
Montgomery County, MD	Montgomery County; Potomac Electric Power Co.	Cofiring with coal	1000	25 MW equivalent power
Oakland, CA	East Bay Municipal Utility District; Pacific Gas and Electric Co.	Pyrolysis	1200	Pyrolysis gas converted to methane; 25 MW equivalent power
Staten Island, NY	City of New York; Consolidated Edison	Cofiring with coal	1500	35 MW equivalent power
TVA Service Area	TVA; several communities	Cofiring with coal	8000	200 MW equivalent power
Washington, D.C.	City of Washington; Potomac Electric Power Co.	Cofiring with coal	300	9 MW equivalent power
Toledo, OH	Ohio Water Development Authority, Northwest Ohio Solid Waste Management	RDF	1000	Shredding, air-classification, magnetic separation

Table XXI-14

EPA SOLID WASTE RESEARCH PROJECTS

Cofiring with coal (St. Louis/Union Electric)  
Cofiring with coal (Battelle/City of Columbus)  
Testing of cofiring with coal in tangentially-fired versus stoker-fired boilers (Ames, Iowa)  
Densified waste cofired with coal in industrial-sized stoker-fired boilers  
Refuse cofiring with coal  
Use of refuse for cofiring in bagasse boilers; feasibility study (Hawaii)  
Technical and environmental evaluation of waste co-firing with sewage sludge in a treatment plant sludge incinerator (St. Paul/Seneca)  
Technical and environmental evaluation of power recovery while disposing of waste and sewage sludge (CPU-400)  
Pyrolytic conversion of mixed waste to fuel (Energy Resources Company)  
Pyrolytic conversion of solid waste to polymer gasoline (Navy at China Lake, California)  
Portable pyrolysis of agricultural waste to transportable fuels (Georgia Institute of Technology)  
Anaerobic fermentation (University of Illinois)  
Enzymic hydrolysis (Army Natick Laboratory)

Source: George L. Huffman, "Processes for Conversion of Solid Wastes and Biomass Fuels to Clean Energy Forms," *Conference on Capturing the Sun Through Bioconversion*, Washington, D.C., March 10-12, 1976.

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