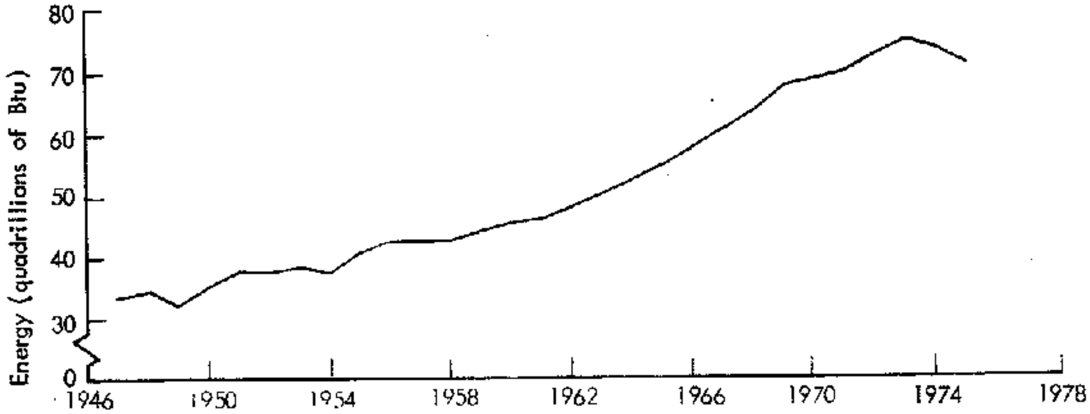
I. INTRODUCTION

The fast-changing world energy situation will influence both the nature of future international conflicts and the effectiveness with which the Air Force can execute its mission. Therefore, the "energy issue" will become an increasingly significant factor in long-range planning, both in the setting of future mission requirements and in the development of corresponding hardware. In the short term, however, existing hardware might have to be modified to suit evolving mission requirements while coping with the various facets of the Air Force's "energy problem." Over the long term, technology and alternative energy sources will have to be more fully exploited to meet future mission requirements.

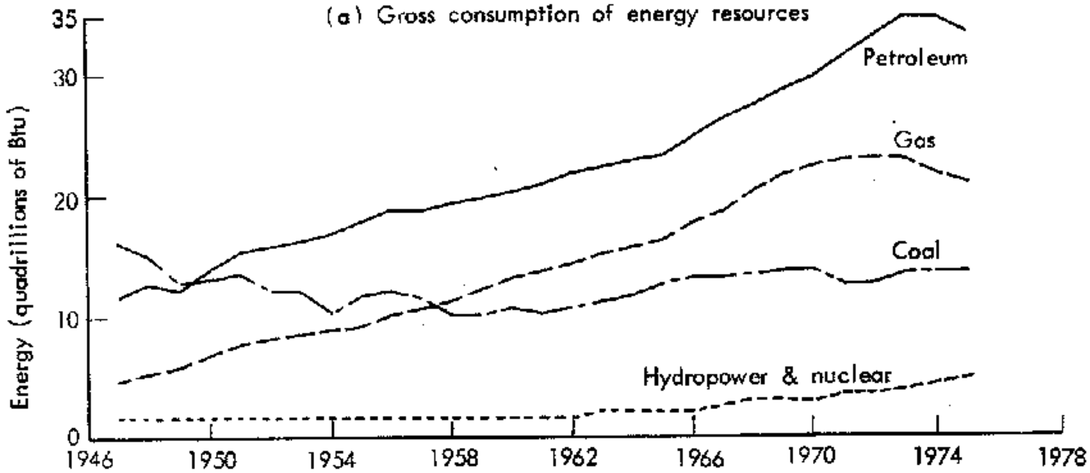
An examination of technological alternatives for easing and perhaps ultimately eliminating the Air Force's total dependence on crude-oil-based fuels for aircraft propulsion essentially defines the scope of the analysis contained in this report. Our overall objective has been to identify and assess the possible benefits from R&D programs that might provide (1) a short-term reduction in Air Force jet fuel consumption through selected aerodynamic and propulsion modifications to the existing fleet, and (2) a long-term option to use noncrude-oil-based jet fuel in future aircraft. This introductory section lays the groundwork for this assessment by putting Air Force energy consumption into perspective and by identifying some of the major problems confronting the Air Force as a result of the evolving world energy situation.

THE COMPOSITION AND GROWTH OF ENERGY CONSUMPTION

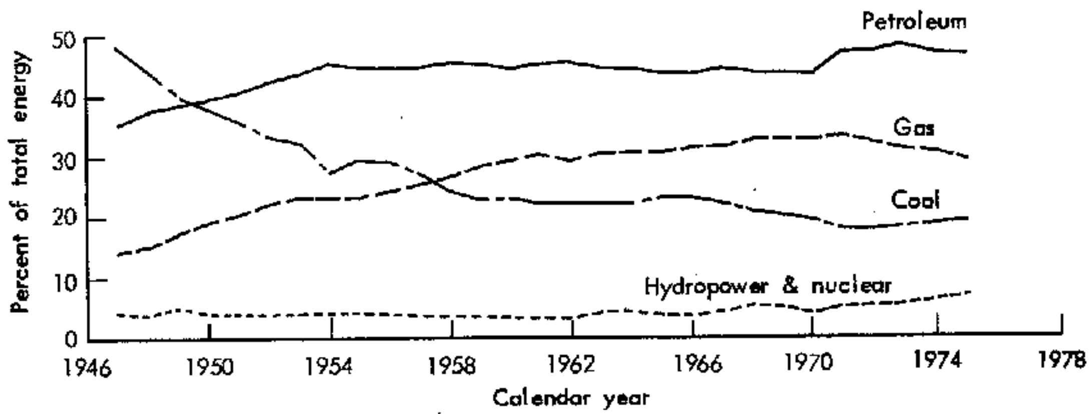
In our modern industrialized society, energy consumption has been growing at a very rapid rate. Figure 1 shows the growth and composition of U.S. energy resource consumption since World War II. Note that during the last decade U.S. energy consumption increased at a 3 percent compound growth rate, which implies a doubling of energy consumption every 23 years (Fig. 1a). Clearly, the major growth has



(a) Gross consumption of energy resources



(b) Energy consumption by resource



(c) Percent of total energy supplied by each resource

Fig. 1 — Level and composition of U.S. energy resource consumption (from Ref. 1)

been in the consumption of petroleum and natural gas (Figs. 1b and 1c). This is not surprising, since in the past these resources were among the most economical, efficient, and transportable. The latter two attributes certainly still hold; however, the recent explosive growth in crude-oil prices, and the anticipated growth in natural gas prices, are forcing the United States and other nations to consider a wide range of alternative courses of action to counter the rising prices of these two traditional energy resources.

World energy demands have been increasing by about 5.5 percent per year, an even greater rate than that experienced in the United States. Some estimates indicate that by 1990 Western Europe's petroleum consumption may equal that of the United States, with Japan consuming about two-thirds to three-quarters that of the United States.(2) It is highly doubtful that the current rate of increase in the demand for energy can be sustained indefinitely. Increasing energy prices, scarcities, and uneven distribution of energy resources, environmental concerns, and lack of capital to support current growth rates will probably tend to temper growth in demand. While Air Force petroleum consumption has been declining in the post-Vietnam time period (see Fig. 2), the Air Force, as a consumer of energy, will be competing with other users in the marketplace for the same scarce resources.

FUTURE SUPPLIES OF CRUDE OIL

The crude-oil supply situation is characterized by diminishing domestic production and an uneven distribution of world crude-oil resources. Projections by the Energy Research and Development Administration (ERDA) indicate that, at best, crude-oil production might remain constant between now and the end of the century (Fig. 3). Moreover, unless new sources of liquid fuels are developed and conservation measures are successful, growing demands for liquid fuels will probably result in even greater dependence on crude-oil imports.* Such a trend could threaten U.S. economic health, policy independence, and security because of North African and Middle Eastern oil-exporting countries'

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*During 1976 the United States imported over 40 percent of its petroleum.

Fig. 2—Annual Air Force petroleum consumption worldwide (from Ref. 3)

control of much of the world's proven oil reserves (Fig. 4). The situation is particularly foreboding for our allies, since Western Europe imports 98 percent of its oil, and Japan imports virtually 100 percent of its oil.(2)

The discussion thus far has centered primarily on U.S. energy supply and demand as a whole. Next we focus on the energy consumption of the Air Force compared to that of the Department of Defense (DoD), the United States, and the world.

A PERSPECTIVE ON AIR FORCE ENERGY CONSUMPTION

The United States, with only about 6 percent of the world's population, consumes annually about one-third of the world's total

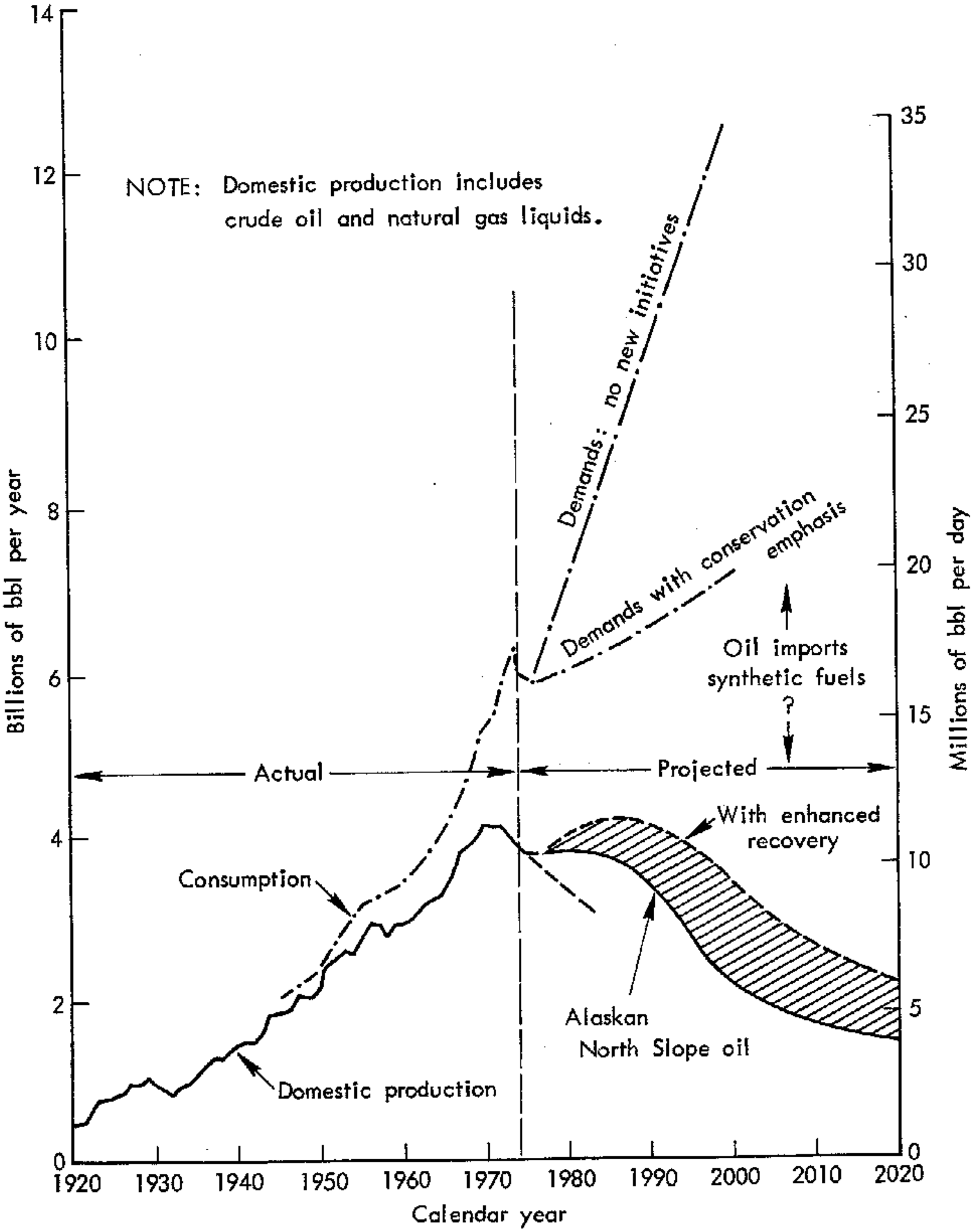
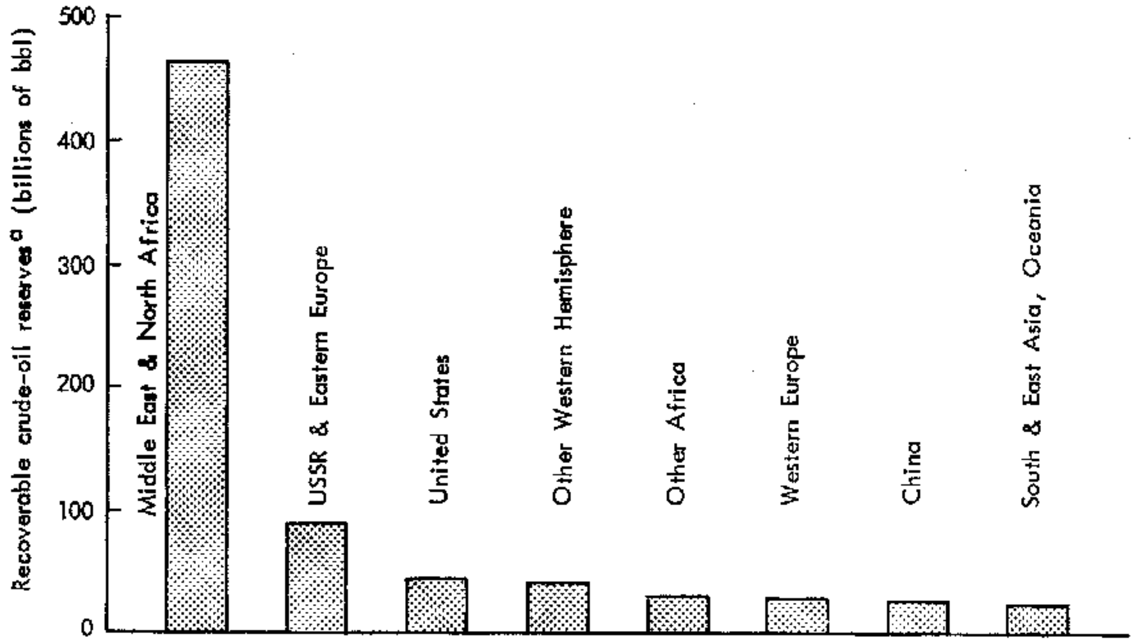


Fig. 3 — Projected domestic crude-oil production and demand (from Ref. 4)

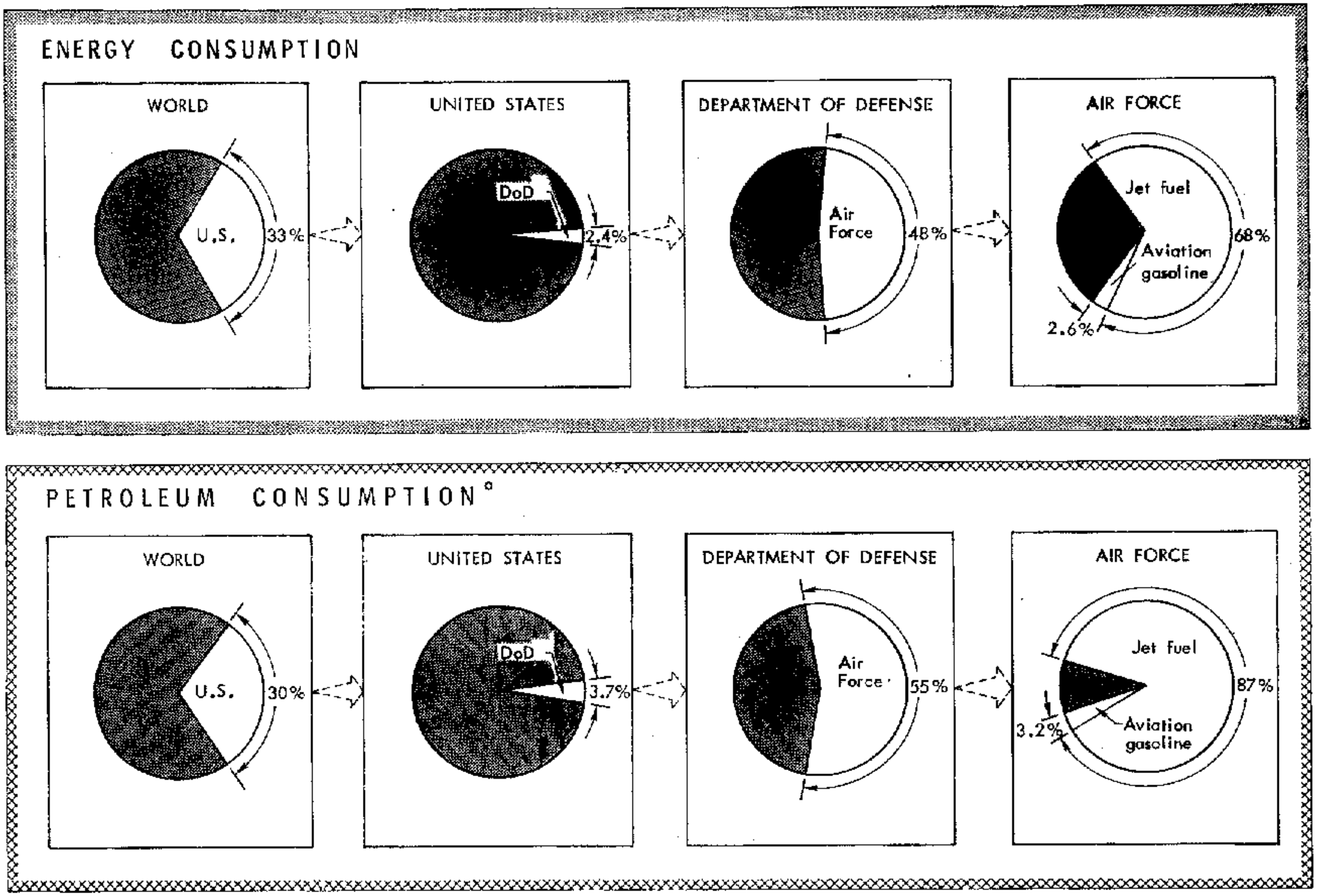


[a] Generally includes measured and indicated reserves as of January 1, 1975.

Fig. 4 — Worldwide distribution of proven crude-oil reserves (from Ref. 4)

energy (Fig. 5). The DoD, in peacetime, accounts for only 2.4 percent of total U.S. energy consumption; however, because of the high energy intensiveness of aircraft, the Air Force accounts for nearly one-half of all DoD energy consumed, with about two-thirds of that energy being consumed in the form of jet fuel for aircraft operations.[2]

The heavy dependence of the United States and other countries on petroleum as an energy source is also shown in Fig. 5. DoD consumption of petroleum is a small but vital fraction of total U.S. consumption. Because aircraft depend exclusively on fuels derived from petroleum, the Air Force consumes over one-half of all DoD petroleum, with 87 percent of that petroleum being in the form of jet fuel. From the standpoint of total national energy consumption, Air Force energy consumption is not large; however, the Air Force and the rest of DoD do account for a large fraction of total U.S. demand for jet fuels. Specifically, military demand in the Continental United States for JP-4



[a] Petroleum accounts for about 43 percent of world energy use.

Fig. 5 — Perspective on peacetime Air Force energy consumption (from Ref. 2)

and JP-5 jet fuels is about 27 percent of total U.S. demand for jet fuels.[2] The largest consumers of jet fuel in the Air Force fleet are the transport and bomber aircraft (because of their large size and greater level of flying activity) and F-4 fighter aircraft (because of their greater numbers) (see Fig. 6).*

ENERGY PROBLEMS FOR THE AIR FORCE

We have noted that the United States and her NATO allies depend increasingly on energy imports, while the USSR is the only so-called developed country that produces more energy from its own resources than it consumes.[2] The energy-production deficiency of NATO countries presents serious problems to the alliance, its members, and the military establishments of its member countries. The problems range from providing energy to support allied military operations to preventing the disruption of the economies of the Free World. As evidenced by the "1973 Energy Crisis," such problems can be orchestrated to serve the political interest of the countries that export energy to the NATO allies. Furthermore, the 1973-74 oil price† escalation showed that in the process of serving their own economic interest, energy exporting nations could synergistically strengthen their political influence by imposing severe hardships on the economies of Free World countries.

Impact on the Budget of Rising Fuel Costs

One immediate impact of the world energy situation has been on the amount spent by the Air Force on energy, annually, three-quarters of which is devoted to jet fuel. Figure 7 shows the explosive growth in jet fuel (JP-4) prices in the last four years. Despite significant conservation efforts, the price that the Air Force pays for jet fuel has risen by over $1 billion during the last two years, such that

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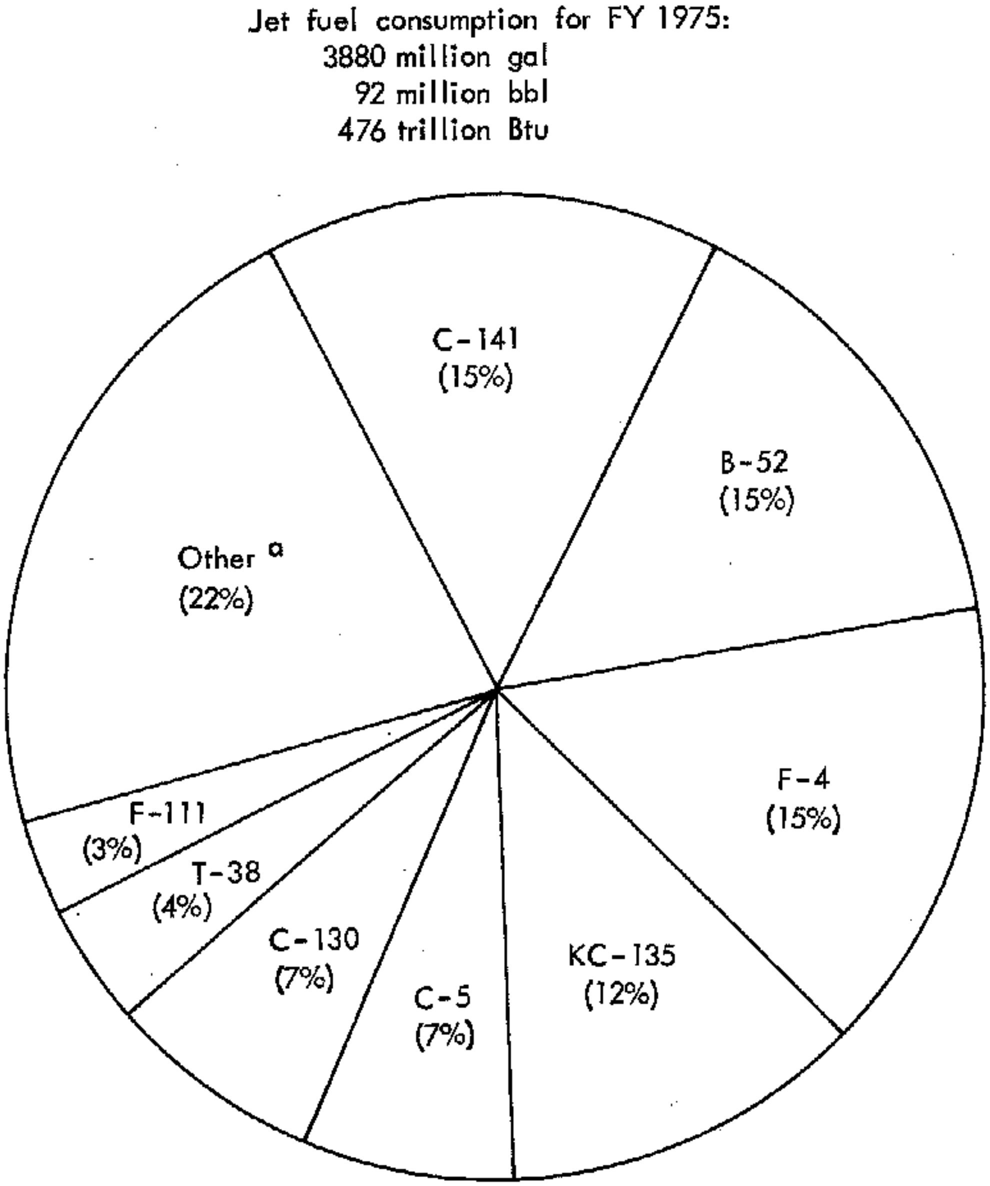
*Personal communication from Willian Vance, Defense Energy Information Service, October 1975.

†Over this period of time, the Organization of Petroleum Exporting Countries about quadrupled the price of their oil exports.



[a] Each aircraft type in this category accounts for less than 3% of total Air Force jet fuel consumption.

Fig. 6—Estimated Air Force jet fuel consumption by leading consumers, FY 1975

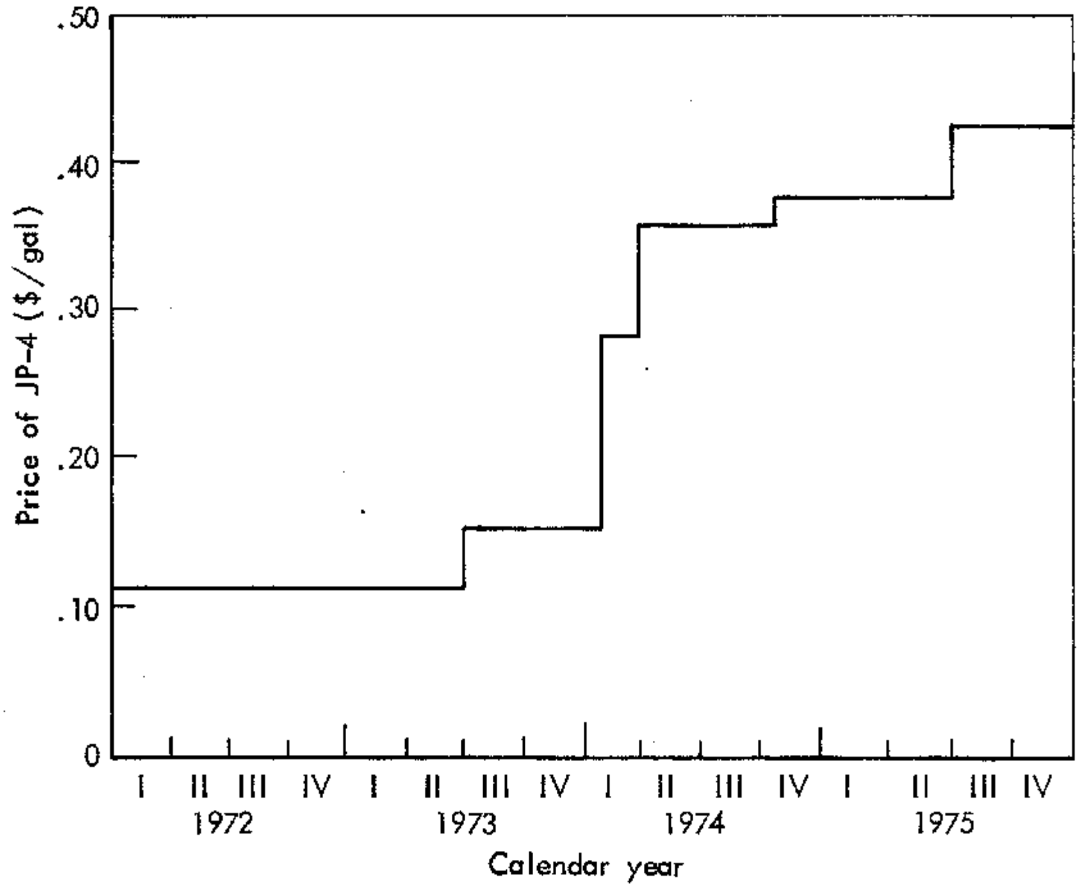


Fig. 7—Price the Air Force pays for jet fuel (from Ref. 6)

expenditures for jet fuel now constitute over 5 percent of the total Air Force budget.(5) *Thus, one energy-related problem for the Air Force is the growing cost of energy in general and of jet fuel in particular--costs that may usurp funds that might otherwise be used to develop and procure new weapon systems.*

Visibility of DoD Energy Consumption

A less quantifiable problem stems from the fact that the DoD and the Air Force are highly visible consumers of petroleum products. This visibility is not a result of the amount consumed by the military. (Indeed, we have already noted that the Air Force accounts for only about 2 percent of U.S. petroleum consumption.) The problem stems more from the manner in which the petroleum is used. When petroleum supplies run low for the domestic sector, the government requests the public to turn down air conditioning, lower thermostats, drive at reduced speeds, and tolerate elevated prices for fuel. At such times, government consumption of energy becomes generally more visible to the public--in particular, military consumption of jet fuel is prone to become highly visible to the public during peacetime. Consequently, the public might expect the Air Force to cooperate in energy conservation, by procuring fewer airplanes and/or reducing peacetime operations to conserve fuel, resulting in a degradation in overall capability.

Reductions in peacetime flying hours influence the Air Force's war-fighting capability in at least two ways. First, there is degradation in pilot proficiency, unless some compensating action is initiated (such as the use of simulators). Second, if substantial reductions are instituted on a permanent peacetime basis, maintenance and supply systems might become "rusty" through reductions in maintenance manpower and spare parts inventories. *Thus, another energy-related problem for the Air Force is that the high visibility of peacetime jet fuel consumption may lead to reductions in war-fighting capability because of restrictions on peacetime operations and/or reductions in aircraft procurement.*

Loss of Overseas Bases or Overflight Rights for U.S. Airlift

The dependence of our NATO allies on oil imports is likely to spawn divergent national interests within the NATO alliance when it comes to dealing with international incidents involving the oil-producing nations. Even in incidents where there is consonancy of national interest within NATO, there may be a widespread reluctance among members to participate overtly. In either case, the U.S. Air Force cannot rely on either the overt cooperation of our allies or on the use of their air bases or their granting of overflight privileges during future conflicts involving the interests of the oil-exporting nations.

The total loss of overseas bases or overflight privileges could significantly reduce the effectiveness with which existing aircraft could quickly deploy U.S. forces to distant parts of the world. It could also diminish U.S. ability to use airlift to offset the Soviet navy's growing capability to challenge sealift forces in some parts of the world. Past reductions in U.S. overseas forces have been predicated on an airlift capability, without which our effectiveness could be significantly degraded. *Thus, one of the significant energy-related problems for the Air Force is the potential loss of overseas bases or overflight privileges during an energy-related conflict.*

Time Required to Develop Alternative Propulsion Technologies

As crude-oil supplies decrease in the face of increasing demand, it is reasonable to expect that the price of crude-oil-based jet fuel will increase to the point where alternative fuel sources and/or propulsion technologies may become cost effective. The implementation of such alternatives, however, could involve many years of research and development and the need to procure entirely new fleets of aircraft. In this latter regard, it is of interest to note that over one-half of the Air Force jet fuel is consumed by aircraft that were initially designed some 20 years ago and are expected to remain in the fleet in significant numbers for another decade. This suggests a 20- to 30-year design replacement cycle. However, long before these aircraft could be replaced by a fleet using a non-oil-based fuel, a technology base would have to be developed and alternative aircraft designs examined. Depending upon the propulsion technology proposed, this could take from 10 to 20 years. Thus, the overall process of developing a new propulsion technology base, evaluating alternative designs and phasing in new aircraft could take from 30 to 50 years to complete. This time frame is commensurate with the time period during which some expect world annual crude-oil production to level off and start declining.[7] *Thus, a long-term energy-related problem for the Air Force is the lead time required to develop and apply alternative non-oil-based propulsion technologies.*

ENERGY ROLES FOR THE AIR FORCE

There are means by which the Air Force can cope at least in part with the aforementioned energy problems--by actions within its roles as a *consumer of energy*, a *provider of technology*, and a *protector of national interests*. However, Air Force actions alone cannot solve the energy problem. Solutions must be worked out at the national and international levels. The primary energy role for the Air Force will be to adapt itself to those solutions and to participate in their implementation.

Consumer of Energy

As a consumer of energy, the Air Force has already taken significant steps to reduce its energy consumption by curtailing nonessential peacetime operations. To further conserve jet fuel, the Air Force can also consider short-term technological options that might reduce the energy consumption of its fleet. An analysis of selected aerodynamic and propulsion options constitute the substance of Sec. II. For the long term, the Air Force can prepare to adapt to alternatives to crude oil in the future. As an energy consumer, the Air Force has a vital interest in when alternative fuels might become available and in the quantity, characteristics, and cost of the alternative fuels. Since national energy policy will influence the development of alternative fuel technologies, the Air Force must be aware of the impact that conversion to an alternative fuel would have on its ability to perform its mission and must seek to influence national energy policy decisions in a way that will make them compatible with Air Force requirements.

Provider of Technology

The Air Force has traditionally been a leader in the development of aircraft, missile, and munitions technology. As an experienced technology developer, the Air Force may play a role in developing the necessary technology for reducing reliance on crude-oil resources. In taking this role, the Air Force can contribute to the solution of the nation's long-term crude-oil-depletion problem, and, being an active technology developer, it can better anticipate and evaluate its own position with regard to alternative fuel-based technologies.

The Air Force could make key contributions in a number of technology areas. For example, the Air Force has long been a major sponsor of the research and development of advanced jet engine technology. This turbine engine technology has obvious applications for the civil sector as well (e.g., high-technology turbines for more efficient electric power generation). Further, the Air Force, through its Aero-Propulsion Laboratory, has much experience in evaluating the impact of fuel properties on the operation of turbine engines. This expertise should prove valuable as the nation begins to use new liquid fuels with properties different from those of petroleum fuels. Other Air Force technology efforts, although not specifically energy-motivated, may provide a valuable contribution to the long-term development of nuclear fusion reactors.

Protector of National Interests

As an instrument of U.S. foreign policy, the Air Force must respond to emergencies around the world on short notice (e.g., the airlift mission). In its role as a protector of the national interest, the Air Force must adjust its fleet capabilities to be responsive and effective in energy-related conflicts, including those situations in which it might be denied overseas base privileges or in which fuel availability becomes critical. One short-term approach to meeting the overseas base problem is to modify the existing fleet to increase the number of aircraft capable of being refueled in flight. Such a modification has already been incorporated on the C-5A. The C-141A fuselage stretch program incorporates an in-flight refueling receptacle to provide more operational flexibility. A longer-term option would be to develop new aircraft of greater size (e.g., gross weights of 1 to 2 million pounds) and range/endurance than those of today. Such aircraft may allow major enhancements in capability while significantly reducing fuel consumption. For example, a companion Rand analysis indicates that a fleet of transport aircraft in the 1 to 2 million pound gross weight class fueled by JP might use roughly 30 percent less energy when deployed in a NATO strategic airlift than a fleet of C-5-class aircraft.(8)

ORGANIZATION OF THE REPORT

Section II of this report examines selected short-term aerodynamic and propulsion modifications that might reduce the consumption of jet fuel in the existing fleet.

Section III examines the resources and technologies that might be used in the development of noncrude-oil-based aviation fuels in the long term. This focus is then narrowed to an evaluation of coal as a future source of jet fuels to highlight some of the energy, cost, and environmental aspects associated with the production of synthetic jet fuels.

Section IV then delineates the conditions under which it would be to the Air Force's advantage to develop a noncrude-oil-based propulsion capability and assesses the possible benefits of such a capability.

Section V draws conclusions based on the material contained in the preceding sections.

II. SHORT-TERM TECHNOLOGICAL MODIFICATIONS

The acquisition of a new fleet of aircraft involves numerous compromises between the performance characteristics believed to be necessary by the operator and the cost of applying and/or extending the state of the art of technology. These compromises are usually struck by identifying the threat, formulating a mission to counter that threat, and then evaluating alternative designs from the standpoint of their cost effectiveness and ability to complete the proposed mission. However, it frequently happens that after the airplane has been put into service, the nature of the threat changes and the perception of the mission requirement is altered, while the state of technology continues to advance. It is possible that the existing inventory of aircraft no longer provides an optimal match (in terms of minimum energy usage) between the available state of the technology and presently perceived mission requirements. Thus, in this section we examine some technological modifications that might reduce the energy needed to meet current mission requirements. We will consider modifications to propulsion systems and alterations of the aerodynamic characteristics of some existing aircraft.

PROPULSION SYSTEM MODIFICATIONS

Turbine engines on many of the aircraft in the Air Force inventory were developed from a 1950s technology base. For a number of aircraft, there are newer engines available with comparable performance characteristics. These newer engines, developed from the 1960s technology base, typically consume from 20 to 30 percent less fuel than their predecessors. On the surface, it would appear that retrofitting existing aircraft with this more recent generation of engines would result in both an energy and a cost savings for the Air Force. This seems to be substantiated in part by two historical precedents: The first concerns the case where American Airlines retrofitted the turbojet engines on the 707-120 with turbofan engines. The second case concerns an engine change when the B-52H model was produced. Note that this is not an example of an engine retrofit. When the H series was produced, the Air Force switched from the turbojet (on the B-52G) to a more efficient turbofan engine.

The potential annual fuel savings from an engine retrofit program is illustrated in Fig. 8 (a modification of Fig. 6). Total Air Force

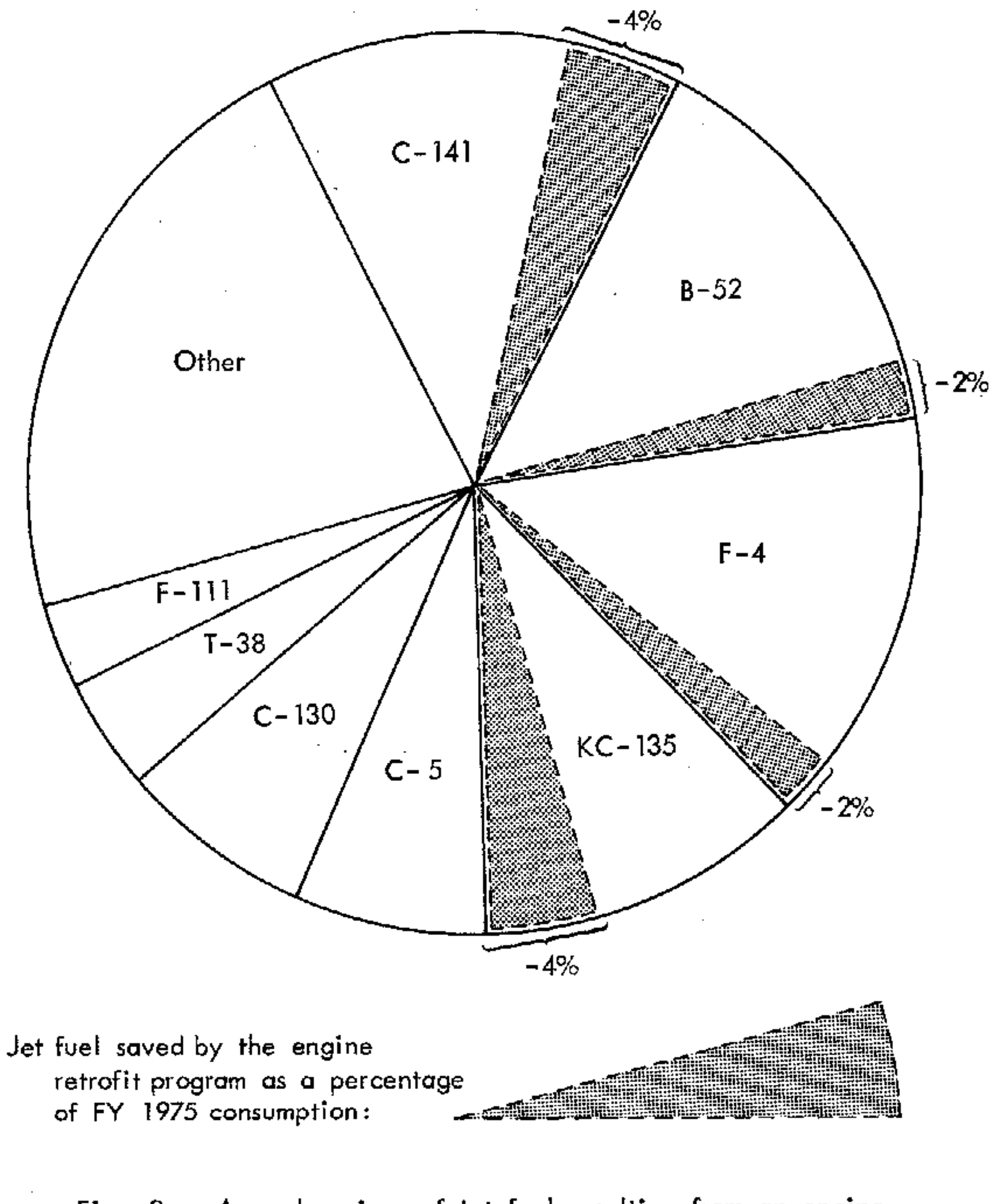


Fig. 8 —Annual savings of jet fuel resulting from an engine retrofit program for the four leading consumers of jet fuel

jet fuel consumption could be reduced by 12 percent if the engines were retrofitted on the leading four consumers of jet fuel (i.e., C-141, B-52, F-4, and the KC-135). In the next two subsections we will examine this idea.*

C-141 Engine Retrofit

It is estimated that by replacing the four TF33 engines on the C-141 with two TF39 engines, the annual fuel consumption for the C-141 could be reduced by about 25 percent. Such a retrofit program could save 190 million gallons of JP-4 annually (equivalent to 23.3 trillion Btu). At 35 cents per gallon, the reduction in the annual fuel cost for the C-141 fleet would be $66.5 million. However, we also need to consider the cost of changing engines and the energy used in manufacturing the new engines and in modifying the aircraft to accommodate the new engines.† These costs and savings are presented in Fig. 9 for energy and in Fig. 10 for dollar savings. The figures display the energy and budget expenditures to modify the C-141 fleet as negative savings. For example, during the peak of the engine retrofit program, a quarter billion dollars would be spent annually from FY 1979 through FY 1981 with the assumed modification schedule of about five aircraft completed per month. The energy expended in modifying the fleet could be recovered by the last year (FY 1982) of the retrofit program,‡ as

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*The analysis considered a wide variety of engine retrofit candidates for the various aircraft. This section discusses only the most promising candidate for each aircraft considered. The JP-4 price of 35 cents per gallon (mid-1974 dollars) assumed in most of the cost-effectiveness calculations was the prevailing price at the time of this analysis. This 1974 price is equivalent to a first quarter 1977 fuel price of about 43 cents per gallon, using the observed general inflation rate of about 7.3 percent, or about 41 cents per gallon using the 6 percent inflation rate assumed in the analysis.

†The average cost of modification was assumed to be $4.6 million (FY 1974 dollars) per aircraft, including RDT&E costs, start-up costs, engine costs, and airframe modification costs, to accommodate the higher thrust level of the new engines. Propulsion characteristics and energy expenditures were derived from Refs. 9 to 11.

‡The energy expenditure to make the modification would be in the commercial sector. Of course, the Air Force would realize energy savings as soon as the first retrofitted aircraft began flying. Thus, the cumulative net energy savings should be thought of in an overall national context.

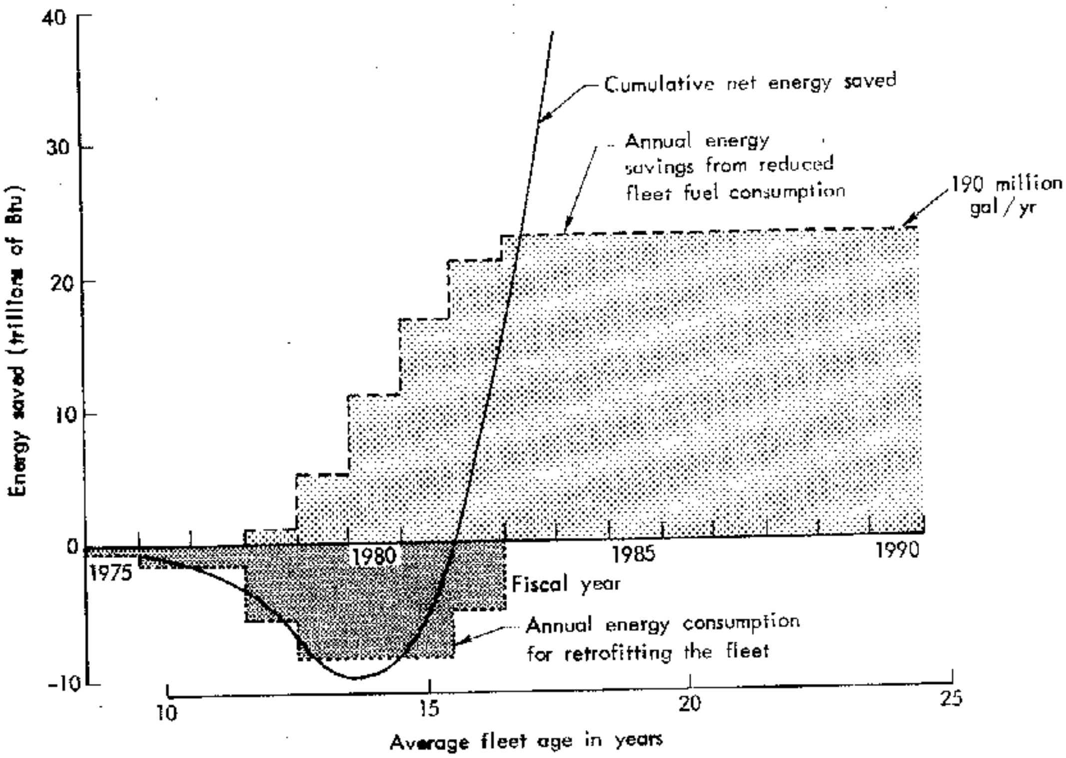


Fig. 9 — Energy impact of a C-141 engine retrofit program

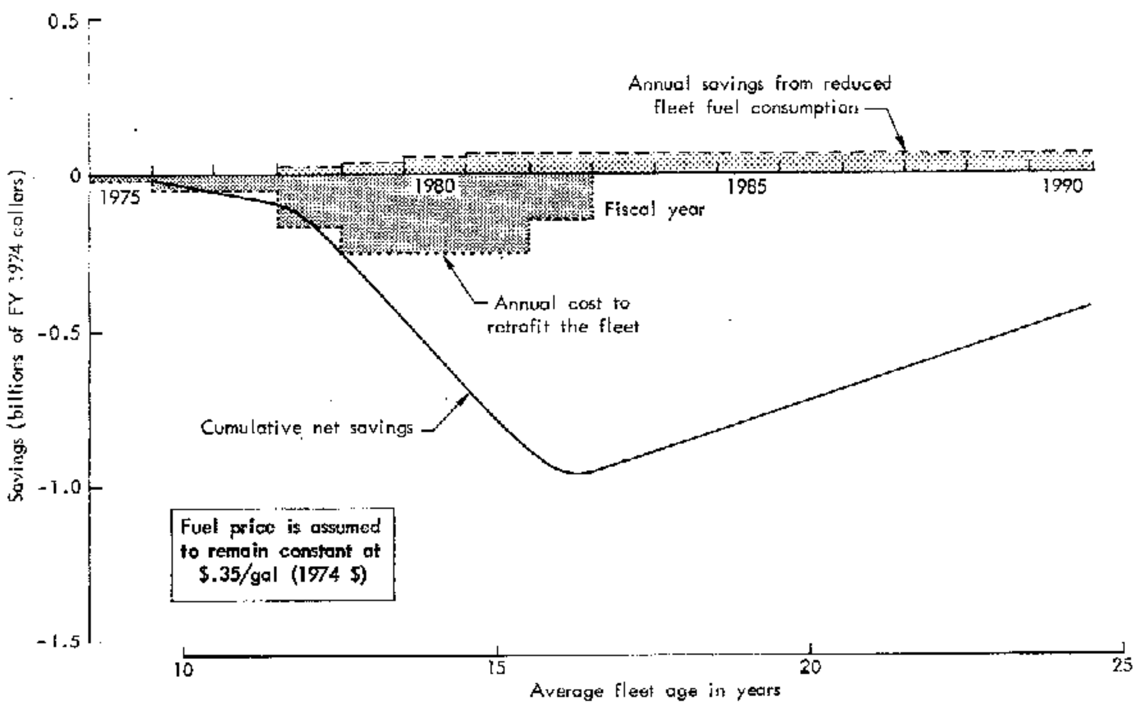
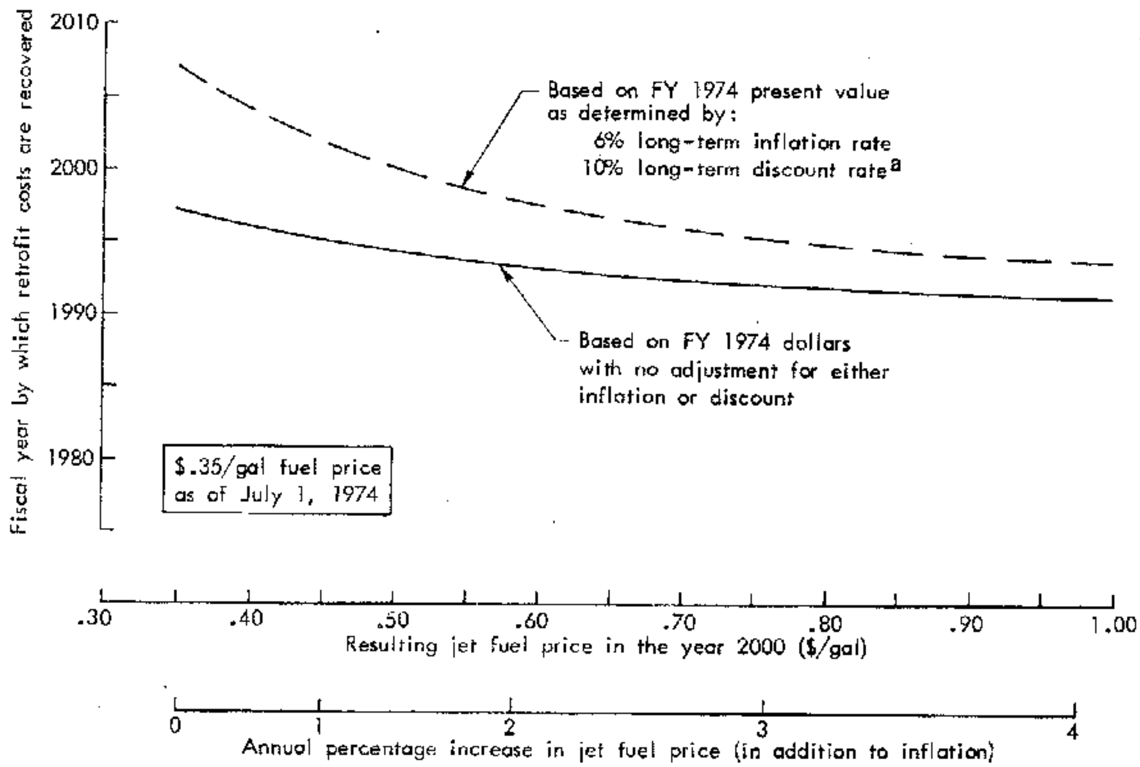


Fig. 10 — Cost impacts of a C-141 engine retrofit program

indicated by the curve labeled "cumulative net energy saved" in Fig. 9. At that time the average age of the fleet would be about 15 years. However, assuming a constant fuel price of 35 cents per gallon, the cumulative net budget savings (undiscounted) would be negative beyond the average fleet age of 25 years (Fig. 10). This means that the budget expenditures for the retrofit program could not be recovered over the remaining life of the airplane through the reduced fuel consumption of the new engines. Figure 11 shows that even if the fuel price rises



[a] These assumptions yield a very conservative net discount rate of approximately 4 percent.

Fig. 11 — Effect of increasing fuel prices on the engine retrofit cost recovery year for the C-141