SOME COST, ENERGY, ENVIRONMENTAL, AND RESOURCE IMPLICATIONS OF SYNTHETIC FUELS PRODUCED FROM COAL FOR MILITARY AIRCRAFT

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ABSTRACT

As the availability and economics of jet fuels derived from crude oil become less certain in the future, the United States Air Force will need to consider the implications of utilizing aviation fuels derived from alternative energy resources. This paper examines the most promising energy resource alternatives to crude oil and the most attractive aviation fuels derivable from the resource alternatives, with emphasis on coal-based aviation fuels.

The findings suggest that coal and oil shale are the most promising energy resource alternatives. A synthetic jet fuel similar to jet fuels in use today appears to be the most attractive aviation fuel derivable from coal, primarily because its production requires lower energy expenditures and results in a less costly fuel product than the other two major alternatives, liquid hydrogen and liquid methane, while offering attractive characteristics for aviation applications. Despite its attractive features, there are definite resource, capacity, and environmental constraints which could tend to limit the availability of synthetic jet fuels in the future.

INTRODUCTION

This paper addresses two basic questions. First, what are the most promising future energy sources for aviation fuels for Air Force aircraft becoming operational in the 1985 to 2000 time frame? The question is motivated by the fact that since mid-1973, the price the Air Force pays for its jet fuel has quadrupled; annual expenditures for jet fuel have increased by over $800 million, such that today jet fuel expenditures account for over five percent of the Air Force budget. Hence, it is quite possible that some time in the

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future, aviation fuels derived from energy sources other than crude oil may become economic.

The question is then asked, what are the most promising aviation fuel forms that can be derived from the energy resource alternatives to crude oil? Some have suggested that liquid hydrogen is the aviation fuel of the future. However, there are other alternatives which are worthy of careful consideration.

We will begin with a brief review of the U.S. domestic fossil resource base, and a description of some representative synthetic fuel supply processes by which promising aviation fuel alternatives may be obtained.

U.S. Fossil Resource Base

FIG. 1 shows the energy embodied in economically recoverable U.S. domestic fossil resources(*). By virtually every estimate, coal is our most abundant fossil resource [1-5]. However, the U.S.also has large reserves of as yet unexploited oil shale. While this paper addresses some of the issues associated with using coal as an energy source for aviation fuels, the extent of the oil shale resource base, and the favorable results of the U.S. Navy in its programs to retort and refine oil shale to liquid military fuels indicates that oil shale should also be given serious consideration as a future energy source for aviation fuels [6].

The crude oil reserves noted in FIG. 1, based on the latest United States Geological Survey (USGS) estimates [7], would be depleted in 37 to 62 years at current rates of domestic crude oil production, which indicates the inevitability of shifts to more abundant domestic supplies of energy. To

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(*) Crude oil and natural gas estimates shown in FIG. 1 include identified resources and estimated undiscovered resources recoverable with current technology (unshaded area). The shaded area refers to additional resources that might be recovered with enhanced recovery techniques. The oil shale estimate (unshaded) includes 25 to 100 gallon per ton identified recoverable deposits in the Green River Formation. The shaded area indicates potentially recoverable 10 to 25 gallon per ton deposits in the same formation, which would require development of new recovery techniques. The lowest coal estimate includes recoverable measured and indicated resources. The highest coal estimate includes recoverable measured, indicated, inferred, and hypothetical resources.

reinforce this notion, we note also in FIG. 1, that while crude oil and natural gas are our least abundant fossil resources, they account for about three-quarters of total U.S. energy consumption. Of course, as greater reliance is placed on oil shale and coal, new processes will be required to convert these solid fuels to portable liquid fuels for transportation.

Fuel Supply Processes

FIG. 2 illustrates a number of the possible energy sources and production processes by which aviation fuels may be obtained in the future. In particular, it seems quite possible that in the future, aviation fuels similar to those in use today may be derived not only from crude oil, but also oil shale and coal. The ability to utilize jet fuels derived from a multiplicity of energy sources might significantly enhance Air Force flexibility in the future as the availability and economics associated with jet fuels derived from crude oil become less favorable. Among the alternatives shown in FIG. 2, the production of fuels from coal and oil shale are of particular interest because of the size of the resource base and the status of current and foreseeable technology for converting coal and oil shale to the fuels shown at the bottom of FIG. 2.

COMPARISON OF ALTERNATIVES

Three of the more attractive aviation fuel alternatives derivable from coal are liquid hydrogen, liquid methane, and a synthetic jet fuel (or synthetic JP to use a common U.S. military designation). These will now be compared in terms of the energy expenditure required to produce, distribute, and store the fuels, and the costs associated with such fuel supply processes. We will then discuss, in somewhat lesser detail, the resource requirements and environmental impacts of the fuel supply processes.

Energy

FIG. 3 shows the major components of representative fuel supply sytems for each of the three alternatives, the characteristics of such systems being developed from a variety of sources [8-19]. Let us focus first on the details of the liquid hydrogen supply system. Typically, surface-mined western coal could be transported from the mine a short distance (about ten miles, for example) via a diesel train to a coal gasification plant utilizing Lurgi technology where the coal would be gasified, shifted, and purified to hydrogen. The long-haul distribution leg would consist of a high pressure pipeline to a liquefaction facility near the airbase. The example shown is equivalent to pipelining the gaseous hydrogen from the Wyoming Powder River Basin to the west coast of the U.S., a distance of about 900 miles. The gaseous hydrogen would then be converted to a liquid state and stored in cryogenic tanks for ultimate distribution to an aircraft fueling manifold via a short liquid hydrogen pipeline, about two miles in length.

The numbers shown above the elements of the fuel supply system trace the flow of resource energy (energy derived from the primary energy resource--coal) from extraction to ultimate distribution. In this example, 289 BTUs of coal resource energy are required to produce 100 BTUs of liquid hydrogen and 35 BTUs of by-products. Of course, other energy must also be expended to fuel the diesel train, build the facilities, generate the electricity required for liquefaction, etc. This energy, termed process energy, is shown below the elements of the fuel supply system. Of primary interest is the large process energy expenditure associated with hydrogen liquefaction and the ortho to para conversion, which is roughly equivalent to the resource energy content of the gaseous hydrogen entering the facility. As a consequence of this large process energy expenditure, about 3.2 BTUs of energy must be input for every BTU of liquid hydrogen and by-products output. Thus, the liquid hydrogen supply process is significantly more energy intensive than today's crude oil supply system, which requires about 1.2 BTUs of energy input for every BTU of refined products output(*).

A Lurgi gasifier is also used in the liquid methane supply system, but in this case the product gas undergoes a methanation reaction which results in a pipeline quality gas which is high in methane. The liquid methane supply process requires less energy than the liquid hydrogen process, primarily because less electricity is required for liquefaction. In this instance, the literature suggests that typically, some of the gaseous methane is used to generate the electricity for liquefaction because the scale of electricity required is sufficiently low as to not preclude on-site power generation [15,19]. With resource energy (the gaseous methane) supplying the energy for

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(*) All of the energy values cited in the comparison are net or low heating values, in which the heat of condensation of water is not included. This is appropriate for controlled combustion systems such as aircraft engines, in which the combustion products are discharged as a gas.

electric power generation, the process energy shown on FIG. 3 for methane liquefaction accordingly reflects only the energy required to build the facility. The energy accounting shows that 1.9 BTUs of energy must be input for every BTU of liquid methane and by-products output.

For the synthetic JP supply system, more coal is required than for the other two alternatives. This is because it is estimated that less than one-half of every barrel of syncrude produced by direct coal hydrogenation could be refined to a kerosene-like jet fuel, the bulk of the remainder being unleaded motor gasoline, which should find a ready market in the 1995-2000 time frame. Thus the greater coal requirement is a direct reflection of the greater amount of energy being delivered. The comparatively large process energy required for syncrude refining is also significant. This is a consequence of the severe hydroprocessing which the coal syncrude must undergo, primarily due to the characteristically high aromatic content of coal syncrude liquids. In the example shown, the syncrude refinery is structured to maximize the output of jet fuel by hydrocracking the heavier distillate fractions to jet fuel and lighter products, primarily gasoline. If a lesser yield of jet fuel were acceptable, the energy requirements could be reduced. The energy accounting shows that the synthetic JP supply process requires that 1.7 BTUs of energy be input for every BTU of synthetic JP and by-products output.

The energy expenditures shown in FIG. 3 are largely characteristic of current or near-term technology. If some plausible future improvements in technology are assumed, particularly with regard to improvements in electric power generation efficiencies, the energy ratio for the liquid hydrogen supply system might become about 2.6, the liquid methane system about 1.8, and the synthetic JP system about 1.6. However, even with this rather optimistic outlook, the work of Mikolowsky and Noggle indicates that the lower energy consumption of a subsonic liquid hydrogen transport aircraft is more than offset by the large energy expenditures associated with the fuel production and distribution process [20]. Thus, while all of the synthetic fuel alternatives require larger energy expenditures than today's crude oil supply process, the liquid hydrogen supply process appears to be dominantly more energy intensive than the processes by which the other two coal-derived fuels are obtained.

Costs

Of course, energy efficiency is but one component of the evaluation process; the costs must be considered as well. FIG. 4 shows the cost per million BTU of the three fuel alternatives for delivery to a group of airbases. The Air Force currently pays the Defense Fuel Supply Center $.42 per gallon for JP-4 jet fuel, which is equivalent to $3.55 per million BTU. The fuel costs are developed using a mix of eastern underground mined coal and western surface mined coal, the average coal price for the mix being about $9.64 per ton, or about $.54 per million BTU. The sensitivity of fuel cost to coal costs and other key parameters will be presented later.

Because the cost contribution of the energy conversion facilities is large for each of the three fuels, the major cost categories have been identified according to the fixed (capital charges), operating (recurring labor costs, property taxes, raw materials, etc.), and energy costs for these facilities. All of the energy conversion facilities are quite capital intensive. The capital cost per daily million BTUs of fuel products are assumed to be $1690 for the coal liquefaction plant, $490 for the coal syncrude refinery, $2590 for the coal gasification to hydrogen facility, $2520 for the hydrogen liquefaction plant, $1730 for the coal gasification to methane facility, and $340 for the methane liquefaction plant. All of these costs include a 28 percent "ownership" cost over and above the basic plant investment to cover interest during construction, working capital, start-up capital, etc. As might be expected from the energy flow analysis, a large component of the hydrogen cost is due to the electricity purchased for liquefaction, even with a comparatively modest electricity cost of 15 mills per kilowatt hour assumed in the computations. If credits are applied for the by-products, particularly the large gasoline by-product credit, costs of $8.20, $3.56, and $2.91 per million BTU are obtained for the liquid hydrogen, liquid methane, and synthetic JP respectively. These costs were developed assuming a 10 percent discounted cash flow return on investment after taxes. It has been suggested that to generate the equity required for the rapid build-up of a synthetic fuels industry might require a return of 15 percent or more [21]. In this circumstance, the fuel costs might exceed $9.00, $4.00, and $3.00 per million BTU for the liquid hydrogen, liquid methane, and synthetic JP respectively.

An important distinction should be made between the "cost" of a fuel and its "price". The costs shown in FIG. 4 represent the operator's costs plus a 10 percent return on investment; they do not necessarily reflect the price the fuel would sell for on the open market. The coal syncrude cost associated with the synthetic JP production in the example is $11.33 per barrel. The cost of the refined synthetic JP is about $.37 per gallon and the gasoline about $.33 per gallon (excluding state and federal taxes). These costs are roughly commensurate with current market prices for refined petroleum products. Thus, it seems apparent that synthetic fuels only begin to become competitive in the environment of the petroleum prices prevailing today.

Assessing the ultimate costs of synthetic fuels is fraught with uncertainties. Consequently, the sensitivity of fuel costs to some key parameters are shown in FIG. 5 and FIG. 6. It should be emphasized that the costs shown on FIG. 5 and FIG. 6 are those associated with supplying one airbase. The costs shown on FIG. 4 reflect the aggregated costs for supplying a number of airbases. Resource (coal) costs, capital investment requirements for energy conversion facilities, and the method of financing those facilities are three of the major factors influencing the synthetic fuel costs. Perhaps the most interesting cost sensitivity shown is that due to changes in capital requirements. Even with a doubling of the capital and operating costs associated with the liquid methane and synthetic JP energy conversion facilities, the liquid hydrogen alternative is still dominantly more costly. In summary, the basic conclusions about the relative costs of the three fuels remain unchanged, even with a wide variation in the key parameters. Liquid hydrogen costs are generally more sensitive to unfavorable changes in the parameters because the hydrogen production and distribution process is less efficient than the other processes.

In addition to the more obvious effects of resource costs, capital costs, financing, etc., on synthetic fuel costs, the dramatic differences in aviation fuel demands by the military during peacetime and wartime operations could have a pronounced effect on fuel costs. The costs shown in FIG. 4 are those costs associated with a fuel system operating at full capacity, assuming all the fuel produced finds a market with the Air Force and other users. However, if a fuel supply system, sized to meet a contingency or wartime requirement, was underutilized during peacetime, Air Force synthetic fuel costs could rise. The results shown in FIG. 7 apply if there were no alternative markets for the excess liquid hydrogen, liquid methane, or synthetic JP during peacetime. If such a situation prevailed, the liquefaction or refinery facility owner would have to cover his substantial fixed costs by charging a higher price for the lesser amount of liquid hydrogen, liquid methane, or synthetic JP being produced. We will consider a single airbase example to illustrate this effect.

In FIG. 7, aircraft utilization rate is used as a measure of the utilization of a fuel supply system. The fuel supply system was sized to support transport aircraft which might achieve a 10 hour per day utilization rate during a contingency situation. However, the utilization rate for such aircraft during peacetime might be closer to 1.5 to 2.0 hours per day, about the same utilization rate that is achieved with the Air Force's C-5A heavy airlifter today. The cost of the liquid hydrogen could rise dramatically at such a low utilization rate. The cost increase associated with the other two fuel alternatives is not nearly as severe because of the lower capital intensiveness of the methane liquefaction plant and the coal syncrude refinery. Furthermore, for the synthetic JP alternative, it seems far more likely that the refined syncrude products would be assimilated during peacetime into existing petroleum markets by the turn of the century.

Of course, the notion of complete reliance by the Air Force on a synthetic fuel system for its fuel needs is somewhat idealistic; and thus the potential supply of synthetic fuels and petroleum fuels in the future needs to be assessed in the context of competition for these fuels, and the extent to which these competitors could use alternative fuels if Air Force fuel requirements were to increase in a contingency situation. To cite an example, the commercial airlines might also be users of synthetic jet fuels. However, they might not qualify as interruptible users, since a significant fraction of the civil fleet might be utilized as part of the U.S. Civil Reserve Air Fleet (CRAF) during a contingency situation.

Resources

In addition to energy efficiency and cost, resource issues must also be considered, such as the rate of coal production required to support a synthetic fuels industry and the long-term availability of coal under such rates of production.

It has often been stated that at present rates of consumption U.S. coal reserves could last for hundreds of years. That is indeed the case; however, if coal is to assume a larger role in the nation's energy future, coal production will have to expand significantly. FIG. 8 shows cumulative coal production as a function of year for several annual growth rates, with a five to seven percent growth rate highlighted. It has been suggested that this rate of expansion would be required to accommodate both the coal needs of a significant synthetic fuels industry and demands by other users for coal [4]. These growth rates can be compared with several interpretations of economically recoverable U.S. coal reserves shown on FIG. 8 to estimate the time period over which coal might be available. Virtually all recoverable reserve estimates begin with United States Geological Survey (USGS) estimates of in-place coal resources and then proceed to exclude all the coal which cannot be economically recovered or which is not sufficiently well defined by mapping or exploration [1]. The National Petroleum Council (NPC) estimate includes only measured and indicated reserves above 1000 feet in thick seams [3]. The United States Bureau of Mines(USBM) further includes intermediate seam thickness coal [5]. Complete information on the Energy Research and Development Administration(ERDA) estimate is not available; however, it clearly must include some coal from the inferred reserves category as well as some coal from the unmapped and unexplored category [4].

In interpreting FIG. 8, an analogy may be drawn to the current problems being experienced with domestic petroleum production. Price and availability problems really began shortly after domestic production peaked, forcing users to search for alternative sources of energy, in this case imported petroleum. Using the USBM estimate of coal reserves, we note that one-half of the recoverable reserves could be depleted by the first quarter of the next century if the high growth rates suggested were to be sustained. From this observation we can conclude that for planning purposes there is a pressing need for a better definition of the extent of our coal resources. Further, it seems clear that aggressive development of advanced extraction techniques would be highly desirable to more completely recover the truly vast in-place resources. Finally, if coal is to be used as a hydrocarbon source for synthetic fuels over the long term, new energy technologies may be required to supplant coal's role in electric power generation to release coal for use by a synthetic fuels industry.

In addition to coal production capacity considerations, the ability and likelihood of a coal synthetic fuels industry meeting the jet fuel needs of the military and other users in the year 2000 time frame must also be assessed. Shown on the left of FIG. 9 are two estimates of what the potential synthetic jet fuel production capacity might be by the year 2000, with the uncertainty in the ultimate jet fuel yield highlighted [3,4]. These two capacity estimates should certainly be regarded as optimistic, since the Synfuels Interagency Task Force recently recommended a synthetic fuels commercialization program to the President's Energy Resources Council that would result in only 50,000 barrels per day of coal syncrude liquids by 1985, 20,000 barrels per day of which might be refined to jet fuel [21]. Clearly, to reach the production levels suggested by ERDA and NPC projections would require an enormous rate of build-up between 1985 and 2000. This conclusion is essentially unchanged when projections of high BTU coal gasification capacity are considered, the closest analogy that can be drawn to the liquid methane or liquid hydrogen supply processes [3,4,21].

These capacity estimates can be compared against overall Department of Defense(DoD) and Air Force peacetime jet fuel demands, the Air Force accounting for over three-quarters of that demand [22]. If the more modest NPC projection is used, we note that while military peacetime needs might potentially be satisfied, they would constitute a large fraction of the overall market. If Air Force jet fuel needs were to double during a wartime situation, characteristic of past Air Force experience, capacity would be taxed even more. These Air Force demands for jet fuel should also be considered in the context of overall U.S. jet fuel demands. During 1975 U.S. commercial air carriers consumed nearly double the jet fuel consumed by the military [23]. Thus it seems highly unlikely that a coal-based synthetic fuels industry could satisfy all of the demands for jet fuel in the year 2000.

The possibility of a synthetic fuels industry growing to the size indicated on FIG. 9 may be hindered by a lack of water in the arid western states which contain a significant fraction of the nation's surface mineable coal deposits [24,25]. The problem is graphically illustrated in FIG. 10, which shows the water requirements for the synthetic fuel facilities we postulated might be located near abundant coal reserves in New Mexico and Wyoming to serve western airbases. Also shown are the water requirements for the National Petroleum Council's postulated New Mexico and Wyoming coal conversion facilities. A coal liquefaction plant might consume over six barrels of water for every barrel of syncrude output [18]. However, the liquefaction plant is not inherently any more water intensive than the other facilities; the greater water requirement reflects the larger amount of energy which is delivered due to the gasoline by-product. The results shown in FIG. 10 indicate that either additional costs may be incurred to bring the water to the facilities, or additional distribution costs may be incurred to ship the coal to areas with more abundant water supplies.

Environment

The creation of a synthetic fuels from coal industry will tax not only the resource base but also the environment. In our analysis, a mix of eastern and western coal was utilized for the fuel supply systems to minimize distribution distances. Shown in FIG. 11 is the average land impact of the surface mining in Wyoming and New Mexico required to support the fuel supply systems of the three alternative aviation fuels considered [26]. The synthetic JP alternative has a greater land impact only because of the larger amount of energy being delivered. The land impact of the mining required to support the liquid hydrogen supply system reflects only the coal which must be mined to provide the resource energy for the process. If it is assumed that the process electricity for hydrogen liquefaction is also derived from coal, the land impact would be far greater than that shown in FIG. 11. The Rhode Island land area is used as a point of reference because some have suggested that an area somewhat greater than the land area of that state has been stripped and not been reclaimed in the past.

The ability to reclaim the land overlying surface mineable coal deposits in the arid western United States is the subject of considerable controversy. If the mined land could be reclaimed in five years, the average land impact could be significantly reduced, as is shown in chart 15. Some suggest, however, that reclamation may be impossible. In that situation, in an absolute sense, the total land overturned and unreclaimed would be double the unreclaimed values shown in FIG. 11.

There is quite a different land impact associated with the underground mining, that of subsidence of the undermined area. The lower bars on FIG. 11 represent the land impact associated with the room and pillar mining used to support the synthetic fuel supply systems. In room and pillar mining, the most prevalent type of underground coal mining practiced in the U.S. today, pillars of coal are left standing in the mine to reduce the amount of subsidence, with the penalty of less than complete recovery of all the coal. Increased adoption of the longwall mining technique, in which almost all the coal is removed, would enhance recovery, but with the penalty of increased subsidence, as shown in FIG. 11.

In addition to the land impact of the coal mining required to support a synthetic fuels industry, the environmental pollutants from the coal conversion facilities must also be assessed. TABLE 1 compares the environmental pollutants from a conventional coal fired steam power plant, a coal gasification plant, and a coal liquefaction facility, all sized to process an equivalent amount of coal [26]. These results must be interpreted with caution, since no commercial size gasification or liquefaction facility has yet been built in this country. The estimates of coal conversion facility pollutants indicate that the new facilities may represent no greater threat to the environment than a conventional power plant, and perhaps less. In the case of air pollutants, the new facilities would remove most of the sulfur contained in the coal from a concentrated stream of hydrogen sulfide gas, rather than "scrubbing" sulfur dioxide out of the exhaust products of coal combustion. The "sludge" which results from this scrubbing process is one of the reasons the power plant has greater solid waste products. In addition, the coal conversion facilities recover much of the nitrogen air pollutants in the form of aqueous ammonia, rather than releasing them to the atmosphere as oxides of nitrogen. It is likely that much of this pollution control technology will be incorporated in future coal-fired power plants as well.

Finally, it should be noted that, while in comparison with a coal-fired power plant, the pollutant discharges from coal conversion facilities may not represent any increased threat to the environment; these plants may be built in areas of the west which now have a comparatively pristine environment, in which case they may represent a substantial threat to the environment in a relative sense.

SUMMARY

The findings can be summarized by noting that the U.S. domestic resource base of coal is adequate to provide a significantly increasing fraction of U.S. energy needs into the next century. If portable liquid fuels derivable from coal and suitable for military aircraft are considered, a synthetic JP jet fuel similar to the kerosene- or naptha-based jet fuels in use today is the most attractive alternative. This conclusion is based on the fact that synthetic JP is less expensive to produce both in an energy and a cost sense while having attractive characteristics for aviation applications. Synthetic JP also has the advantage of being far more similar to jet fuels in use today than the other alternatives, which should ease transitional problems for military users, as well as promote its assimilation into a domestic fuels market now dominated by crude-oil-based fuels. Despite these attractive features, there are definite resource, capacity, and environmental constraints which could tend to limit the availability of synthetic JP in the future.

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TABLE 1--POLLUTANT DISCHARGE COMPARISON

FORM OF POLLUTANT	POLLUTANTS DISCHARGED* (tons/day)		
	1000 MWe COAL FIRED STEAM POWER PLANT	HI-BTU COAL GASIFICATION PLANT	COAL LIQUEFACTION PLANT
WATER	4	0 - 10	0 - 14
AIR	137	20 - 26	16 - 28
SOLID	3230	826 - 1170	722 - 1110

* Assuming facilities operating at full capacity, with equivalent coal inputs

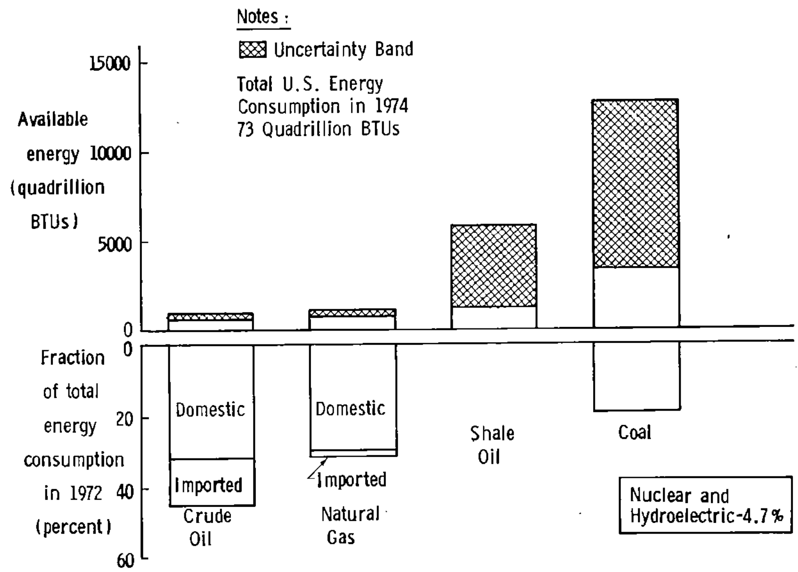

Fig. 1--Recoverable U.S. Fossil Resources

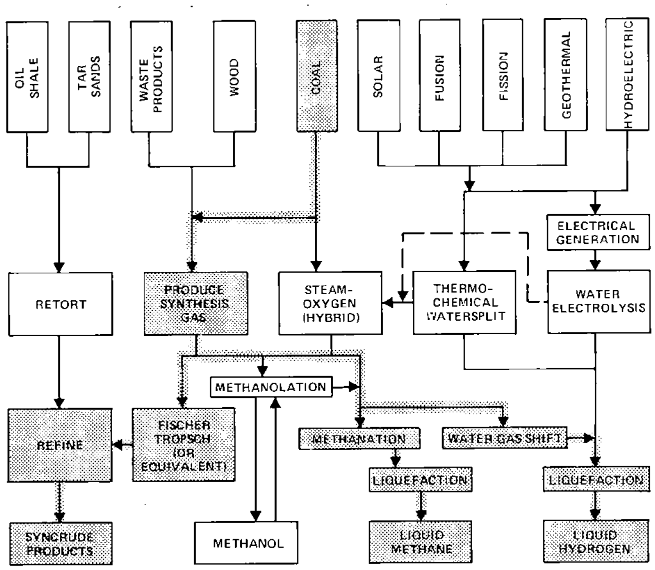

Fig. 2--Overview of Synthetic Fuel Supply Processes

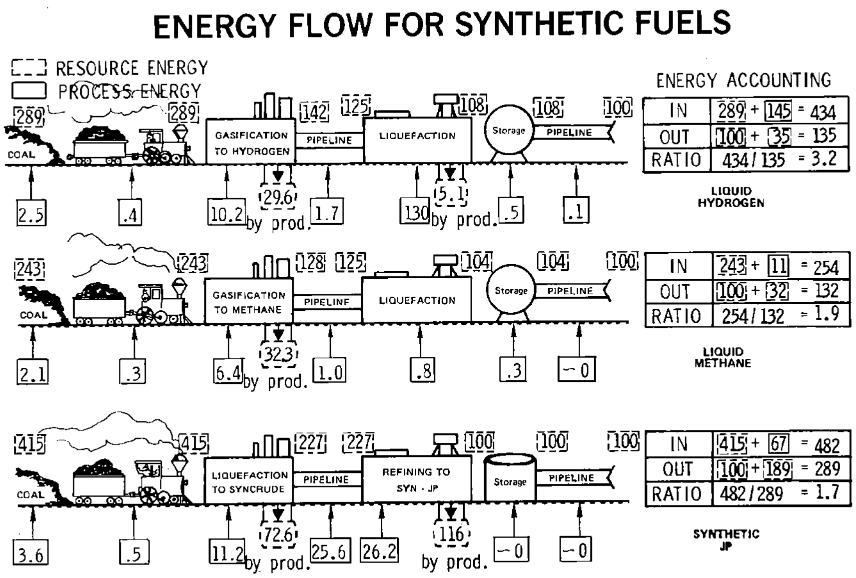

Fig. 3--Energy Flow for Synthetic Fuels

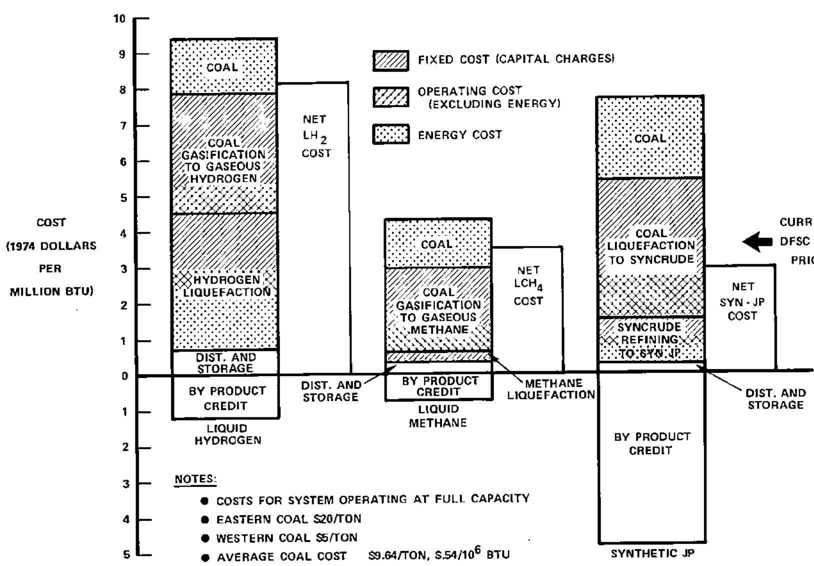

Fig. 4--Synthetic Fuel Costs

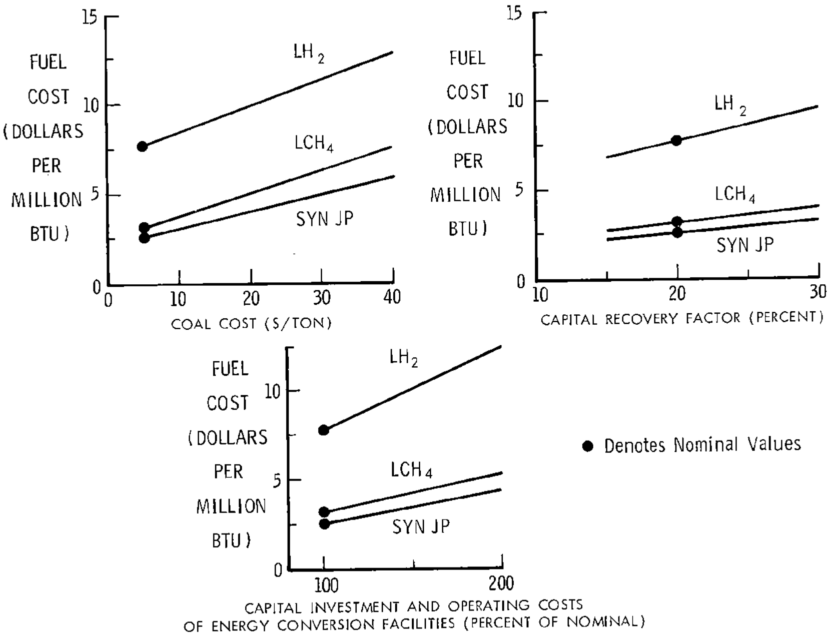

Fig. 5--Synthetic Fuel Cost Sensitivities

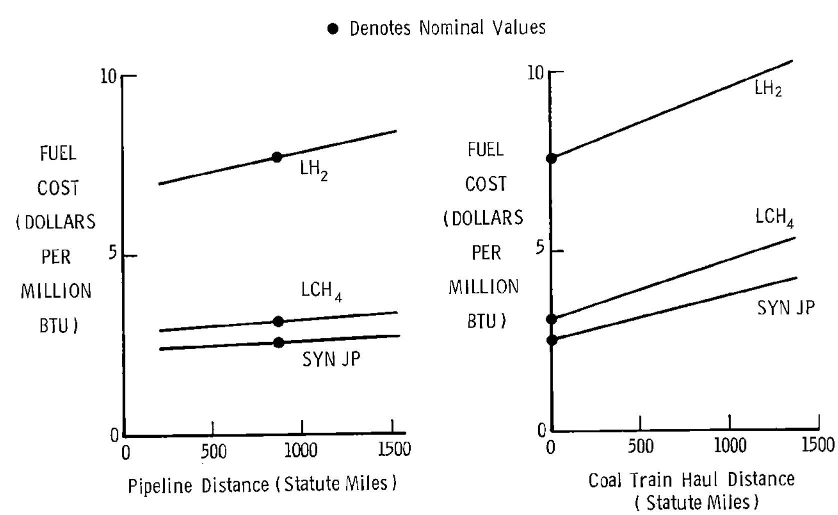

Fig. 6--Synthetic Fuel Cost Sensitivities (continued)

WLS

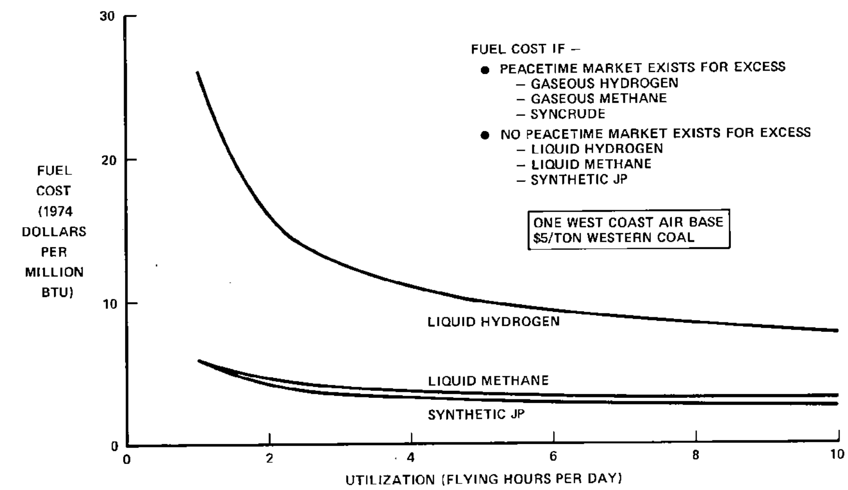

Fig. 7--The Effect of Reduced Peacetime Aircraft Utilization

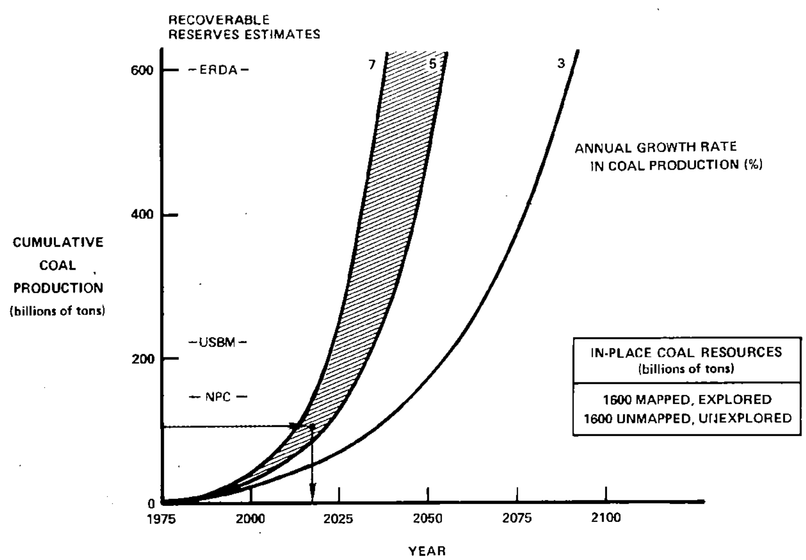

Fig. 8--U.S. Coal Resource Availability

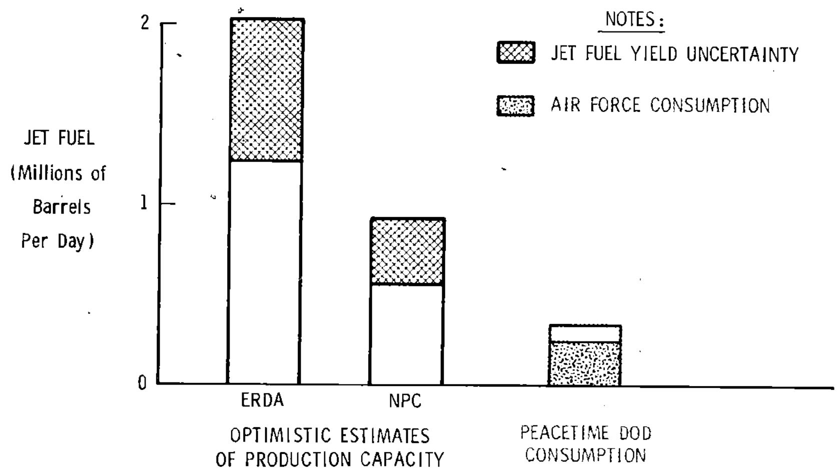

Fig. 9--Coal-Based Jet Fuel Production Capacity in 2000

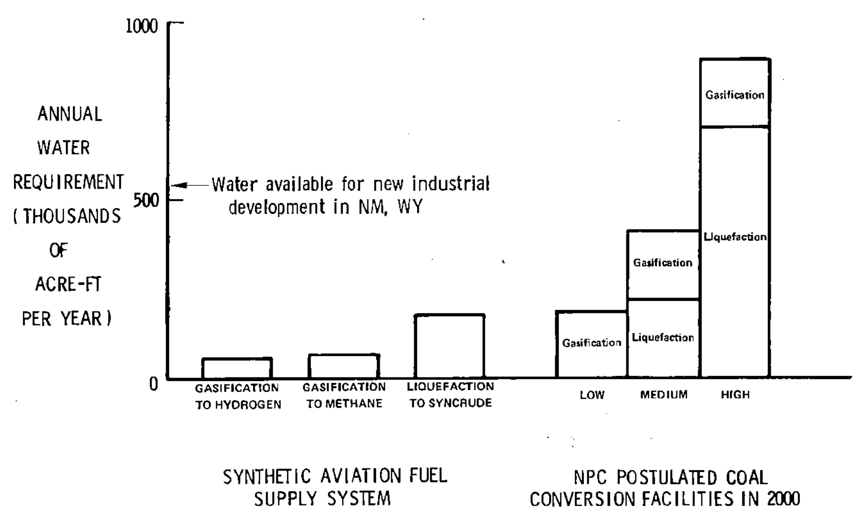

Fig. 10--Water Requirements for Coal Conversion Facilities
in New Mexico and Wyoming

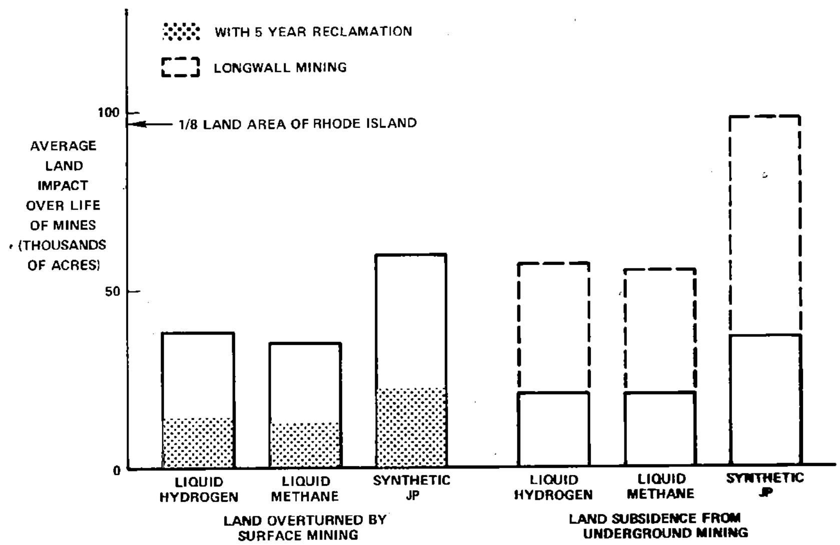

Fig. 11--Land Impact of Coal Extraction for Synthetic Fuels