Industrial complexes. The concept of nuclear-powered industrial complexes,[36] based in part on processes making use of hydrogen and oxygen, would appear to offer an opportunity for the large-scale applications of hydrogen in industry. In this concept, with industrial plants located adjacent to the power/hydrogen facility, the costs for hydrogen and oxygen storage and transportation are minimized.

Research and development needs. The use of hydrogen in industry will not likely require long-range research and development. Its use appears to be within the range of existing technology or of technology that can be readily developed by industry when the economic and environmental factors dictate. Some advance detailed studies, however, do appear to be warranted, particularly in the area of refining the estimates of the production costs of many industrial products as a function of the cost of hydrogen. Also, overall studies of the use of hydrogen (both with air and with oxygen) to provide process steam should be made.

5.1.2 Urban uses of hydrogen

Relatively little research and development appears to be necessary. That which is necessary need not be federally supported, since sufficient incentive and short-term returns exist to suggest that this effort can and will be undertaken by private industry. If it is determined to be in the national interest to accelerate the implementation of a hydrogen-based energy system, federal funds would be needed to support demonstration projects.

Conversion to a hydrogen system should be possible with only a minor amount of capital expenditure. Although gas distribution systems already exist, they may require some upgrading to meet leakage and increased flow requirements. Gas burners would require modification, but the procedures appear straightforward.[40]

Safety problems associated with the use of hydrogen are comparable with those associated with the use of natural gas. An education program will be required to familiarize the public with the use of hydrogen.

The efficiency of use of hydrogen would likely be higher than for natural gas due to lower (or perhaps zero) flue heat losses. Also, with hydrogen it appears more likely that the pilot light system could be eliminated in favor of electrical or catalytic ignition, thus realizing about a 15% savings in gas use. In particular, fuel cells using hydrogen rather than reformed natural gas would also be more efficient and likely more trouble free. A further potential efficiency advantage for hydrogen that may be realized in some applications is in making partial use of the heat of condensation of the water vapor that is formed during combustion. If, for example, the flue gas from a hot water or space heater can be cooled to 140°F (by the water or air to be heated) then the effective heat of combustion is increased by as much as 10% of the LHV of hydrogen. Cooling to 100°F would give up to a 16% increase. The corresponding increases obtainable in the combustion of methane are 0% and 8% respectively.

A series of total-energy systems based upon hydrogen and of progressively increasing size and complexity would eventually need to be undertaken in order to demonstrate their practicality. These demonstrations might consist of certain military systems, shopping centers, apartment complexes, and eventually model cities.[41] Projects such as these will necessarily be costly and will require substantial federal assistance and support. These systems would most likely make use of fuel cells or turbine-generators to convert a portion of the delivered hydrogen to electricity. Both of these systems would require further development (see Sect. 5.1.4.)

5.1.3 Use of hydrogen fuel for transportation systems

Hydrogen, with air from the atmosphere or with oxygen supplied on board, offers an impressive potential for fueling future transportation systems. Hydrogen, the most energetic of chemical fuels, offers these critically important advantages: (1) it is available from water resources through the addition of energy from fossil, nuclear, or perhaps solar, sources; and (2) it can be consumed with minimal environmental degradation.

Some background of experiments with hydrogen-fueled conventional engine types, especially gas turbines and gasoline reciprocating engines, is available.[42,43] For example, in the mid-sixties NACA's Lewis Flight Propulsion Laboratory (now NASA Lewis Research Center) conducted flight tests of an experimental turbojet-powered aircraft in which one of the engines was operated on hydrogen carried in cryogenic form in a wing tip tank. This program was entirely successful in substantiating the theoretical performance of hydrogen in a flight environment.

In addition to conventional engine types, all of which appear to be amenable to hydrogen operation, unconventional power plant designs based on hydrogen-oxygen have been identified as being of significant promise in both mobile and stationary prime mover roles.[44] These systems offer the potential of extremely high thermal efficiencies and produce only water as exhaust. They can also be operated essentially noiselessly.

One of the key problem areas which must be addressed with hydrogen is the mode of on-board storage. Hydrogen in its densest form (as a cryogenic liquid) is ten times the volume by weight of gasoline. Fortunately, it has approximately 2 1/2 times the heating value per unit weight as a partial compensation. Four methods of storage aboard a transportation vehicle can be considered:

1. as a cryogenic liquid at $-423°F$,
2. as a pressurized gas at ambient temperature,*
3. within a metal hydride at essentially ambient temperatures (heat exchange with engine exhaust may be used thus giving a cool exhaust steam),
4. in a chemical compound such as ammonia.

The cryogenic form is best developed in terms of existing technology discounting pressurized gas, which appears to be too heavy and bulky (and hazardous) for most applications. Research work is under way in hydride and chemical compound storage of hydrogen, but it is too early to assess ultimate feasibility.

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*Pressurized gas at reduced temperature may also be a possibility, e.g., at liquid nitrogen temperature the storage volume could be reduced about 1/4.

A general conclusion is that hydrogen storage by any of these methods will take up considerably more volume than conventional hydrocarbon fuels and that a substantial cost may be incurred in converting hydrogen gas to the stored form. Also the container will tend to be very heavy or otherwise sophisticated and probably relatively expensive. In addition, the filling and emptying of the storage unit will no longer be a simple operation. This appears to be an inherent problem with hydrogen, particularly for small vehicles. For large vehicles, developments with liquid hydrogen in the aerospace industry have progressed to the point where cryogenic hydrogen is handled routinely.

Hydrogen for ground transportation systems. The automobile, bus, truck (and other utility vehicles), train and advanced high-speed (300 mph) ground transportation systems were reviewed for hydrogen fuel applicability.[45] It was concluded that all these vehicle types are capable of being operated on hydrogen fuel, but sizable problems exist relative to fuel tankage and logistics.

With overall logistics in view and, in particular, examining the problems associated with distribution of hydrogen fuel and vehicle services aspects, there would appear to be a certain advisable progression among these systems with regard to the ease of "conversion" from hydrocarbon to hydrogen. Perhaps the logical place to initiate hydrogen as a fueling standard would be in new unprecedented applications like the high-speed ground transportation units. These would have the assumed advantage of a minimum of required fueling points where trained personnel and adequate equipment can be located.

Next in turn might be conventional vehicles such as intercity and urban trucks and city buses. Once again controlled central servicing centers are normally used, with the vehicles carrying enough fuel for extended endurance. Probably the last place that hydrogen will be put into service will be the private automobile since it requires a very large number of "filling stations" attended by relatively unskilled personnel. Nevertheless, such a service station operation can be conceived and, with the application of sound engineering principles, even an unskilled operator will be able to service hydrogen safely and efficiently. The routine servicing of LNG (essentially cryogenic methane) into a number of city fleets of "clean" air cars testifies to this potentiality.

Ground transportation vehicles may utilize conventional internal combustion engines converted to hydrogen fuel or unconventional hydrogen or hydrogen-oxygen power plants. In conventional engines some improvement in specific power output and thermal efficiency may be intrinsic to the shift to hydrogen. However, major gains can be obtained from the development of basic cycle improvements and/or new operating cycles which can capitalize on hydrogen's outstanding heating value, combustion characteristics, and excellent cooling performance. Such improvements in efficiency would help to counter the otherwise very large volume of hydrogen which must be carried for the equivalent range achieved by hydrocarbon-powered vehicles. No doubt the bulky hydrogen storage requirements will have a substantial impact on automotive and other vehicle layout and design.

Tests of a modified 3.5-hp standard 4-cycle engine fueled with hydrogen showed NO_x emissions to be one-fifth to one-half those fueled with gasoline.[41]

<u>Hydrogen for water transportation systems</u>. Adding the concept of a hydrogen-fired steam boiler to the other conventional, but hydrogen-converted, prime movers cited above, it appears plausible to power ships over the full range of size on hydrogen. A special case of interest would be that of a liquid hydrogen "cryotanker" analogous to present-day LNG tankers. Assuming there would be a need for ocean shipment of hydrogen, it would be anticipated that, as with LNG ships, boiloff hydrogen would be used to power the shipboard propulsion system.

Hydrogen-oxygen-fired steam cycle power plants of types which have been suggested by a number of researchers may be of special interest to nuclearpowered ships, to provide large amounts of reserve speed, for example, and for submersibles. This power plant's completely condensable exhaust (water) offers a number of system advantages.

Hydrogen for air transportation. Cryogenic liquid hydrogen as an aircraft fuel has been under examination for some time. It is in aircraft performance that the superior heating value of hydrogen (gravimetric basis) can have a real payoff in range, payload, or gross weight reduction. Once again, it is hydrogen's great bulk and very low temperatures that have impeded more active pursuit of hydrogen fuel - this, and its unavailability - for it was only the advent of the Apollo space program which induced large-scale routine distribution and handling of liquid hydrogen.

In the realm of very high-speed aircraft, those for hypersonic flight conditions (approximately speeds in excess of Mach 4), the use of hydrogen is probably mandatory. This is because of the great cooling demand of the hypersonic engines as well as the entire aircraft structure. Of all fuels, only hydrogen has sufficiently good physical and chemical properties (e.g., high specific heat and noncoking nature, respectively) to meet this requirement. Additionally, hydrogen provides the best aircraft performance because of its high heat content per unit weight.

Evidence has recently been developed at NASA's Langley Research Center suggesting that hydrogen would be a good choice for any "second generation SST" we might contemplate. Range and payload may be improved 32 or 45%, respectively, over an equivalent JP-fuel version of Mach 3 cruise conditions.

If properly optimized to account for the hydrogen storage peculiarities, it would be expected that a superior subsonic aircraft design could be developed. Logically, a large transport-type aircraft would be appropriate since the tankage problems are relatively smaller than with a smaller aircraft. Additional design studies of this type of aircraft appear to be needed.

A recent preliminary investigation of the potential of the liquid-hydrogen-fueled subsonic commercial transport performed by Lockheed-California Company for the panel is most encouraging. A modified-for-hydrogen version of a three-engine, wide-bodied commercial transport revealed a gross weight at takeoff of 30% lower value than the original

Jet-B (conventional hydrocarbon) fueled version. This is at the same payload and range, 272 passengers plus 5000 lb cargo, and 3200 nautical miles respectively. The payoff of hydrogen can also be taken as improved range or increased payload capability. These results were achieved without assumed improvement in engine cycle performance and reduced weight, which manufacturers such as Pratt & Whitney Aircraft have indicated are possible with hydrogen fuel.

Recommended research and development. A significant number of research and development areas are evident in developing hydrogen as a practical fuel for transportation systems applications. A few of these are generalized and listed below.

1. The conversion of conventional engine types to optimal hydrogen operation should be more thoroughly investigated with emphasis on delineating engineering improvements and design criteria. A careful assessment of the missions performance and routes for reducing emissions should be included.

2. Conventional and unconventional on-board storage methods for hydrogen should be given priority research support. Cost optimization and amenability to large-scale factory production, as well as compatibility with the eventual vehicle and "service station" environment, should be stressed. The two major storage systems to be investigated are outlined below:

a. Liquid H_2 system
   - boil off control
   - development of superinsulators
   - controlled venting
   - hydride systems including AB_5* hydrides for back up, boil off gas absorption and storage
   - safety

b. Metal hydride systems
   - heat exchanger design and exhaust energy utilization
   - reaction kinetics and bed mechanics
   - startup systems, vehicle modification, sealing, material compatibility, and recharging methods

*Where A represents a rare-earth metal and B is either nickel or cobalt.

- use of other, lighter hydrides
- safety of handling depleted beds
- productive use of heat of reaction during bed recharging

3. Compatibility with existing highway and urban safety and general operating regulations and design codes in hydrogen vehicle operation must be carefully studied. Where necessary, new legislation should be prepared and introduced as appropriate.

4. Unconventional power plants which offer significant improvements with hydrogen (or hydrogen-oxygen) over hydrogen-converted conventional engines should be researched and promising systems carried into engineering development.

5. Hydrogen-fueled subsonic and supersonic aircraft design investigations and economic performance studies should be performed.

5.1.4 Use of hydrogen for electrical generation

The use of nonfossil synthetic fuels for electricity generation would seem to apply only in special situations such as to meet a relatively remote small requirement or as a part of an energy storage power peaking system.

One possibility is that electricity will be generated near the load center from hydrogen fuel or hydrogen-oxygen taken from pipelines as it is transmitted long distances from remote production sites. Both thermomechanical and nonthermomechanical systems appear plausible for converting hydrogen energy into electrical form. Examples are gas turbines, magnetohydrodynamic generators, and fuel cells.

Principal points to consider outside of basic feasibility of operation on hydrogen are (1) what "busbar efficiency" can be developed and what will the capital investment be and (2) what will be the environmental impact of the generation systems operating on hydrogen.

It is observed that hydrogen and electrical energy are quite compatible; one can be converted to the other (given water or oxygen as the case may be). Hydrogen could become an effective storage form in an electrical system, and its ready availability would add to the stability and economics of the electrical utility function.

Thermomechanical electrical generation from hydrogen. For most of the generation prime movers used in the electrical utility industry, steam turbines, gas turbines, diesel generators, etc., hydrogen can be considered a feasible replacement for currently used fossil fuels, particularly in the case of natural gas systems. Certain changes might be required in a natural gas-fired boiler, for instance, but it would seem that the basic unit would be amenable for hydrogen operation. Questions of metallurgical effects (both adverse and beneficial) remain with hydrogen, and this suggests a number of research areas to be pursued. Possibly the characteristics of hydrogen being what they are (excellent combustion performance, clean products of combustion, etc.), boiler performance might be improved somewhat with favorable effects on station heat rate (Btu/kWhr).

Hydrogen is expected to be a very favorable fuel for gas turbine operation, permitting increased turbine inlet temperatures to be reached, provided that the excellent cooling virtues of hydrogen can be used to keep metal temperatures under control. If cryogenic hydrogen is used, precooling of inlet air and/or compressor intercooling might be advantageous in increasing efficiency and/or output. Efficiencies of 35% are anticipated for the hydrogen-air turbines. The hydrogen-oxygen turbine offers the ultimate in efficiency and may exceed 60% with several generations of development. The hydrogen-oxygen turbine also prevents air pollution since the exhaust is pure water and may be condensed; that is, since air is not used in the combustion process no NO_x can be formed.

Magnetohydrodynamic (MHD) generation. A number of nonshaft-power methods are under investigation for generating electrical power. Among these are magnetohydrodynamic, thermoelectric, thermionic, and thermophotovoltaic systems. Of these, it is not apparent that any but MHD will be competitive for large-scale electrical generators. The other systems may serve well in specialized local generation roles in the context of available hydrogen fuel.

MHD operation on hydrogen-oxygen (or possibly hydrogen and preheated air) appears favorable since the combustion products are very clean compared with, for example, pulverized coal and air, which are being investigated presently. This should assist in the difficult process of recapturing the "seed" material which is added to ionize the hot gases prior to passing through the magnet/electrode area. Hydrogen should aid in the problems of overheating and erosion of the electrodes. There may, however, be problems of chemical reactions between the seed material and the combustion products, so that research and development work is clearly indicated. Since both require oxygen in addition to hydrogen for optimum operation and both promise very high operating efficiencies, it is expected that MHD and the hydrogen-oxygen steam turbine systems will be in competition with fuel cells in the advanced systems area.

Fuel cells. In the following section, discussion is limited to the consideration of stationary small dispersed electricity generation by fuel cells. Use of fuel cells for large central station or small units for transportation application are not discussed since these topics will be covered by other panels in this series.

(a) Physical principles of concept. In the fuel cell process, electricity is generated by converting the latent chemical energy of fuel directly into direct current electricity in an electrochemical process. It is basically the reverse process of water electrolysis (see Section 3) and makes use of somewhat similar technology and hardware. One difference, however, is that with fuel gas and a liquid electrolyte, a stable interface must be maintained between the reacting gases (fuel and oxidizer) and the electrolyte. The basic reactions using hydrogen and oxygen with an acid electrolyte are

$$H_2 \rightarrow 2H^+ + 2e^- \quad \text{(anode)} ,$$

$$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \quad \text{(cathode)} .$$

The electrochemical conversion of chemical to electrical energy occurs isothermally, unlike the heat engine, which operates between two different temperature levels. The Carnot cycle, which applies to all heat engines, theoretically limits their efficiency. Since the fuel cell has no such limitation it can, at least in theory, be a far more efficient device.

Besides its high available efficiency, the fuel cell operates with no moving parts, which leads to noiseless and reliable operation. The comparative simplicity of the electrochemical reactions makes it likely to achieve complete combustion to inoffensive exhaust products, and the principle of modular construction enables large units to be constructed from the same basic components as smaller ones.

(b) Status of technology. The major development work on fuel cells was initially directed toward transportation applications. A number of major industrial corporations invested heavily in this development over the past decade. They include Allis Chalmers, General Electric, Monsanto, and Union Carbide. This work has essentially been discontinued because of the difficulty in obtaining reasonable lifetime, compact, low-weight energy units at cost levels suited to transportation purposes. The American Gas Association* which sponsored work on high-temperature fuel cell systems for stationary applications during the period of 1960-67, is no longer active in this field primarily because of the gas and utility industries' support of the TARGET (see below) program. Central station[46] applications of fuel cells using gas produced from coal has been studied by Westinghouse under Office of Coal Research sponsorship but is currently nearly dormant.

Fuel cells are now used routinely in specialized space and military applications. The major U.S. effort now active in developing a commercial fuel cell unit for general utility service is being done by Pratt & Whitney Aircraft and is called TARGET (Team to Advance Research for Gas Energy Transformation). It has been in progress since 1967 and has expended more than $50 million, more than half of which was provided by a group of natural gas and combination utility companies. In addition, there has been a concurrent program (also performed by Pratt

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*Westinghouse, Texas Instruments, and General Electric also had significant fuel cell research and development programs.

& Whitney) in the last year with ten electric utility companies and the Edison Electric Institute. About one-third of the total investment has gone into the technology associated with reducing cost and increasing cell operating period. The remainder has been spent in developing experimental fuel cell power plants, in producing and field testing prototype power plants, and in building a technology base to make the power plant concept more versatile (e.g., handle all liquid and gaseous fossil fuels, scaling of cell and reformer component elements to multimegawatt size, and improved efficiency of ancillary components).

Small-scale fuel cell power plants have been built and have demonstrated in actual field test operation the ability to satisfy completely all the functional requirements for electric utility service. Further testing is required, however, to demonstrate trouble-free, long-term operation. These 12.5-kW power plants operate on air as the oxidant and either gaseous or sulfur-free distillate fuels. Several power plants are now in operation, and shortly a total of 60 power plants will be operational in various installations. These systems consist of three main components: (1) a steam-methane reformer to convert the incoming natural gas to H_2 (and CO_2), (2) the fuel cell module for reacting the fuel gas with air in a catalyzed acid-electrolyte fuel cell stack, and (3) a power conditioning system to convert the dc electric current to ac power compatible with an existing electrical network.

An alternative type of fuel cell making use of a molten carbonate electrolyte is being studied by IGT under sponsorship by P&W. This type of cell operates at about 625°C, requires no precious metal catalyst, and is generally more tolerant than the low-temperature cells to impurities in fuel gas supply. An applied research program is in progress with the intent of developing this concept as a second-generation technology.

The present estimated specific cost (by P&W) of the fuel cell power plant on a production basis is about $350/kW, and the economic operating period is estimated to be approximately 16,000 hr. Pratt & Whitney further estimates that a specific cost of about $200/kW and a 40,000-hr operating period would be required to establish the fuel cell power plant as an economic electric generator for a variety of duty cycles and applications. The limiting factors to achieve lower specific cost are (1) the power output per square foot of cell area and (2) the amount and cost of materials of construction. The limiting factors in extending the economic operating period are associated with the development of stable, lower-cost materials to withstand the chemical and electrochemical environment of the system. Substantial progress has been made in the past five years; since 1967, specific material cost has been reduced by a factor of nearly 10, and economic operating life increased by a factor of 5. The rate of progress in both areas has been limited by the rate of funding.

(c) Ultimate potential. The fuel cell power plant can contribute to the United States energy system in three formats. One is as a dispersed generator for the electric utilities, that is, multimegawatt power plants are placed within an electric utility transmission-distribution system at substation locations. A second is as an on-site transformer of gas to electricity (20 to 200 kW) for natural gas utilities. The third is as a remote on-site generator for rural electrification and for developing areas such as Alaska or Micronesia. In these uses the fuel cell power plant complements the very large-scale fossil or nuclear bulk power generators by permitting a selective attack on critical problem areas. Among its benefits are:

1. Reduced transmission requirements. By locating power plants near, or at, the load center the need for additional transmission capacity and right of way is reduced. Raw fuel energy is transported to the fuel cell power plant by gas or liquid pipeline or trucked liquids. Community planning is more flexible because power can be provided at the point of need with minimal lead time and at minimum interference with other communities.

2. Improved site availability. Dispersed fuel cell power plants are quiet and clean. They do not require a source of cooling or makeup water and can be transported to the installation site using standard trucks. These features increase the number of suitable sites and permit

present utility right of way, air rights over existing buildings, or sites of retired plants to be utilized.

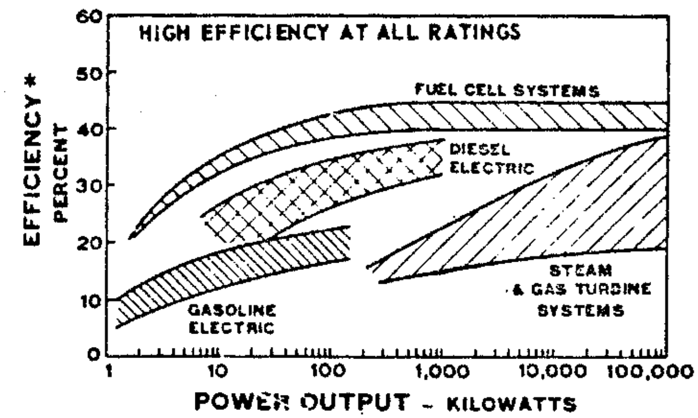
3. Capacity added in phase with growth. Fuel cell power plants are economic in small-scale units; therefore, they can be installed in blocks as load requirements grow to provide a more effective use of capital.

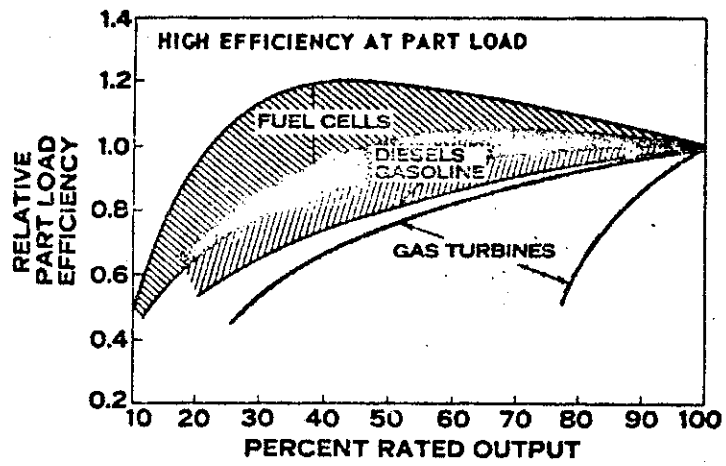
4. Factory assembly. Assembly in standard modular units provides mass production economics, reduces lead times, and minimizes expensive field construction.

5. System security. Parallel operation of the dispersed generation units with the conventional utility system provides enhanced reliability and reduced vulnerability of the generation and transmission system to sabotage, attack, or natural disasters. In addition, the multifuel capability of the fuel cell power plant eliminates reliance on one specific fuel system.

Initial electric utility fuel cell power plant installations will provide power in areas with particularly difficult transmission and/or siting problems. They will be sited in areas experiencing rapid load growth due to new commercial or industrial facilities, in urban areas where renewal projects have increased power demands, and onsite for customers with critical loads such as hospitals, industrial processing plants, and government agencies. Fuel cell power plants may in special cases be used with water electrolysis cells to provide utility system peaking power using stored hydrogen produced with off-peak electricity. This system is not likely to achieve the efficiency of a pumped hydrosystem but does offer an alternative where topography is limiting.

With present-day technology, characteristic fuel cell power plant peak efficiency when operating on hydrocarbon fuels is in the range of 40% even at power levels as low as 100 to 200 kW (Fig. 10). On hydrogen and air, the efficiency (based on ac power out) would be about 55%, and on hydrogen-oxygen, nearly 60%. Efficiency remains high over an extremely broad operating range from approximately 25 to 125% of the nominal power rating of the power plant. With pipeline hydrogen





*BASED ON LOWER HEATING VALUE

available, the fuel processing (steam-reformer) plant would be eliminated, thus saving about \$25/kW in the capital cost of the unit.

(d) Environmental and resource effects. Data from the initial installations have verified that fuel cell power plants have minimal air pollution (as shown in Table 10), can reject their waste heat to air, are quiet, and are highly efficient at both rated power and at part load. When fueled with hydrogen, the primary waste product is water or water vapor. It is possible to use a fuel cell plant with the "Total Energy" concept, where productive use can be made of the waste heat and hot water.

The availability of precious metal catalysts will not limit the widespread use of fuel cells in any practical sense. First, not all fuel cell concepts require precious metal catalysts; the molten carbonate cell, for example, uses nickel as the catalyst. Second, even if it is assumed that (1) no further reductions in the amount of precious metal catalyst required per kilowatt of output are possible (in spite of a tenfold reduction in the past four years), (2) only platinum is satisfactory as a catalyst, and (3) all the utility companies in the U.S. add 10% of their projected new installed capability as fuel cells every year, less than a 15% addition to the world's average annual production of platinum would be required. Platinum mining industry executives have given assurances that such an increase is entirely practicable.

Recommended research and development. Topics for consideration as additional study or research in the area of hydrogen/electrical generation are summarized below:

1. The optimal mix of hydrogen and electricity should be developed and means for achieving a synergistic interfacing of the two energy forms defined over the entire national system.

2. Equipment (both conventional and unconventional) operation on hydrogen should be investigated and engineering criteria developed. Particular heed should be given to the potential for performance improvement and the nature of emissions under hydrogen operation.

Table 10. Minimum pollution contribution (pounds of pollutants per thousand kWhr)

Federal Standards[a]

	Gas-fired utility central station	Oil-fired utility central station	Coal-fired utility central station	Experimental fuel cells
SO_2	No requirement	7.36	10.90	0-0.00026
NO_x	1.96	2.76	6.36	0.139-0.236
Hydrocarbons	No requirement	No requirement	No requirement	0.225-0.031
Particulates	0.98	0.92	0.91	0.00003-0

[a]Federal Standard (effective 8-18-71) values converted to lb/1000 kWhr.

3. Nonthermomechanical systems of generation should be examined for applicability with hydrogen fuel, particularly MHD systems. Indicated research areas should be pursued to determine if a role exists for these systems in the "hydrogen economy."

4. Hydrogen-oxygen turbines should be developed and demonstration plant operation initiated. Subsequently, very high temperatures should be approached with the development of appropriate cooled turbines toward the achievement of very high efficiencies.

5. The main problem areas remaining in developing the fuel cell for general application are in increasing the cell lifetime and reducing the initial cost. Both areas are closely related to work on the electrodes and involve schemes for minimizing the platinum catalysis content and overcoming the gradual cell performance deterioration with time.* The evaluation and development of potentially superior fuel cell concepts such as the molten carbonate, solid electrolyte and redox cells would also appear to be a worthwhile long-term objective.

One of the most critical cost reduction factors lies in the achievement of a mass-production based industry. This will depend on continued research and development funding to attain the lifetime cost performance goals plus perhaps some subsidy for a relatively large-scale demonstration project.

5.2 Potential For Utilization of Synthetic Fuels Other Than Hydrogen

In seeking a synthetic nonfossil fuel that could be made from such "unlimited" energy resources as nuclear and solar power, hydrogen seems to be the most attractive prospect. However, being a low density gas, its handling properties are not as convenient as a liquid or solid fuel, so attention should also be given to candidates in the liquid and solid forms.[48] If we restrict ourselves to fuels which can burn in air under ideal conditions to form innocuous products, we are limited to compounds of hydrogen, nitrogen, and carbon (the latter only if we are not concerned about buildup of atmospheric CO_2). In practice, we must also be concerned with the possible formation of CO, additional nitrogen

*Use of hydrogen is expected to improve the prospects of achieving these objectives.

oxides, and other undesirable products once we move away from pure hydrogen as a fuel.

Fuels such as ammonia (NH_3), hydrazine (N_2H_4), methanol (CH_3OH), and ethanol (C_2H_5OH) can be readily synthesized and are therefore discussed here. Another category of fuels which would be recycled in the oxidized form to the generating station are the metals. The only reasonable way to consider a metal fuel seems to be as an electrochemical fuel, and in this study rechargeable batteries are therefore given brief consideration.

Ammonia, hydrazine, and methanol all require hydrogen for their production. They may be considered as hydrogen carriers. Ammonia and hydrazine will also involve nitrogen from the atmosphere, while methanol requires the input of carbon dioxide, either from limestone or from the atmosphere,[18] which contains abundant CO_2, but only at a concentration of about 0.03%. Ethanol can be produced by fermentation of vegetable material[23] or from municipal and biological waste. So can methane (and other liquid hydrocarbons), which could become an important synthetic fuel. Methane, however, is already in widespread use as natural gas, so its utilization is not discussed further in this report.

5.2.1 Utilization as a transportation fuel

The transportation sector by definition uses mobile power plants, and liquid synthetic fuels may have the greatest utility in this sector. In aircraft and vehicles with conventional engines, methanol, ammonia, and ethanol could be used without requiring major developments. Considerable work has been done in the operation of both piston engines and gas turbines on these fuels.

Methanol. Several studies of the use of methanol as the fuel in conventional internal combustion engines show that it possesses considerable potential for the combination of engine performance and reduced emissions of unburned fuels, CO, and NO_x. A theoretical anaylysis of fuel behavior predicts that methanol will generate about 90% of the cylinder pressure and 80% as much CO and 95% as much NO_x as does isooctane at an equivalent fuel-air ratio.[49] Work on an engine test stand showed methanol to produce, in comparison to gasoline, without catalytic treatment of exhaust gases about 1/20 the unburned fuel, 1/10 the CO, and about the same NO_x.[50] Another experimental study used road performance and test stand measurements of a methanol-fueled Gremlin engine equipped with a catalytic exhaust reactor to obtain the following results[51] (data is also given on the proposed 1975-76 Federal Standards and on the emission from a 1971 Gremlin gasoline-fueled engine):

	Emissions g/mile		
	UHC	CO	NO
1975-76 Federal Standards	0.41	3.4	0.40
Gasoline	2.34	22.08	4.01
Methanol	0.69	3.83	0.28

Since the heat of combustion of methanol (8580 Btu/lb) is 55% less than that of gasoline (as isooctane at 19,080 Btu/lb), the rate of fuel consumption is greater for methanol. The Gremlin road test showed methanol to require about 60% more fuel (in gallons/mile) than did gasoline. Finally, it is significant that methanol is a liquid much like gasoline and can readily replace gasoline in the distribution system, proceeding from point of manufacture to area distributor to service station to vehicle tank to vehicle engine.

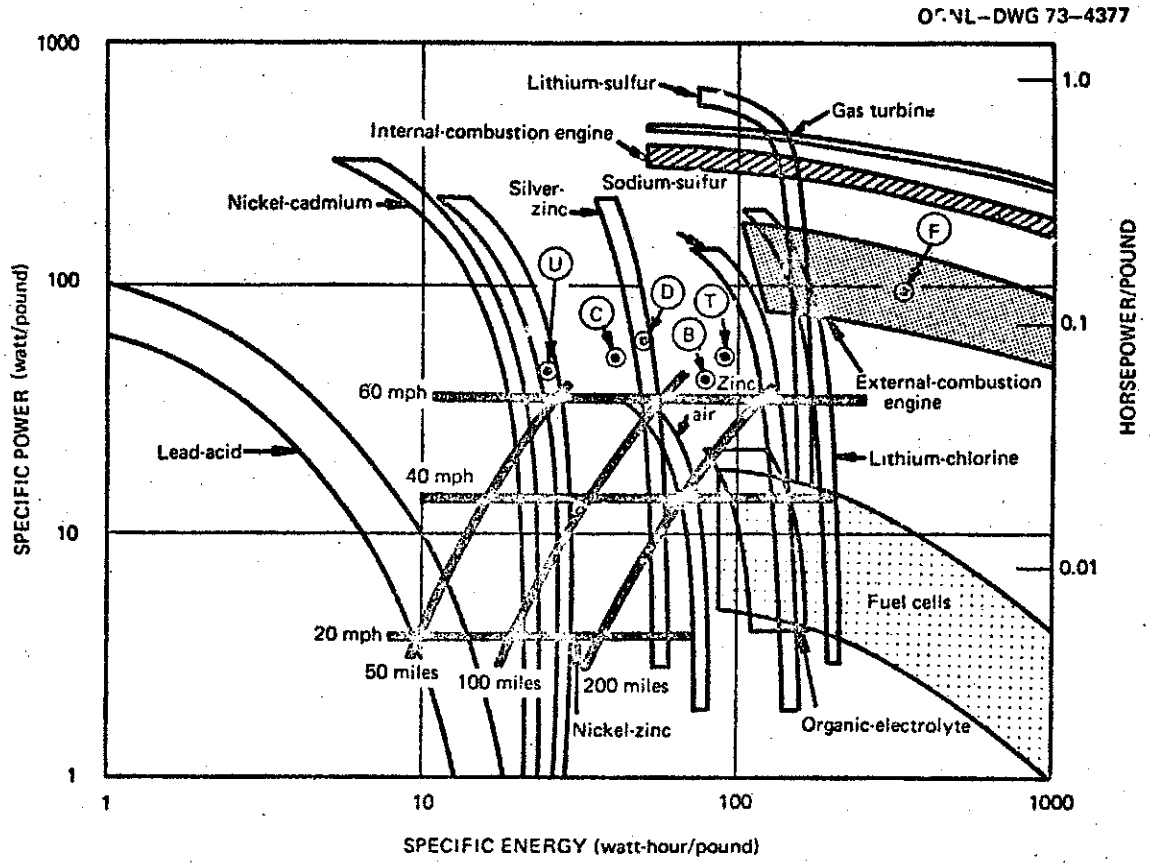
Ammonia. Because of the poor ignition and combustion properties of ammonia, dissociation to hydrogen over a hot catalyst prior to entering the engine would appear to be advantageous.[52] The technology for this is well developed. Emissions from ammonia engines present a potential hazard of NO_x and unburned ammonia, while those from methanol and ethanol might be a little cleaner than those from gasoline. The fuel tankage for the same energy content of gasoline, ammonia, and methanol is in the ratio of 1:2.1:1.7 by volume and 1:2.4:2.1 by weight. This assumes the same engine efficiency, but adequate practical data are not available to verify this assumption. There seems to be no insurmountable difficulty in developing small private automobiles to run reliably and clean on these fuels if sufficient research and development effort is applied. It should be easier to use them to operate larger vehicles, for example, trains and ships.

Fuel cells. An alternative use of synthetic fuels which would lead to far more efficient and possibly cleaner use is in a fuel cell, on board an electric vehicle. Considerable work[53] has been done in developing fuel cells for ammonia (dissociated to hydrogen), methanol (both directly and reacted with steam to produce hydrogen), and hydrazine. Only the latter[54] has indicated sufficient promise for automotive, or even bus and truck use, but the toxicity and high cost of the fuel have discouraged further work. At the present time, there is little if any research in the U.S. toward an automotive-type fuel cell to operate on ammonia or methanol. A substantial program to develop an automotive fuel cell running on methanol sponsored jointly by Esso and Alstholm, is in progress in France,[55] while ASEA in Sweden has had, but has now abandoned, a program directed toward an ammonia fuel cell for submarine use. Since synthetic fuels will be far more costly than today's gasoline, every effort should be made to develop such devices as fuel cells which would use them more efficiently.

5.2.2 Battery vehicles as a reference standard

A vehicle operating on a synthetic liquid fuel must be compared with the potential alternative, the electric vehicle. In order to obtain adequate performance, a vehicle "engine" must have sufficient energy density and power density.[56] (One is the ratio of stored energy to vehicle weight, basically affecting the range of the vehicle, and the other is a measure of how fast the energy can be released, basically affecting the acceleration and maximum speed.)

As indicated in Fig. 11, at the present time no battery or fuel cell exhibits sufficiently high energy density or power density.[57] That is not to say that the goal is impossible, but that very considerable research and development is necessary. The most promising batteries so



F – Family Car
C – Commuter Car
U – Utility Car

D – Delivery Van
T – Taxi
B – Bus

far is the lithium- or sodium-sulfur cell and the lithium-chlorine cell, although they have the disadvantage of having to be kept hot when not in use. There is a little industrial research and development going on in this area, but very little on a national basis.

There is very little hope of any form of electric airplane, so that synthetic liquid fuels or hydrogen appear to be the only alternative to fossil-fuel-based aviation.

5.2.3 Residential and industrial fuels

Because of its high toxicity and very poor combustion characteristics, ammonia is not suitable for direct use as a cooking or heating fuel. It can be cracked to a hydrogen-nitrogen mixture wherein its combustion properties would be similar to pure hydrogen. Research and development is necessary to obtain complete cracking or to evaluate the results of incomplete cracking on pollution when burning the resulting mixture. It might be possible to design industrial furnaces to operate directly on ammonia, but NO_x pollution could be a problem. Methanol and ethanol would make suitable fuels for domestic and industrial heating, although new appliances with new burners would have to be developed. There would be handling problems due to potential abuse of the fuel by adulterating it with water to confuse metering systems and drinking it.

5.2.4 Fuels for electricity generation

If ammonia can be burned directly in an industrial burner without undue pollution, it can be used to generate electricity in a conventional steam plant. Methanol and ethanol should present no problems in this application. Concern, of course, would still exist over pollutants such as nitrogen oxides and possibly CO. A more important potential use of these fuels would be in high-efficiency fuel cells in decentralized units. In stationary applications, criteria of power and energy density applied to vehicles are not critical, but capital cost, operating cost, and system lifetime become dominant. There appears to be no significant research and development in the U.S. on this type of fuel cell. All the known work on stationary fuel cells is concerned with natural gas or oil feedstocks. Much of this work is, of course, relevant but is incomplete in the context of a synthetic fuel economy. It appears quite likely, however, that the fuel cells being developed in the TARGET program, mentioned previously, can be easily adapted to use other synthetic fuels.

Research and Development. The overriding research and development need for the use of synthetic fuels should be directed toward using them as efficiently as possible. To this end, the development of fuel cells for both transportation and static installation, capable of operating on ammonia, methanol, or ethanol is a major requirement. Specifically, improved materials of construction for contact with hot corrosive electrolytes and lightweight flexible systems for converting these fuels to hydrogen-rich streams are dominant problems. The development of tailor-made electrode structures to extract maximum utilization from mixed gas streams is a new and promising field for basic research.

In the area of conventional burners for these fuels, there is a real need for burners capable of complete combustion with low flame temperatures, so that toxic effluents such as nitrogen oxides are not produced.

Research directed toward the improvement of total combustion without pollutant formation in gas turbines and reciprocating engines is worthwhile and presents a short-time-scale way of using synthetic fuels with a high chance of success, though not meeting the high efficiency goal. Specifically, development of methanol as an interim automotive fuel appears desirable. Specific tasks would include conversion methods or kits to change from gasoline to methanol, reduction of exhaust emissions, and improved engine efficiency.

Research on the low-cost production of hydrazine for use as a transportation fuel in fuel cells is a worthy long-range goal.

In the specific area of transportation, continuous review of the required criteria for various types of vehicles and of the status of novel power plant development would enable proper focusing of the research and development goals and objectives of both vehicles and power plant researchers.