(at a constant percentage rate)[*] to a dollar a gallon (in 1974 dollars) by the year 2000, the retrofit costs would not be recovered until the early 1990s. At that time the average fleet age would be 25 years or more, depending upon whether the present value curve (dashed) or the undiscounted curve (solid) is used.

Other Engine Retrofit Candidates

Similar analyses were made of various engine retrofit modifications for the B-52G, KC-135A, and F-4C/D/E.[†] The results are generally the same as those for the C-141, except that it would take even longer to recover the retrofit costs (Figs. 12 and 13). In the case of the B-52G, we considered a retrofit that would replace the eight J57 turbojet engines with four TF39 turbofan engines and that would reduce the B-52 annual fuel consumption by about one-third. The KC-135A retrofit would involve replacing the four J57 turbojet engines with two TF39 turbofan engines. The F-4 retrofit would involve replacing the two J79 turbojet engines with two TF41 turbofan engines (modified to include an afterburner).

The results of the engine retrofit analysis are summarized in Table 1. Although there would be a net energy savings by the time each fleet reached an average age of 25 years, there would not be a net budget saving. This is generally due to three factors: the high cost of new turbine engines, the age of each fleet by the time the retrofit program is completed, and the comparatively low number of peacetime flying hours for military aircraft (as compared to commercial transports).

AERODYNAMIC CHARACTERISTICS

Airframe modifications that could reduce aerodynamic drag and hence reduce fuel consumption have been proposed for several Air Force aircraft. In particular, the Lockheed-Georgia Company has conducted

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[*] In addition to inflation.

[†] The average modification cost per aircraft was assumed to be $5 million for the B-52G, $4.3 million for the KC-135, and $2.1 million for the F-4 (FY 1974 dollars).

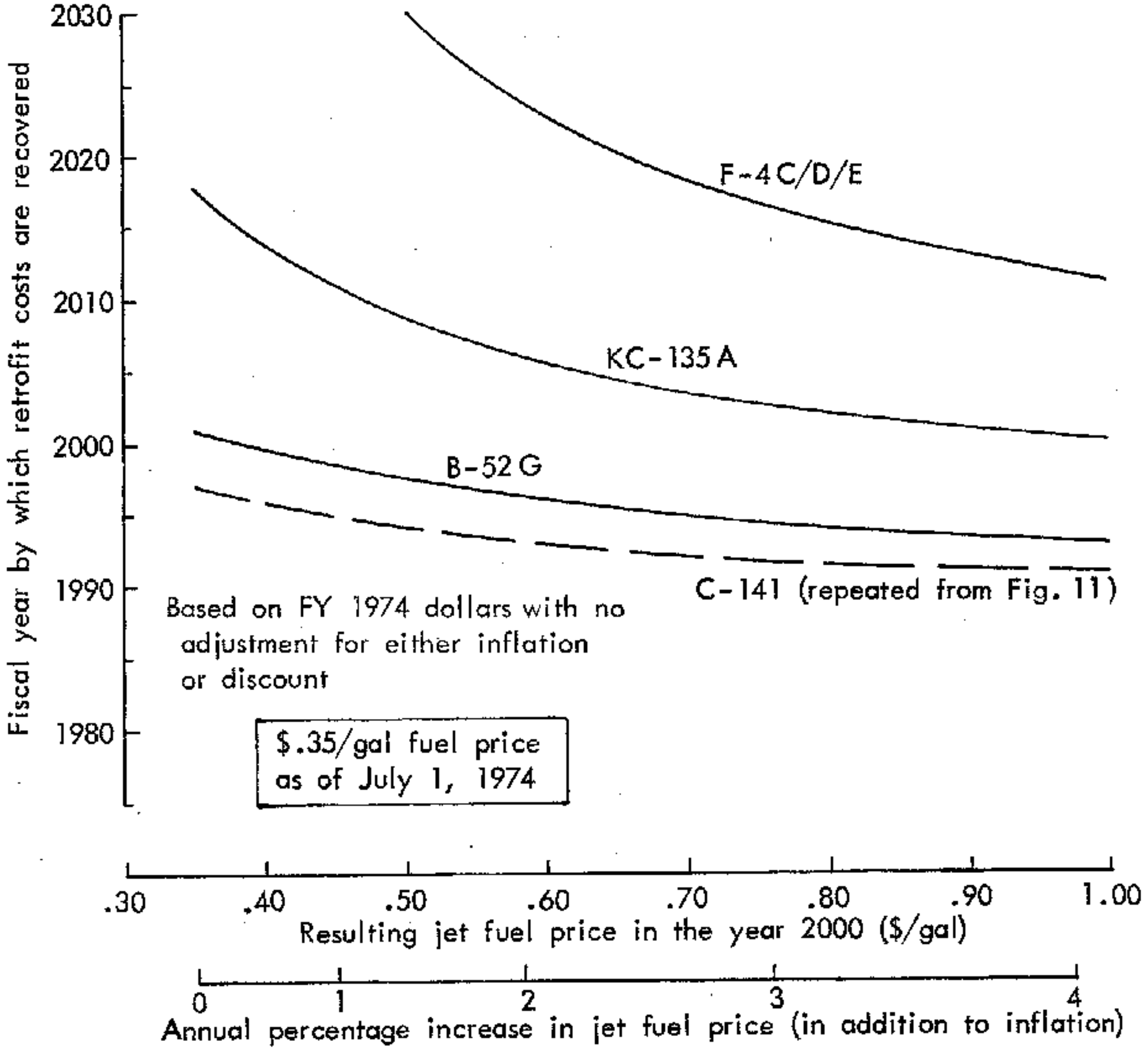

Fig. 12 — Effect of increasing fuel prices on the engine retrofit cost recovery year for the B-52G, KC-135A, and the F-4

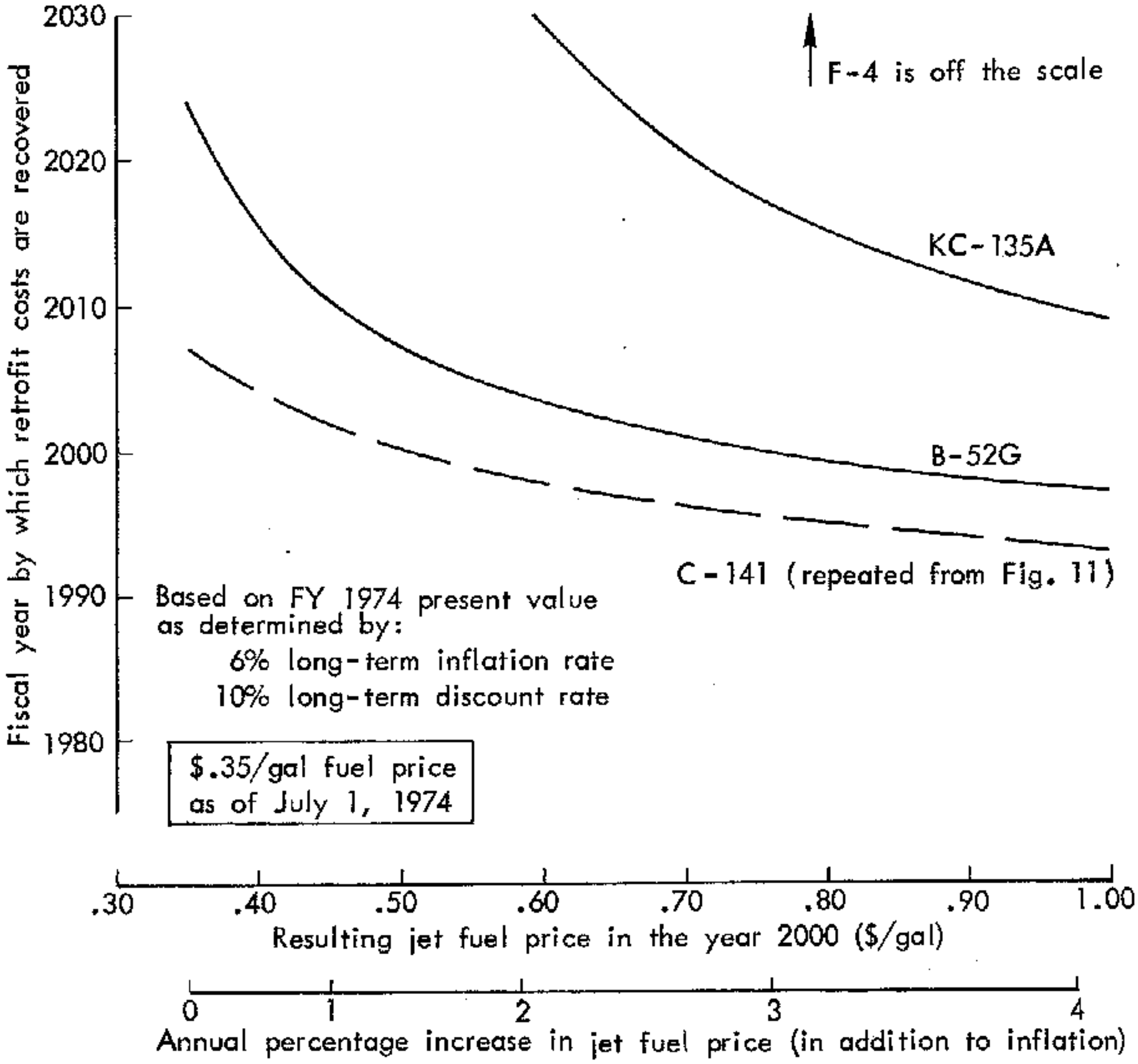

Fig. 13 — Effect of increasing fuel prices on the engine retrofit cost recovery year for the B-52 G, KC-135 A, and the F-4 (with consideration of discount rate and inflation)

Table 1

SUMMARY OF THE ENGINE RETROFIT ANALYSIS

Item	Fleet			
	C-141	B-52G	C-135A	F-4C/D/E
Energy (trillions of Btu[a])				
Used for retrofit	39	27	81	111
Saved by age 25	236	54	114	159
Net saving by age 25	197	27	33	48
Cost (billions of dollars, FY 1974 present value[b])				
Used for retrofit	1.0	.7	2.0	2.7
Saved by age 25	.5	.2	.3	.4
Net saving by age 25	-.5	-.5	-1.7	-2.3
Average Fleet Age (years)				
Retrofit program completed	16	22	21	15
Retrofit energy recovered	16	23	25	21
Retrofit dollars[b] recovered	41	64	66+[c]	66+
Time (FY)				
Retrofit program completed	1982	1982	1982	1982
Retrofit energy recovered	1982	1983	1986	1988
Retrofit dollars[b] recovered	2007	2024	2033+[c]	2033+[c]

[a] Air Force consumption of jet fuel was about 476 trillion Btu in FY 1975.

[b] 10% discount rate, 6% inflation rate, and fuel price of $.35/gal is assumed to remain constant.

[c] Dollars still not recovered at indicated age/time.

wind-tunnel tests and other supplemental analyses that indicate that modest drag reductions may be achievable by modifying the aerodynamic characteristics of the C-141A and C-130 transports. Determining the impact of these modifications is of particular interest, since these two aircraft consume about 22 percent of all Air Force jet fuel. Our major focus will be on a C-141A modification, since both performance *and* cost information are available for this aircraft; however, parametric cost/performance tradeoff curves for other Air Force aircraft have been developed to gain further insights into the utility of aerodynamic modifications.

C-141A Wing Fillet and Vortex Generators

During the late 1960s, wind-tunnel tests by the Lockheed-Georgia Company indicated that removal of the vortex generators on the wing and an improvement in the design of the fillet at the wing/fuselage interface on the unstretched C-141A aircraft might reduce aerodynamic drag by about 8 percent--3 percent from removal of the vortex generators and the remainder from the improved fillet (Fig. 14).(12) The original cost estimate for these aerodynamic modifications was less than \$100,000 (FY 1974 dollars) to modify each aircraft.*

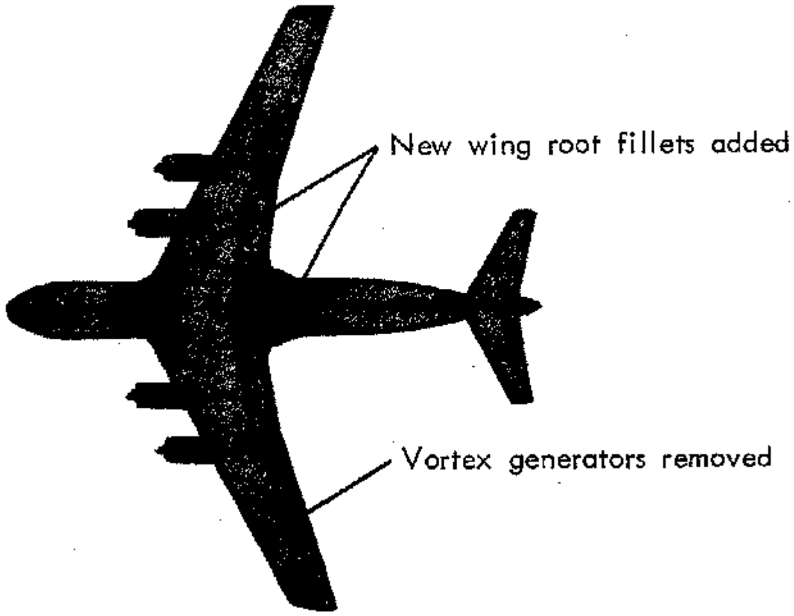

Fig. 14—C-141A drag reduction modifications (from Ref. 12)

Energy Efficiency. Figure 15 shows the impact on fuel consumption if the C-141A aerodynamic modification were made to the entire fleet over an eight-year period. (Note that the energy expenditure to

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*Personal communication from William Lamar, Air Force Flight Dynamics Laboratory, 1974.

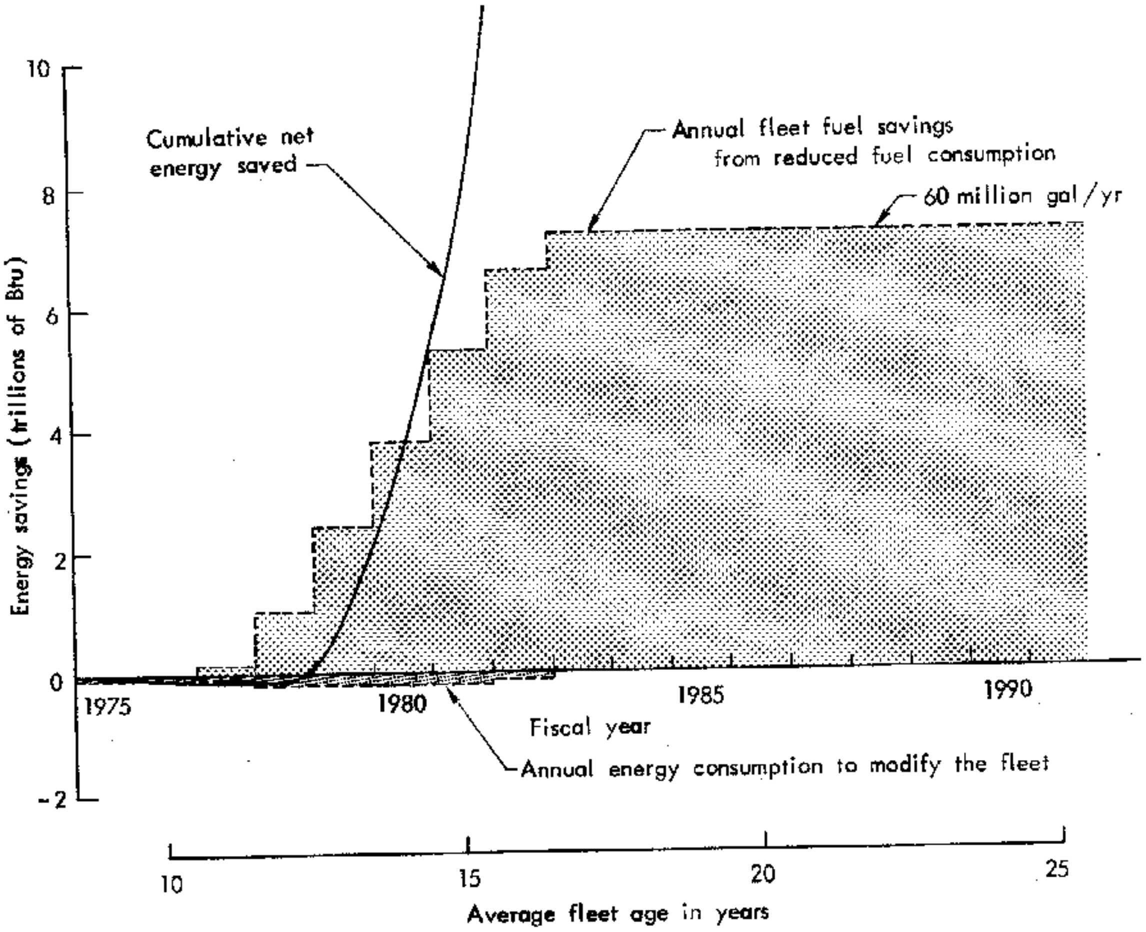

Fig. 15 — Energy impact of a C-141A aerodynamic modification

effect the modification would be quite modest.*) If an 8 percent reduction in consumption were achieved, 60 million gallons of jet fuel would be saved per year by the program. The modification program would produce net energy savings soon after its inception, and even at the completion of the program the fleet would still have a significant number of years of useful life remaining. Thus, we conclude that this aerodynamic modification would be highly energy-efficient.

Cost Recovery. Figure 16 shows the impact on the budget of a C-141A aerodynamic modification. Note that if the modification could be completed at a cost of about $120,000 per aircraft (including RDT&E expenditures), savings in jet fuel expenditures would allow recovery of the

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*Derived from Ref. 11.

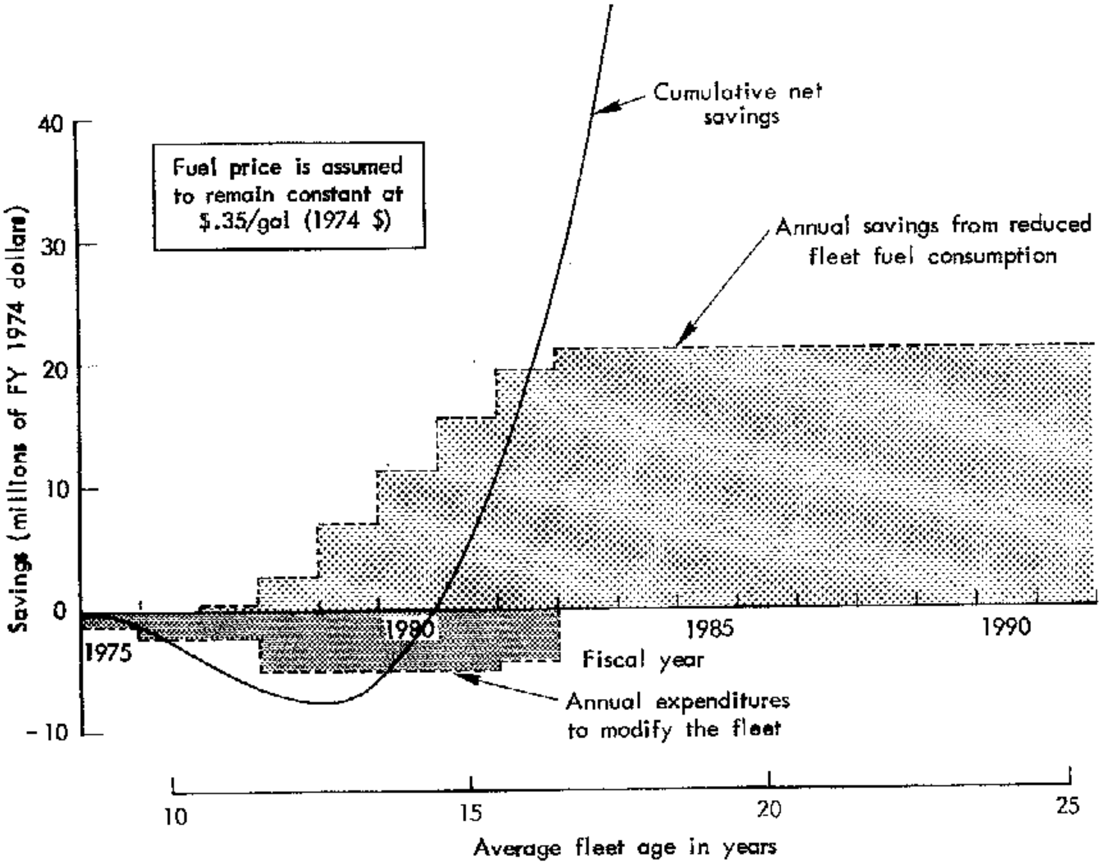

Fig. 16 — Cost impact of a C-141 aerodynamic modification

modification costs even before completion of the program. We conclude, therefore, that the proposed aerodynamic modification would clearly allow cost recovery at a modification cost per aircraft of $120,000.

Because cost estimates are inevitably subject to change, we have chosen to parameterize the cost recovery potential of an aerodynamic modification to the unstretched C-141A for a range of plausible modification costs and fuel consumption reductions (Fig. 17). Whether costs can be recovered through savings in fuel expenditures before the fleet is retired will depend upon the ultimate cost of the modification, its effectiveness, the service life of the aircraft,* and

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*Considerable uncertainty exists regarding the ultimate service life of the C-141A. The Durability and Damage Tolerance Assessment Study currently being performed by the Air Force Logistics Command and Air Force Systems Command is attempting to evaluate the validity of the 40,000 hour service life estimate presently being used for

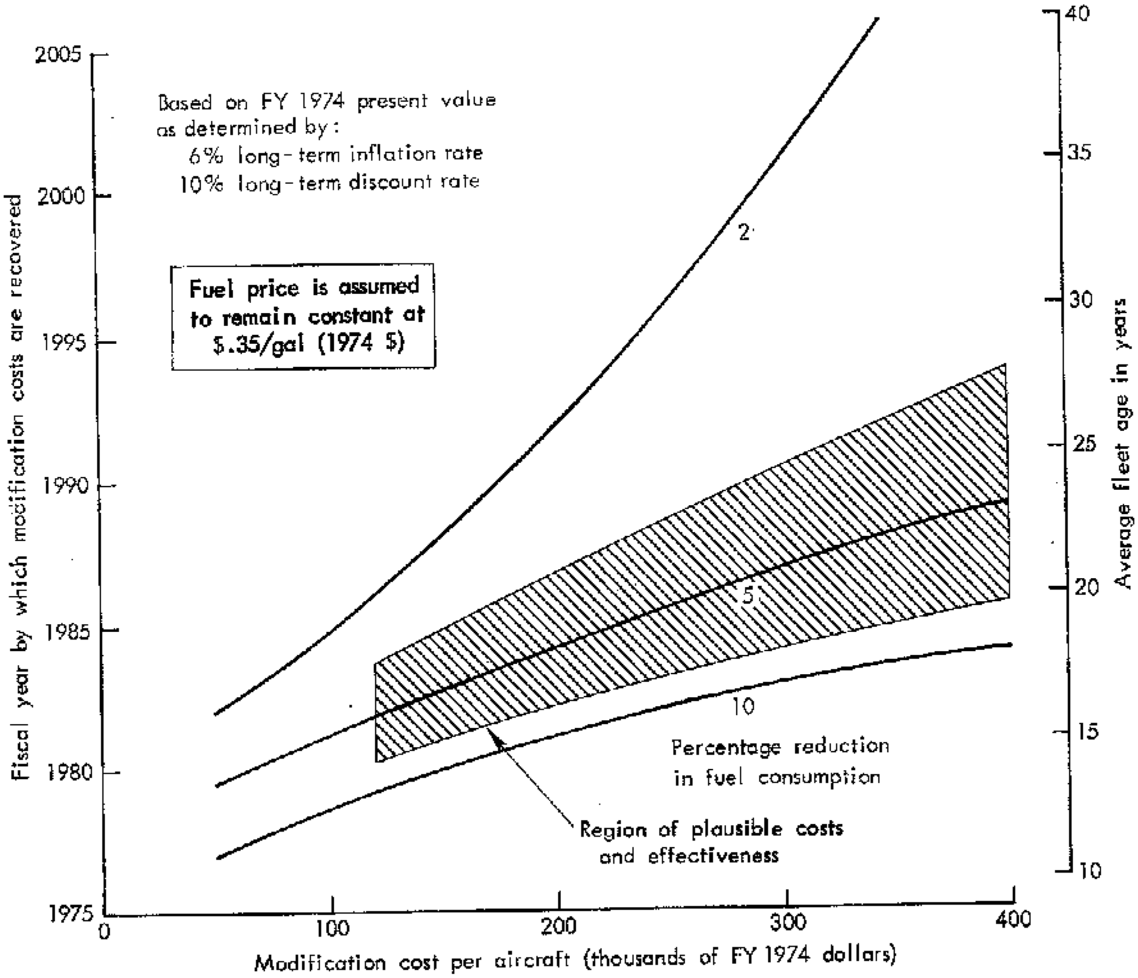

Fig. 17—Cost recovery potential for an aerodynamic modification to the C-141A

future escalations in fuel costs. Figure 17 indicates that if costs were to rise to $250,000 to $400,000 per aircraft to accomplish the modification, there would be some doubt as to whether cost recovery would be possible. Nevertheless, further exploration of the cost of an aerodynamic modification and a determination of the additional years the C-141A is to be kept in service seem desirable.

C-130 Afterbody

Lockheed has also analyzed, in considerably less detail than for the C-141, possible changes to the C-130 aircraft to decrease aerodynamic drag, and in so doing decrease fuel consumption. Some of the

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planning purposes. At current utilization rates, this 40,000 hour service limit translates to an average fleet life of approximately 31 years.

approaches considered include the addition of wing/fuselage fillets, refairing of the afterbody, vortex control on the afterbody, or moving pylon-mounted fuel tanks to the wing tips.(14) The analysis was originally motivated by a desire to increase the range of the Dedicated Electronic C-130s of the Navy.

Wind-tunnel tests have been made with strakes (or cusps) along the chine of the aircraft, in an attempt to reduce the pressure drag associated with the afterbody. It is important to note that this type of modification will not interfere with the operation of the aft cargo door. Preliminary results indicate that such a modification might reduce drag by about 3 percent. Lockheed engineers believe that more extensive wind-tunnel testing might result in modifications that would reduce drag slightly more. For those applications that do not require use of the aft cargo doors (USMC use of KC-130s), an extensive afterbody modification is available that would reduce drag an estimated 9 percent.*

Figure 18 shows the cost recovery potential of an aerodynamic modification to the Air Force C-130 fleet as a function of the modification cost per aircraft and the reduction in fuel consumption. For most reasonable sets of fuel consumption and cost assumptions, it appears that costs cannot be recovered through savings in jet fuel expenditures before the fleet has exceeded its useful life. This is a consequence of the fact that the average Air Force C-130 was already 14 years old in 1976. Thus, we conclude that the costs of an aerodynamic modification to the C-130 will most likely not be recovered through savings in jet fuel expenditures.

We also investigated an alternative modification strategy--one that would modify only the newer C-130s in the Air Force fleet. However, our results indicate that even if only the newest 25 percent of the Air Force C-130 fleet were modified, substantial reductions in fuel consumption and very low modification costs would be required, if costs were to be recovered. For example, the costs for a modification requiring a $135,000 expenditure per aircraft, yielding a 10 percent

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*Personal communication from Skip Bolling, Lockheed-Georgia Company, August 30, 1974.

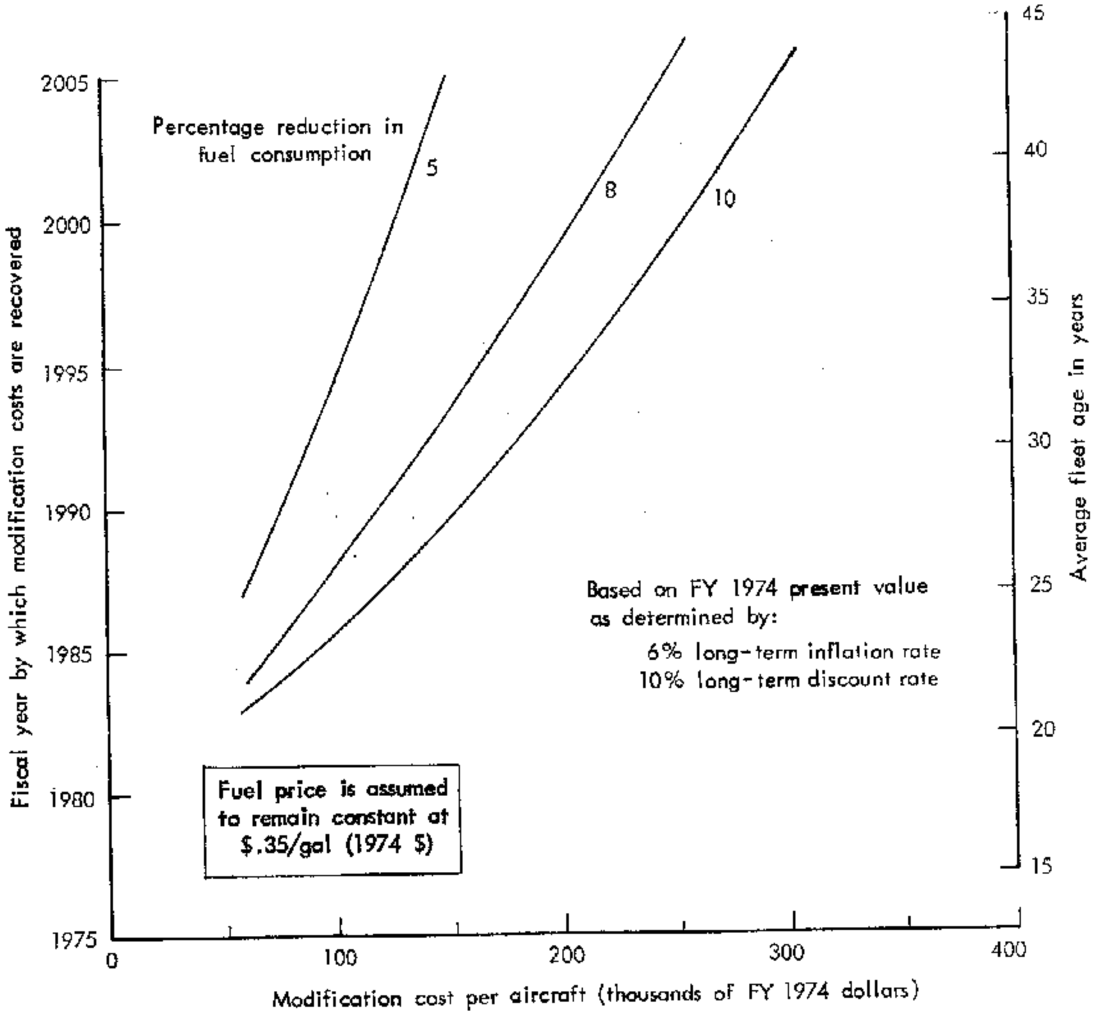

Fig. 18—Cost recovery potential for an aerodynamic modification to the C-130

reduction in fuel consumption, could be recovered at an average fleet age of 20 years (for the newest 25 percent of the fleet).

B-52 Modifications

The B-52 fleet, since it accounts for about 15 percent of Air Force jet fuel consumption, is yet another candidate for fuel conservation measures. In the event modifications are proposed for this fleet, we show in Fig. 19 the cost recovery potential for the Air Force B-52 G/H fleet as a function of the modification cost per aircraft and potential reduction in fuel consumption. The results indicate that only for relatively low-cost, highly effective modifications could costs be recovered before the useful life of the aircraft is exceeded.

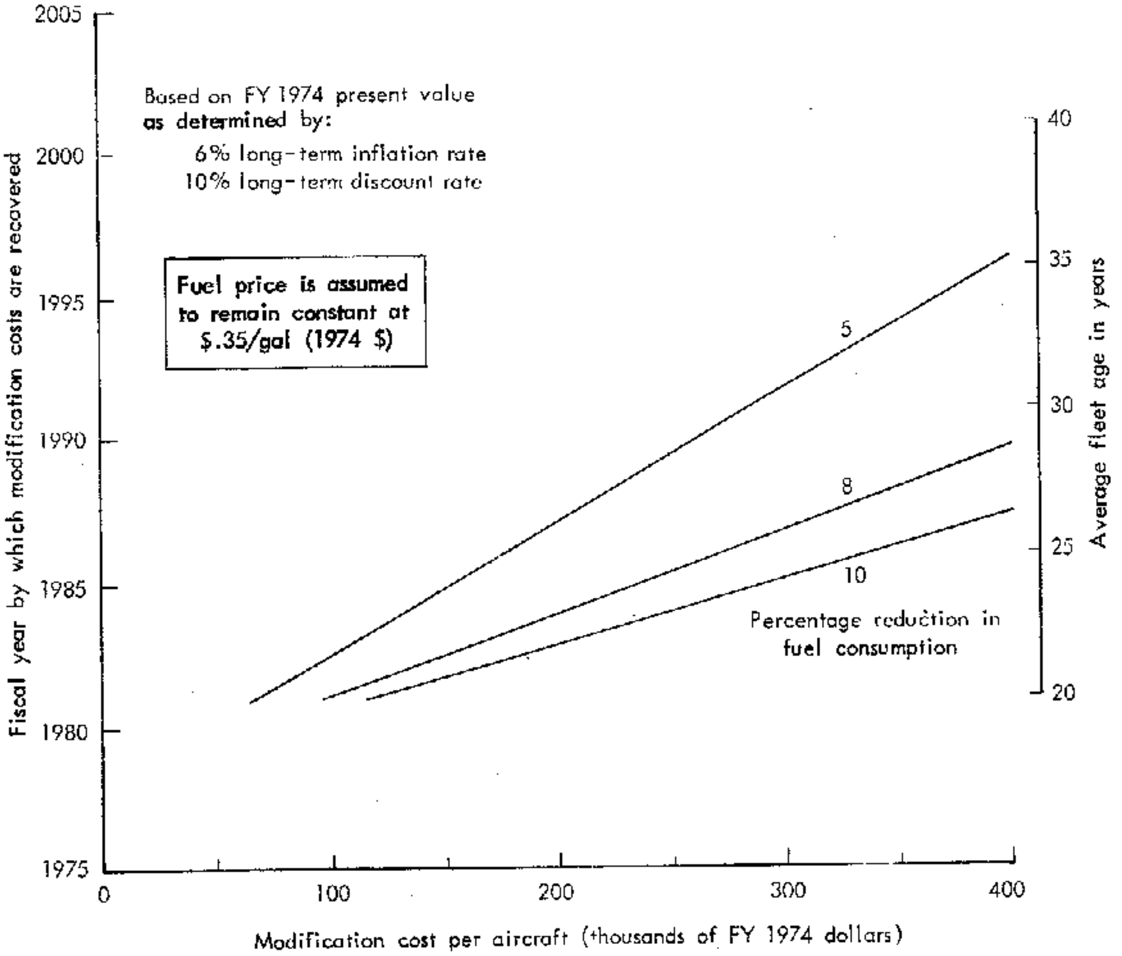

Fig. 19 — Cost recovery potential for an aerodynamic modification to the B-52G/H

Winglets

Wind-tunnel tests of wingtip devices termed "winglets" have indicated that drag reductions on the order of 5 to 10 percent may be achievable for transport-class aircraft. The Air Force and NASA are currently installing winglets on a KC-135 test bed to investigate the drag reduction potential of such an aerodynamic modification.(15) Any assessment of the cost recovery potential and energy efficiency of winglets will have to await the results of the flight-test program. However, in the event such a modification is subsequently suggested for the C-141, C-130, or B-52, the parametric results shown in Figs. 17, 18, or 19 can be used to gain insights into the cost recovery potential of a winglet modification.

OTHER MODIFICATIONS

Lockheed has also suggested that loading cargo aircraft such that the center of gravity is near the allowable aft limit could reduce cruise drag. Apparently, this may reduce the drag of the C-5A by 1.6 percent, of the C-141 by 2 percent, and of the C-130 by 1 percent, assuming the center of gravity shifts from about the middle of the allowable range to the aft limit. One drawback of this operational change is that the flying qualities of the aircraft may be degraded--the aircraft may tend to "wander" because it is less stable. This effect has been confirmed in the Dedicated Electronic Navy C-130s, which nearly always fly with the center of gravity near the aft limit.* Despite the drawbacks, this modification appears potentially attractive, since it offers reductions in fuel consumption at little or no expense.

We can summarize by noting that all of the short-term technological modifications we have examined appear to be energy-efficient. In general, engine retrofits save more energy than modest aerodynamic modifications. The engine retrofit option does not allow full recovery of costs through savings in jet fuel expenditures because of the huge investment costs required to make the modification. Hence, any proposal attempting to justify the cost effectiveness of the engine retrofitting option will have to do so not solely in terms of reduced expenditures for jet fuel, but also in terms of possible operational advantages offered by enhancements in capability (e.g., greater range) that the option might permit.

Aerodynamic modifications could allow full recovery of costs through savings in jet fuel expenditures if made early in the life cycle of an aircraft. Further study of the C-141A modification seems warranted; however, an aerodynamic modification to the C-130 fleet does not appear to be an attractive option, unless only the newer aircraft in the fleet are modified. While the prospects of conserving energy while fully recovering modification costs through reduced fuel expenditures do not appear altogether attractive for the aforementioned

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*Personal communication from Tom Blackby, Lockheed-Georgia Company, August 30, 1974.

aircraft, the relatively lower cost of simple aerodynamic modifications (as compared to engine retrofits) and the potential reductions in fuel consumption (5 to 10 percent) lead us to conclude that modifications may be viable for future aircraft if they are accomplished early enough in the aircraft life cycle to allow cost recovery.

With this background on the energy and cost impacts of short-term technological modifications to reduce fuel consumption, we will now consider the long-term prospects for using alternative aviation fuels. The assessment begins in Sec. III with an examination of the energy resources and production processes from which future jet fuels may be derived. The production of jet fuels derived from coal, the nation's most abundant fossil resource, is then examined in some detail to highlight some of the major cost, energy, resource, and environmental issues associated with synthetic jet fuel production. Section IV then delineates the conditions under which it would be to the Air Force's advantage to develop the synthetic jet fuel option for the future and assesses the possible benefits from possessing a synthetic jet fuel capability in the future.

III. ALTERNATIVE JET FUELS

INTRODUCTION

The ominous prospect of declining domestic petroleum supplies in the future and the uncertainties associated with the economics of those supplies pose a distinct challenge to the Air Force, which relies totally on petroleum for its jet fuel needs. The Air Force will be bidding for liquid fuels in a highly competitive U.S. transportation market which today derives over 95 percent of its energy needs from petroleum, accounting for about 56 percent of total U.S. petroleum consumption (nearly equal to all domestic petroleum production), and about 25 percent of total U.S. energy consumption.(16)

There are strong indications that the demands of the transportation sector alone for liquid fuels from petroleum will significantly exceed U.S. domestic production by the end of the century. Estimates developed by ERDA indicate a substantial shortage of liquid fuels in the future, even with the development of the outer countinental shelf and Alaskan crude-oil reserves and enhanced recovery techniques (Fig. 20). Depending on the ultimate success of these efforts and the extent to which more fuel-conservative vehicles are introduced, the shortage might range from roughly 5 to 12 million barrels per day by the year 2000. The demands by other sectors for petroleum, accounting for 44 percent of consumption today, will further exacerbate the liquid fuel shortage. To meet demands, aggressive energy conservation efforts and development of alternatives to petroleum will be required. If these efforts fail, we will face the undesirable alternative of relying even more on crude-oil imports to satisfy our energy needs.

From an Air Force perspective, any new source of energy for aircraft will have to be derivable from an abundant energy source, be economic, be easily portable in a liquid state, have a high heat of combustion, and be suitable for use in military engines. This section begins by examining the domestic energy resource alternatives to crude oil that might be used in the future production of jet fuels, by identifying the most attractive jet fuel forms derivable from these resources,

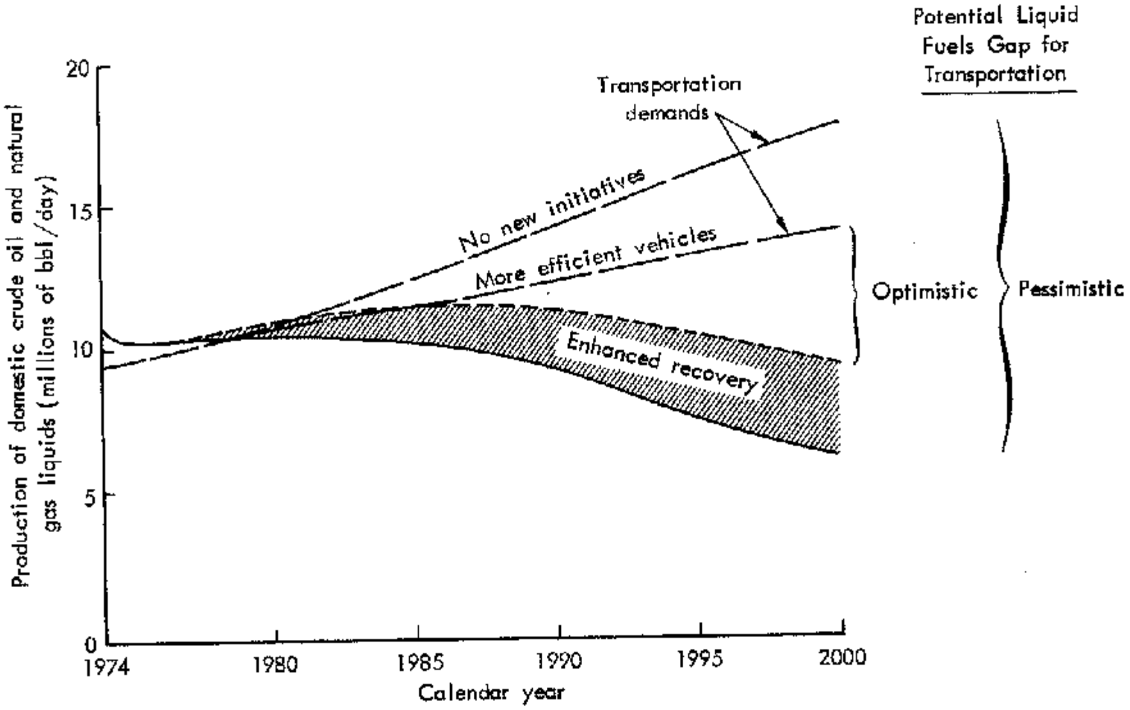

Fig. 20—ERDA projections of U.S. crude-oil supply and transportation demands (from Refs. 17 and 18)

and by describing the production processes that might be used to produce jet fuels from domestic resources. The production of the three most attractive jet fuel candidates derivable from coal are then compared in terms of cost, energy requirements, resource requirements, and environmental impacts, to highlight some of the major issues associated with synthetic jet fuel production. The section concludes with a discussion of the R&D areas that would have to be pursued to provide a synthetic jet fuel option for the future.

ENERGY RESOURCES FOR JET FUELS

The spectrum of potential domestic energy resource alternatives to crude oil and natural gas is sizable. However, the extent to which these alternatives will replace or supplement diminishing crude oil and natural gas supplies will depend critically on the development of technology to extract useful energy from these resources in an economic and environmentally acceptable manner. Domestic energy resources can be grouped into two very broad categories: (1) the carbonaceous resources (those containing carbon), and (2) the noncarbonaceous resources. Each of these categories may be further subdivided into resources that are essentially inexhaustible or renewable and those that are essentially nonrenewable (at least when measured in time periods of hundreds rather than millions of years) (see Fig. 21).* In principle, hydrocarbon fuels can be obtained solely from carbonaceous energy resources or in combination with noncarbonaceous energy resources. Hydrogen fuel can be obtained, in principle at least, from any of the sources shown in Fig. 21.

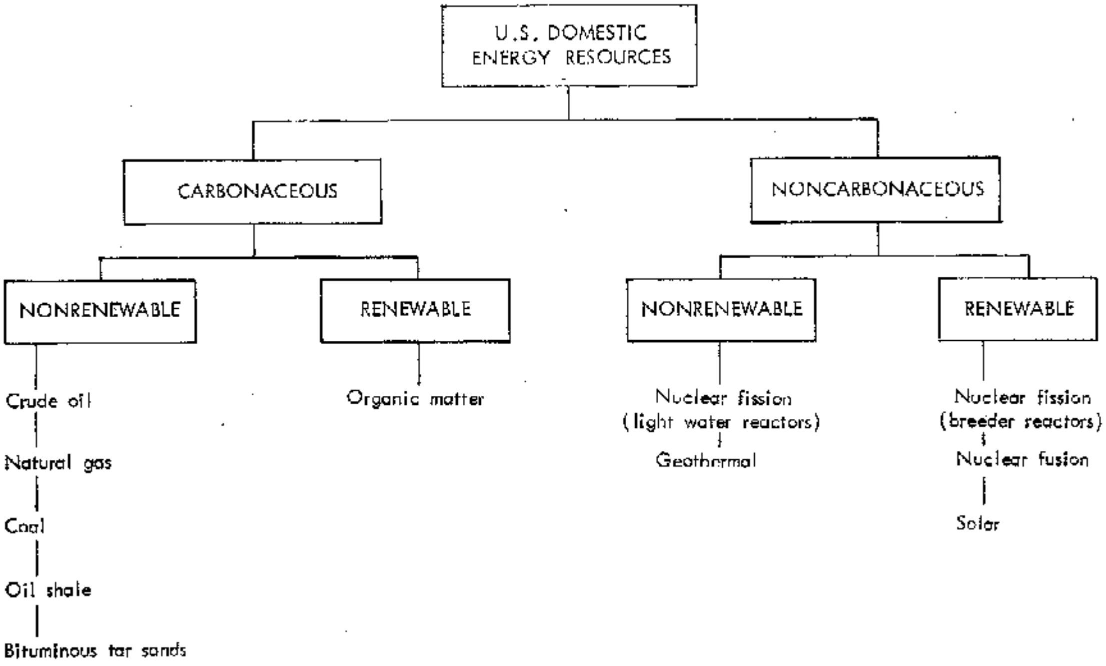

Fig. 21 — Categorization of U.S. domestic energy resources

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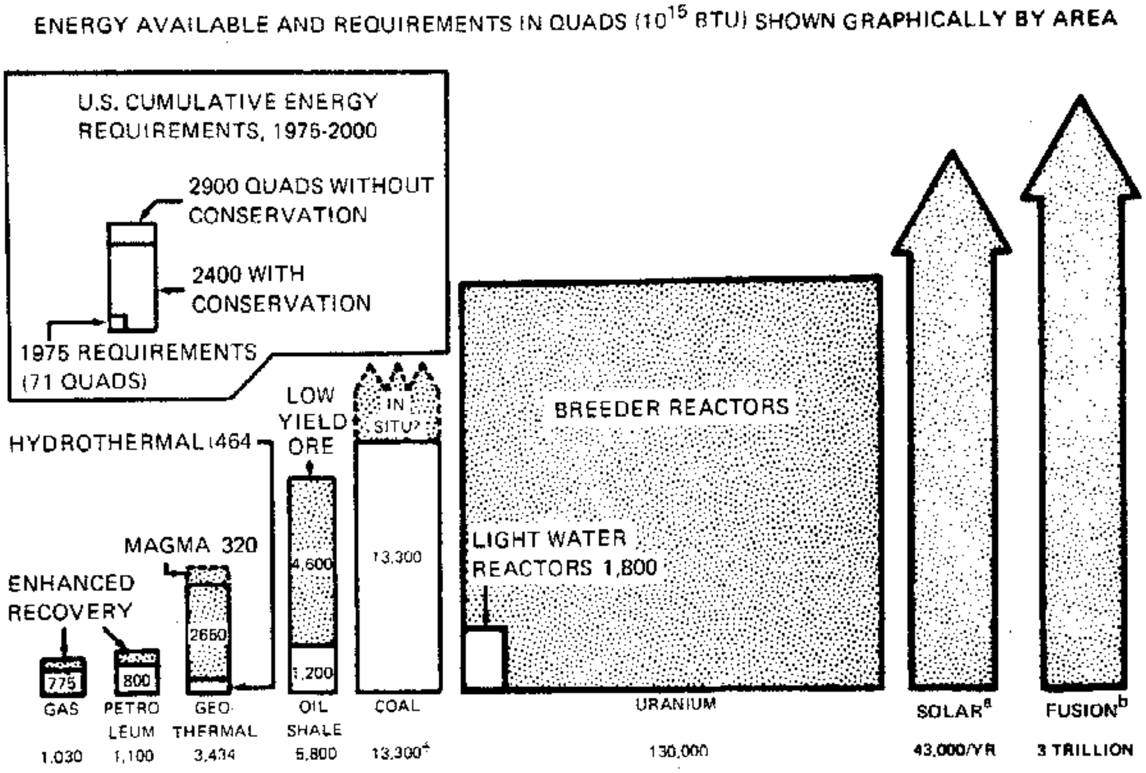
*Recognize that there is some degree of arbitrariness in this classification scheme. Carbonaceous nonrenewable energy resources could be considered renewable over time periods of millions of years. Likewise, some fissionable resources are finite, as are lithium and deuterium used in the fusion reaction; nuclear fission from breeders and nuclear fusion could be considered nonrenewable energy sources when measured in thousands to billions of years. Ambiguities exist with regard to various sources of geothermal energy as well.

Figure 22 shows ERDA's interpretation of domestic U.S. energy supplies.* Several compelling messages are apparent from an examination of Fig. 22 and consideration of present U.S. energy consumption patterns.



NOTE: Shaded areas indicate additional resources that may become recoverable if suitable technologies are developed.

[a] Represents the total average solar flux incident on the United States per year

[b] Total potential energy that could be derived from the deuterium in the world's oceans.

Fig. 22 — Potentially recoverable domestic energy resources (from Ref. 4)

First, while the United States is richly endowed with energy resources capable of supplying energy needs for many years to come, the nation currently relies heavily on a narrow and declining resource base of crude oil and natural gas for 74 percent of its energy needs.† Consideration of the alternatives to crude oil and natural gas indicates that

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*The interested reader is referred to the appendix for more details about the extent, distribution, and characteristics of the domestic energy resource base.

†Derived from Bureau of Mines and Edison Electric Institute data for 1975.

oil shale and coal are the nation's most abundant fossil resources. As will be discussed below, technologies have been and are being developed for converting these solid resources to gaseous and liquid forms suitable for processing into jet fuels.

The ultimate size of the uranium resource base depends on the type of technology assumed to be available to convert the uranium to useful energy. Figure 22 indicates that the introduction of breeder reactors that could convert abundant but nonfissionable uranium-238 into fissionable isotopes could dramatically expand the energy recoverable from our uranium resource base. From an aviation perspective, the most immediately apparent application of nuclear-generated heat or electricity would be in the production of hydrogen--one aviation fuel candidate for the future.

Solar energy and fusion hold the promise of providing virtually limitless energy supplies for the future, *if* economical technologies can be developed to cope with the intermittent and low energy value of the solar flux, and the formidable problems of controlling thermonuclear reactions. Energy from these resources would also probably be most easily exploited for aviation in the production of hydrogen fuels.

Department of Interior estimates of U.S. tar sand deposits (an energy resource not explicitly mentioned in Fig. 22) indicate that the recoverable energy content of U.S. tar sands would amount to, at best, perhaps 83 quadrillion Btu--less than 10 percent that of any of the other resources shown in Fig. 22.(19,20) Hence, it seems unlikely that U.S. tar sands could ever constitute the basis for any large domestic synthetic fuels industry.

Deriving energy from organic matter (e.g., waste products, energy crops), another energy resource not mentioned in Fig. 22, is just one of the means by which the solar flux can be harnessed to provide useful energy (e.g., wind generators, tides, hydropower, photovoltaic conversion, central station thermal electric generation). However, it is distinguished from many of the other solar technologies in that it provides an alternative carbonaceous energy source to fossil fuels that is renewable. The potential contribution of this component of solar energy technology to future energy supplies will have to await resolution of technical and economic uncertainties.

We can summarize this overview of domestic energy resources by noting that the energy resource alternatives to crude oil and natural gas are many; however, the ultimate recovery and use of each of these alternatives over time will be dictated by the development of economical technologies to supply this energy to energy consumers, including the military.

PROSPECTIVE JET FUELS

Background

Used either singly or in combination with other energy resource alternatives to crude oil, the resources just described can be processed into a wide variety of alternative jet fuels. The extensive list of fuel candidates in Table 2 was narrowed down to three alternatives by (1) examining the comparative physical properties of the fuels in the context of aviation applications, and (2) developing conceptual aircraft designs for the most promising alternatives to evaluate their performance.* One of the primary driving mechanisms in reducing the list of viable candidates was the very low gravimetric heats of combustion (heat content per pound) of many of the fuel candidates (e.g., ammonia, methanol, and hydrazine). This undesirable physical characteristic resulted in aircraft gross weights far in excess of those using the most attractive fuels. To a lesser extent, the energy required for production, cost considerations, and technical difficulties in fuel production also reduced the list of viable fuel alternatives. In particular, for the cases of acetylene and propane, which have gross characteristics similar to JP-type fuels, we were unable to identify any synthesis processes in which either of these relatively complex hydrocarbons could be manufactured at a lower unit energy cost than that projected for a JP fuel.

As a result of the screening process, three fuels were tentatively identified as being the most attractive--liquid hydrogen, liquid methane, and a synthetic jet fuel that might be similar to either naphtha-based

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*The reader is referred to Ref. 8 for the details of this screening process.

Table 2

PROPERTIES OF CANDIDATE FUELS

Fuel	Heat of Combustion		Density (lb/ft^3)	Boiling Point (°F)	Autoignition Temp. in Air (°F)	Flammability Limits in Air (%)
	Btu/lb	Btu/gal				
Acetylene (C_2H_2)	20,700	106,900	38.6	-119	635	2.5-80.0
Ammonia (NH_3)	8,000	45,600	42.6	- 28	1204	15-27
Ethanol (C_2H_5OH)	11,600	76,600	49.4	173	--	3.3-19.0
Hydrazine (N_2H_4)	7,200	60,100	62.4	236	518	4.7-100
Jet-Fuel (JP-4) (Naphtha-like)	18,700	121,100	48.7	210	480	0.8-5.6
Jet-Fuel (JP-8) (Kerosene-like)	18,600	128,300	51.6	400	450	0.6-5.0
Liquid Hydrogen (LH_2)	51,600	30,400	4.4	-423	1085	4.0-74
Liquid Methane (LCH_4)	21,500	74,400	25.9	-259	1000	5.0-15
Methanol (CH_3OH)	8,600	58,100	50.5	149	867	6.7-37
Monomethylamine (CH_3NH_2)	13,500	76,700	42.5	45	806	5.0-21
Propane (C_3H_8)	19,900	97,100	36.5	- 44	--	2.1-9.4
Gasoline[a] (C_8H_{18})	19,100	111,800	43.8	257	--	1.1-7.0

SOURCE: Ref. 8.

[a] Included for reference only.

jet fuels (e.g., JP-4, JET-B) or kerosene-based jet fuels (e.g., JP-5, JP-8, JET-A) in use today as derived from crude oil. Before describing some of the processes by which these fuel candidates may be produced, we first briefly discuss some of the physical properties of the fuels.

Liquid Hydrogen

Recent interest in hydrogen as a fuel has resulted from the growing awareness that our current fossil energy resources are indeed finite. Consequently, because hydrogen can be produced from water--a renewable and universal raw material--using relatively inexhaustible energy sources such as nuclear fission (given the development of breeder reactors), nuclear fusion, or solar energy, it has been suggested that hydrogen may be the universal fuel of the future. The concept of an energy industry based on using hydrogen for energy storage, distribution, and utilization has been termed "The Hydrogen Economy."(21)

Under standard conditions hydrogen is a colorless, odorless, nontoxic gas. In its liquid state, hydrogen requires sophisticated cryogenic storage, because of its very low boiling point. Given the excessive weight penalties associated with storing hydrogen in its gaseous form, or in a metal hydride, cryogenic storage of liquid hydrogen appears to be the only viable method for using hydrogen in aircraft applications using current or foreseeable technology.(22)

Perhaps the most attractive property of liquid hydrogen for aviation applications is its high gravimetric heat of combustion. Since the heat of combustion is nearly 2.8 times that of JP-4, the specific fuel consumption of the hydrogen engine is therefore reduced by approximately that factor, so aircraft fuel weight is accordingly reduced. These weight savings can translate into energy savings in aircraft operations; however, the energy required to produce and distribute the liquid hydrogen must also be considered. This subject is addressed later in this section.

Liquid hydrogen also offers some other advantages not apparent from the few physical properties noted in Table 2. The high specific heat of hydrogen might allow it to be used as a heat sink for aircraft and engine cooling. The heat from the hot engine and aircraft parts could be transferred to the hydrogen fuel via a heat exchanger before it entered the combustion chambers, thereby forming a regenerative, no-loss cooling system, which could result in smaller, lighter, and more efficient engines, further reducing specific fuel consumption and aircraft fuel weight beyond that due to the high heat of combustion.

Experts also estimate that the purity of liquid hydrogen and the fact that it can be injected into the combustor in gaseous form might significantly improve the life of gas turbine components and reduce maintenance requirements. The rapid mixing and diffusion characteristics of hydrogen in air promote smooth ignition and uniform temperature profiles that could reduce thermal stresses in metal parts. The low emissivity of the hydrogen flame could also reduce metal temperatures. All of these qualities might tend to impose a less rigorous operating condition on the liquid-hydrogen-fueled engine than on a JP-fueled engine of comparable performance.(23)

The comparative safety of liquid hydrogen and conventional aircraft fuels is a controversial issue. When liquid hydrogen spills or leaks, the fuel immediately vaporizes and dissipates rapidly into the air, unlike conventional hydrocarbon fuels. Conversely, the wide flammability limits of hydrogen and low energy levels required for its ignition would call for careful handling by skilled personnel. Coping with the boil-off from cryogenic tank storage would also require procedures far different from those used for conventional fuels. Liquid hydrogen has, however, been routinely handled in the U.S. space program by skilled personnel without serious accidents for many years.(23)

Perhaps the greatest disadvantage of liquid hydrogen is its low density, requiring nearly four times the tank volume as a JP-type fuel to carry an equivalent amount of energy. Such increases in tank volume may result in increased drag, reduced lift-to-drag ratios, and tank configurations not commonly used on JP-fueled aircraft. This characteristic also probably limits the use of liquid hydrogen to transport-class aircraft. Despite the drawbacks, airframe manufacturers feel there are no major airframe or propulsion technological impediments to the development of a liquid-hydrogen-fueled subsonic transport in the next 15 years.*

Liquid Methane

Methane, the primary constituent of natural gas produced in the United States, has found great use both as a clear burning gaseous fuel and as a chemical feedstock. The importation of liquefied natural gas (LNG), the fuel form in its cryogenic state, has increased significantly in recent years as domestic natural gas production has diminished.

Methane, a gas under standard conditions, is colorless, odorless (without the addition of odorants), and nontoxic, except as an asphyxiant. It has a gravimetric heat of combustion about 15 percent greater than that of conventional petroleum-based jet fuels, but this is offset by its 40 percent lower volumetric heat of combustion, a consequence of its low density. As with liquid hydrogen, the cryogenic form of methane would require fuel tank designs and handling techniques different from those used for more conventional liquid fuels. Liquid methane, when spilled, does not diffuse as rapidly as hydrogen because of its greater specific weight at standard conditions, which could represent a greater safety hazard.

Synthetic JP

JP-4 and JP-5 are the military designations for the petroleum-based jet fuels currently used by the Air Force and the Navy, respectively. JP-8 is a new military jet fuel similar in characteristics to kerosene-based jet fuels such as JET-A-1 used by commercial air carriers. Inclusion of existing JP fuels in Table 2 is not meant to imply that synthetic jet fuels derived from sources other than petroleum will exhibit physical and chemical properties identical to those in

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*Personal communications from G. Daniel Brewer, Russ Hopps, R. L. Dickinson, Russell Sessing, and Don L. Kelley, Lockheed-California Company, October 1974, and from P. E. Whitener, R. B. Brown, and D. G. Andrews, Boeing Aerospace Company, Seattle, Washington, October 16 and 17, 1974.