Table 7

POLLUTANT DISCHARGE COMPARISON

Form of Pollutant	Pollutants Discharged (tons/day)[a]		
	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

SOURCE: Ref. 72.

[a] Assuming facilities operating at full capacity, with equivalent coal inputs.

UNCERTAINTIES IN THE EVALUATION

The assessment of fuel alternatives in this section has indicated that the production of synthetic JP requires less energy and is less costly than the other two alternatives. A related analysis of the use of the fuel alternatives in large subsonic military airplanes performing strategic airlift or station-keeping missions has indicated that for a broad class of missions, the synthetic JP alternatives would be more cost effective and energy effective than aircraft using the other fuel alternatives. Notwithstanding this fact, highlighted below are some of the uncertainties involved in the evaluation of the fuel production processes.

First, let us consider the initial coal conversion processes--coal gasification or liquefaction. It was postulated that all of the initial coal conversion processes used Lurgi technology, with the hydrogen process adding a water gas shift to enrich the gaseous product with hydrogen, the methane process adding a methanation step to enrich the gaseous product with methane, and the syncrude process using a high pressure H-Coal hydrogenation reactor to liquefy the coal using a hydrogen-rich gas produced in Lurgi gasifiers. The energy expenditures required for the Lurgi gasification process are relatively well understood, since it is a commercialized process, albeit not in the United States. However, considerable uncertainty does exist in the costs of Lurgi gasification.

The cost estimate for the high-Btu coal gasification plant being planned by the El Paso Natural Gas Company increased by a factor of five between 1973 and 1975 (then year dollars).(73) Since most of the coal gasification or liquefaction processes are sensitive to similar factors, such as costs of large pressure vessels, costs for equipment to handle and inject coal at high pressures, etc., each of the processes would probably experience similar escalations in costs for many items of equipment in the facilities. However, although it has been demonstrated quite successfully in small pilot plant operations, the H-Coal gasification reactor is still probably subject to greater uncertainties in energy requirements and costs than either water gas shift equipment or methanation equipment.

One interesting aspect in the relative comparisons between gaseous hydrogen and syncrude production processes is that about two-thirds of the plant investment for coal liquefaction by the H-Coal process is devoted to hydrogen production facilities.(46) Hence, it seems likely that any major technological advances that help reduce the costs or energy requirements for the production of hydrogen from coal will also directly benefit coal syncrude production, and possibly even syncrude refining, if supplemental gaseous hydrogen is required.

Of the second-stage energy conversion facilities, large-scale methane (or natural gas) liquefaction is probably the best understood. The refining of crude oil is also a mature, well-understood technology. One major uncertainty about coal syncrude refining centers on determining the optimum tradeoff between reducing the aromatic content of coal liquids at the refinery, or designing jet engines to use fuels of higher aromatic content. Hence, the basic technology elements to refine coal liquids exist on a commercial scale, with the definition of the mix of technologies to be used and the degree of processing desirable still to be specified.

Considerable experience has also been accumulated in liquefying gaseous hydrogen for the space program. However, production has been on a scale that is only a fraction of that required for aviation applications. Hence, while costs and energy expenditures for current small liquefaction facilities are relatively well understood, the costs and energy requirements for larger facilities, and particularly the prospects for achieving the improvements in liquefaction efficiency already noted (including evolving improvements in electric power generation), are subject to considerable uncertainty.

Little uncertainty exists about the distribution system for synthetic JP. Today both crude-oil products and refined products are routinely distributed via pipelines; much the same is true of liquid methane, since natural gas (high in methane) is widely distributed in the United States; liquid natural gas is also routinely loaded and unloaded from tankers. Of course, modifications would be required for high volume throughput operations at airports.

In contrast to the other two alternatives, gaseous hydrogen is not routinely distributed long distances via high pressure pipelines. The literature suggests that no existing gaseous hydrogen pipelines have intermediate compressor stations,(21) hence, the economics and energy intensiveness of gaseous hydrogen pipelines are certainly subject to greater uncertainty than the other alternatives. Similarly, while a quarter-mile liquid hydrogen pipeline is used at the Kennedy Space Center for fueling space launch vehicles,(61) high volume distribution and fueling of aircraft with liquid hydrogen are subject to considerable uncertainty. The NASA Langley Research Center is currently attempting to resolve some of these questions about ground handling of liquid hydrogen at airports.(74-76)

Aside from uncertainties in the costs and energy requirements for energy conversion and distribution facilities, there seems little question that the domestic coal resource base is adequate to support production of any of the alternatives. However, the rate at which synthetic fuels will be introduced in the United States will depend not only on the development of the technology and the resource base, but also on a complex set of interrelated factors including national energy policies, world oil prices, the resolution of environmental and water availability issues, and the availability of investment capital. These considerable uncertainties exist and would tend to have an impact upon the development of any of three aviation fuel alternatives being evaluated.

RESEARCH AND DEVELOPMENT AREAS

The previous subsections have indicated that synthetic JP derived from coal would be less expensive to produce than the other alternatives both in an energy and in a cost sense and would have attractive characteristics for aviation applications. Synthetic JP also has the advantage of being far more similar to jet fuels in use today than the cryogenic alternatives, which should ease transitional problems for military users and promote its assimilation into a domestic fuels market now dominated by crude-oil-based fuels. What R&D areas, then, would have to be pursued if the Air Force is to prepare itself to exercise this fuel option in the future?

Table 8 highlights in very broad terms some of the key R&D activities that would be required to develop coal as a future source of jet fuels, with an indication of those agencies within the federal government that might sponsor the R&D either solely or in cooperation with the private sector. The three broad R&D areas address the central question: Do technology and economics dictate that major emphasis be placed on developing coal liquefaction and refining technologies to produce jet fuels that meet or approach current jet fuel specifications, or that jet engines be designed to operate efficiently on a wider range of possible fuels?

The items noted under liquefaction technology mainly refer to the progressive development from pilot-plant-size coal liquefaction facilities to demonstration-size facilities to define the economics, energy requirements, and environmental impacts of the candidate coal liquefaction technologies. This work clearly falls within ERDA's R&D charter and responsibilities. However, an inevitable part of this program would be an evaluation of the suitability of the various synthetic crude oils obtained from the different liquefaction technologies for alternative applications, including feedstocks for jet fuel production. Such a program would be required to ensure that the proper mix of technologies is developed to help meet the spectrum of civilian and military fuel needs in the future. Large quantities of coal synthetic crude oils will be required for refinery tests and subsequent full-scale engine tests for NASA and the DoD, including the Air Force, to

Table 8

R&D FOR THE SYNTHETIC JP OPTION

	Potential Sponsors				
Technology	ERDA	NASA	DoD	AF	Private Sector
Liquefaction Technology					
Establish sustained process feasibility	X				X
Identify most suitable refinery feedstocks	X	X	X	X	X
Determine feasibility and economics of large-scale operations	X				X
Refining Technology					
Improve catalyst technology		X	X	X	X
Determine optimum combination of catalysts and operating conditions		X	X	X	X
Establish jet fuel yield potential		X	X	X	X
Determine feasibility of large-scale refining of syncrude	X				X
Engine Technology					
Advance engine technology to allow relaxation of fuel specifications		X	X	X	X
Determine modifications for existing engines to use such synthetic fuels		X	X	X	X

determine the most suitable feedstocks for jet fuel production. Because ERDA has responsibility for developing and demonstrating coal liquefaction technologies, NASA and the DoD will be dependent upon ERDA to assure them of adequate supplies of coal syncrudes for R&D purposes.

The second broad technology area concerns defining the process requirements and economics of refining coal syncrudes into jet fuels. To do so will require identifying the most suitable catalysts and operating conditions for economically refining coal syncrudes. This work is currently being accomplished on a laboratory scale, the current activities already having been described. However, ultimately, the feasibility of coal syncrude refining will have to be demonstrated on a larger scale, perhaps under ERDA sponsorship in cooperation with the major oil companies.

The last category involves determining the financial, physical, and chemical effects of coal-derived jet fuels on military jet engines and fuel systems. If the commercial economics and technological difficulty are such that jet fuels refined from coal syncrudes will necessarily be higher in aromatic content than the jet fuels of today, then the engine designer must consider whether there are technological options available that would allow military engines to use fuels of higher aromatic content. For example, changes in combustor designs, fuel pumps, and fuel tank seals may be required to cope with fuels of higher aromatic content. To address these issues, the Air Force Aero-Propulsion Laboratory is currently using crude-oil-based jet fuels mixed with additives to imitate the characteristics of coal-derived jet fuels as well as using limited quantities of coal-derived jet fuels refined in laboratories. However, ultimately, large quantities of coal-derived jet fuels will be required for the full-scale tests that will determine the long-term effects of these fuels on military jet engines.

For several reasons, it does not seem at all clear that the Air Force can rely on NASA or on the other military services to accomplish the R&D necessary to develop the capability to use jet fuels derived from coal. First, the Air Force has been designated as the lead service for the development of improved aircraft turbines that may have to operate using synthetic jet fuels in the future. NASA emphasis on a synthetic jet fuel technology might focus on those economic issues to which the airlines are most sensitized. A fuel and engine technology developed for subsonic commercial applications might not meet high-performance military mission requirements. Finally, there is still some limited sentiment within NASA that the aviation fuel of the future is liquid hydrogen. From a military perspective, this does not appear to be a viable option. Hence, it would seem that the Air Force would have to assume at least part of the R&D burden if synthetic JP from coal is to be a viable jet fuel option for the military in the future.

The Air Force is entering an era when the economics and availability of jet fuel will be less certain than they have been in the past. The Air Force may have to use jet fuels derived from a variety of primary energy resources, including crude oil, coal, and oil shale. The capability to use a variety of fuels may be one way in which the Air Force can maintain the operational flexibility that it has enjoyed in the past when fuel availability and economics were less of a problem.

The next section delineates the conditions under which it would be to the Air Force's advantage to acquire a multifuel propulsion capability and quantifies some of the possible benefits from having that capability. The R&D planner can then measure these benefits against his expectations of the costs of developing multifuel technology, some of those technology items having been highlighted in Table 8.

IV. POTENTIAL BENEFITS FROM DEVELOPING A MULTIFUEL PROPULSION CAPABILITY FOR FUTURE AIRCRAFT

INTRODUCTION

In the previous section, we indicated that coal and oil shale could be attractive domestic energy resource alternatives to crude oil for the future production of jet fuels. A synthetic JP fuel appears to be the most advantageous form derivable from these resources for use by the military. Synthetic JP fuels may have somewhat different characteristics than current petroleum jet fuels. The degree of difference will depend on the costs and technological difficulties of refining synthetic crude oils compared with the costs and technological difficulties of designing engines that could use broader specification jet fuels. Hence, R&D will be required to develop a multifuel propulsion capability (e.g., the capability of using fuels derived from crude oil, oil shale, or coal), with the ultimate balance between emphasis on refining or on engine technology yet to be determined. Ability to use a variety of fuels might significantly enhance the flexibility of the military because the Air Force would no longer have to depend on a single energy resource (e.g., crude oil) for future jet fuels. Of course, for the most part, such a capability would be valuable only if a synthetic fuels industry develops in the United States. The analysis presented in this section indicates a strong likelihood of this occurring sometime between 1990 and 2025, with the switch from crude-oil-based aviation fuels to coal- or oil-shale-based fuels in this time period being dictated by comparative economics rather than by a total lack of availability of crude oil.

At the present time, it is too early to tell how much it would cost to acquire the capability to use a variety of fuels. Nonetheless, the probable state of the geopolitical imbalance of crude-oil reserves at the turn of the century, in conjunction with the lead time required to develop and phase in new propulsion technologies, suggest that advanced basic research on the concept should start now. In the previous sections, we indicated that part of this R&D burden would probably have to be assumed by the Air Force, a major domestic consumer of jet fuel, to assure a suitable fuel for use in military engines.

The analysis developed in this section indicates that in addition to the benefit of flexibility in wartime, there may be, under certain circumstances, a peacetime economic benefit associated with possession of a multifuel propulsion capability. Although the potential economic benefits from such a capability are extremely difficult to predict because of the future uncertainty associated with world and domestic prices for fossil resources, determination of potential benefits will, nonetheless, be the principal objective of this section. Specifically, we will seek to determine under what conditions an Air Force R&D investment in multifuel propulsion technology might result in an economic benefit.

Background

The life cycle through which a propulsion technology advancement evolves can last from 25 to 50 years. For example, it is not infrequent that a 5 to 10 year basic research effort precedes a 5 to 7 year engine development program, which then results in a 5 to 15 year production run of a family of engines, each of which has a 10 to 15 year life of operational usage, resulting in a total cycle of 25 to 47 years. Therefore, if a new propulsion technology is desired for aircraft operating around the year 2000, it is not unreasonable to expect that basic research should commence in the 1970s.

The Air Force Aero-Propulsion Laboratory has already initiated some limited research on the use of oil shale and coal as sources for future aviation fuels. Although NASA and the Air Force Aero-Propulsion Laboratory have undertaken a joint 10 year, $8 million study of synthetic aviation fuels derived from both oil shale and coal, they are placing a significant emphasis on oil shale. The emphasis on oil shale may in part be due to budget limitations. Although the research thus far has been promising, major questions still exist regarding the financial, physical, and chemical effects of synthetic fuels on jet engines and refinery operations. The problems posed by the characteristically high aromatic content of synthetic fuels (causing increased combustor liner temperatures, greater smoke emissions, larger infrared signatures, etc.) and their high nitrogen content (causing catalyst poisoning in some refinery processes) need to be resolved. Furthermore, questions about ignition, thermal stability, material compatibility, etc., need to be explored. A significant amount of additional basic research will probably be needed; against the cost of that research, we can weigh the military value of the capability to use a variety of fuels and the potential economic benefit.

General Approach

The economic benefit that may ultimately be attributed to an R&D investment in the development of a multifuel propulsion capability will be influenced by three principal factors: (1) the resolution of a complex set of national energy policy issues; (2) the depletion of our domestic crude-oil reserves; and (3) the future price levels for crude-oil imports. Each of these factors is systematically considered in our assessment. For a given assumption about each of these factors, the economic benefit is assessed in terms of the cost avoidance opportunity that would be offered by the multifuel propulsion capability. If the Air Force were able to use a variety of fuels by 1995 (actually, some aircraft might be converted prior to 1995, others after 1995), then they could buy the cheapest jet fuel available that year rather than being forced to buy a perhaps more expensive crude-oil-based jet fuel.

For example, our analysis indicates that in the year 2000 the Air Force might spend $2 billion for jet fuel (1974 dollars) if they depended solely on jet fuels obtained from crude oil. On the other hand, if the Air Force could buy the cheapest fuel then available (whether derived from crude oil, coal, or oil shale), then they might spend only $1.6 billion annually on fuel. The cost avoidance attributable to the multifuel engine technology in the year 2000 would then be $0.4 billion (1974 dollars).

Data Sources. Principal data used in the analysis were extracted from the Stanford Research Institute (SRI) decision analysis that supported the President's Synfuels Interagency Task Force Report.(29)

The national energy policy scenarios formulated by ERDA were used as a representative set of possible national energy policies.(17) Data from the United States Geological Survey (USGS) were used to represent the alternative expectations of recoverable crude-oil resources in the United States.(77) And finally, although the Air Force annual consumption of jet fuel was assumed to remain constant at its current peacetime level of 3.9 billion gallons per year,[*] the results of the analysis are presented in such a way that they can be linearly scaled to other consumption levels.

It might be appropriate to consider reduced fuel consumption levels during peacetime, in light of the current trend towards decreasing fuel consumption as prices escalate and additional flight simulators become available. To the extent that such a trend continues in the future, the assumption that fuel consumption remains constant over time might cause the fuel cost avoidance potential to be overstated. Thus, if one believes that the Air Force's fuel consumption during peacetime might be reduced by 50 percent by the turn of the century, then one should correspondingly reduce the calculated cost avoidance by 50 percent.

The Model. Previous research has not been oriented toward forecasting jet fuel costs over the time scale of interest in this study. As a consequence, we employed a model developed at Rand(78) that uses an approach similar to that of the Brookhaven National Laboratory energy model, used in the development of ERDA's national energy policy scenarios.(79) The model used in our analysis, however, emphasizes the refinery sector and the temporal evolution of the U.S. energy system, whereas the Brookhaven model is a static model that does not consider the depletion of resources over time. The primary function of the model we used is to track the depletion of domestic resources by extraction cost categories ($6 per barrel of oil, $23 per barrel of oil, etc.), which enables a projection to be made of the cost of producing jet fuels from the primary fossil resources of interest.

It was our initial belief (subsequently indicated by our analysis) that a projected increase in extraction costs for domestic crude oil

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[*] Reference 5 and personal communication from William Vance, Defense Energy Information Service, October 1975.

from the current average of about $6 per barrel to costs in excess of $20 per barrel might provide an economic stimulus for the development of a synthetic fuels industry in the United States, which could ultimately lead to the near total replacement of crude oil as a liquid fossil fuel resource.

Because our model is relatively inexpensive to run, we were able to explore the sensitivity of future jet fuel production costs to a wide range of factors. This was accomplished by systematically combining a set of forecasts of future crude-oil import prices with alternative national energy policies and with a set of assessments of domestic crude-oil and natural gas reserves in order to simulate the range of alternative paths over which the United States energy system might evolve. For each simulation, the model was given a forecast of crude-oil import prices, a national energy policy scenario, an assessment of domestic fossil resources, and an assessment of the assumed demand for energy as a function of time, with the price elasticities of energy demands considered exogeneous to the model. The model, through a linear programming approach, then explicitly adjusts the rate of addition of energy conversion facilities (e.g., refineries, power plants) and the rate of resource depletion in order to minimize the cost of satisfying U.S. energy demands over the next 60 years. Hence, the decision to commercialize a given technology (e.g., production of synthetic fuels from oil shale) and interfuel substitution decisions (e.g., derivation of jet fuel from crude oil or from oil shale) are predicated on which technology minimizes the 60 year life cycle cost of satisfying U.S. energy demands. Because the model simulates the consumption of domestic resources over time, increases in resource extraction costs over time can be observed as consumption patterns force the U.S. energy system to resort to more expensive extraction methods (e.g., deeper wells).

<u>The Economic Benefit Attributable to the R&D Program</u>. For a given combination of national energy policy, crude-oil import price forecast, and assessment of domestic resources, the costs of producing jet fuels from crude oil, oil shale, and coal were estimated as a function of time. Then for each year commencing with 1995, the Air Force's

annual expenditure for jet fuel was estimated for two alternative cases. In case 1, the Air Force could procure only a jet fuel derived from crude oil, and in case 2, the Air Force could procure the least expensive jet fuel as derived from crude oil, coal, or oil shale. At worst, the annual expenditures for case 2 would be the same as for case 1 (e.g., if crude oil were the least expensive alternative). However, in those years when it would be cheaper to produce aviation fuel from coal or oil shale, there would be a net cost avoidance for case 2. This cost avoidance is the economic benefit that would be attributable to the R&D program (recall that there are other benefits, for example, enhanced military flexibility).

The economic benefit of the R&D program will be assessed in two steps. In the first step, the focus is principally on the cost of producing the alternative aviation fuels. Market price-setting mechanisms are then treated briefly in the second step, where the Air Force's market share is evaluated.

We begin the next subsection with a nominal projection of future jet fuel costs based on: (1) the ERDA synfuels scenario, (2) the nominal forecast for crude-oil import prices, and (3) the nominal assessment of the domestic fossil fuel resource base. These fuel cost projections are then used to assess the economic benefit attributable to a multifuel propulsion capability. The sensitivity of the economic benefit to other scenarios and resource cases (Fig. 34) is then addressed. The other scenarios include a baseline case with no major technology initiatives, a scenario in which improvements are made in the devices that use energy (e.g., autos, airplanes) a scenario in which breeder reactors constitute a major source of energy, plus various combinations emphasizing more than one technological approach. Since the foregoing aspects of the benefit assessment are by and large a cost analysis which does not purport to take into account marketplace supply and demand pricing, a limited attempt is then made to examine the sensitivity of the Air Force's crude-oil market share to the scenarios described above. Finally, the section is concluded with a summary of our observations.

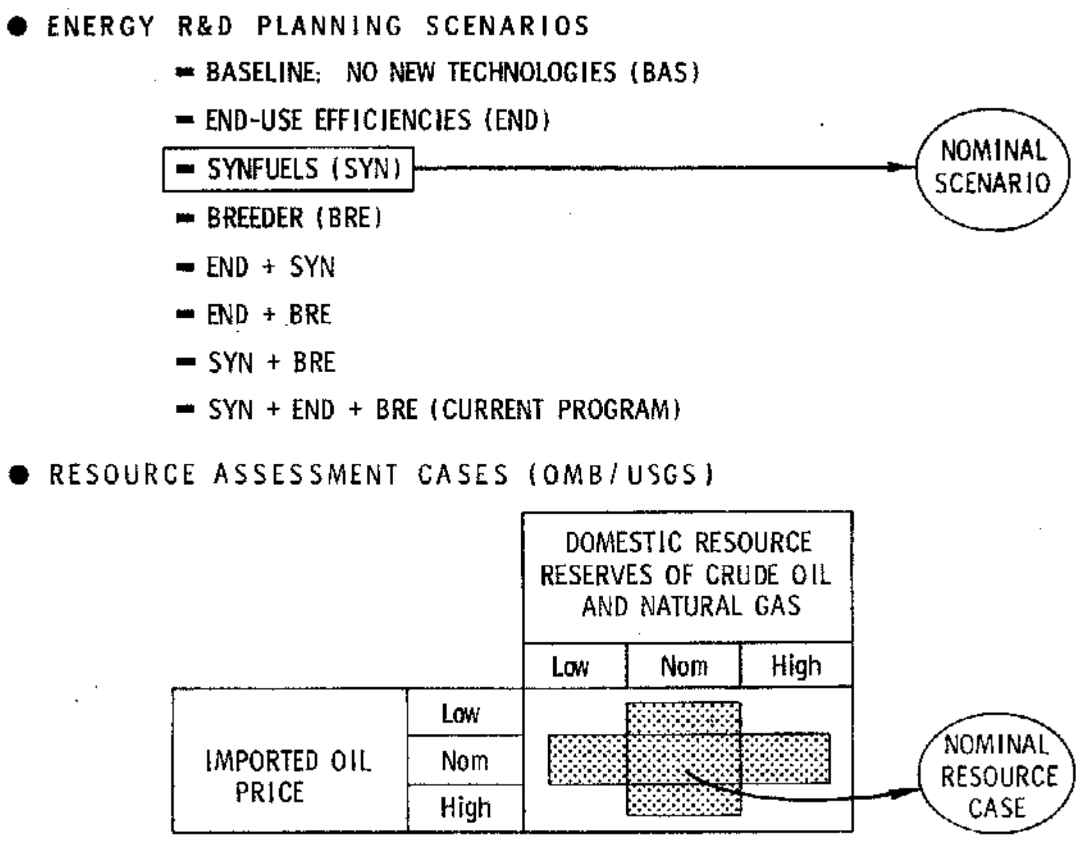

Fig. 34—Scenarios and resource cases (from Refs. 17, 29, and 77)

PROJECTION OF JET FUEL COSTS

We now make projections of the comparative cost of producing jet fuel from crude oil, coal, and oil shale, given: (1) a nominal assessment of the domestic availability of those resources, (2) the ERDA synfuels scenario as the national energy policy guideline, and (3) a nominal forecast for crude-oil import prices.

Data Sources

National Energy Policy. The ERDA synfuels scenario(17) is based upon the assumption that the United States aggressively pursues the research, development, demonstration, and commercialization of coal gasification liquefaction and oil-shale liquefaction in order to provide a lower-cost alternative to crude oil as a liquid fossil fuel resource. This scenario would have the effect of slowing down our rate of consumption of crude oil in the low extraction cost category, thereby forestalling the need to resort to the extraction of higher cost crude-oil reserves.

Domestic Resource Base. The domestic resource assessment used in this section is a nominal estimate of the total resources that could be extracted at various costs (Fig. 35(a)). This assessment is based on the nominal estimates for demonstrated and inferred reserves reported in the President's Synfuels Interagency Task Force Report,(29) adjusted to include the expected undiscovered reserves estimated by the USGS.(77) The low and high estimates of domestic crude-oil reserves illustrated in Fig. 35(a) are considered in a subsequent sensitivity analysis.

The domestic resource extraction costs in Fig. 35(a) are for the resource delivered to the minemouth in the case of coal, the wellhead in the case of crude oil, and the wellhead in the case of *in situ* extraction of oil shale (or the output from the retort facility if it is mined). To facilitate comparisons, the resource supply costs are expressed in terms of the cost of a quantity of energy equivalent to that contained in a barrel of crude oil.*

Coal is the least expensive domestic resource on the basis of extraction costs per unit of energy as presented in Fig. 35(a). However, observe that raw coal is quite unsuitable for input to a refinery, whereas the shale oil is just one upgrading step away from being a comparable replacement for crude oil. When the cost of liquefying the coal is taken into account, the difference in cost between the shale oil and coal (shown by the curves in Fig. 35(a)) is altered substantially.

For our purposes, it is useful to present data on the cost of domestic resource extraction as a function of the cumulative consumption after a fixed point in time, as in Fig. 35(a). For example, the USGS estimated that the United States had somewhere between 50 and 150 billion barrels of oil that could be extracted at a cost of about $6 per barrel, as of the end of 1974.(77)

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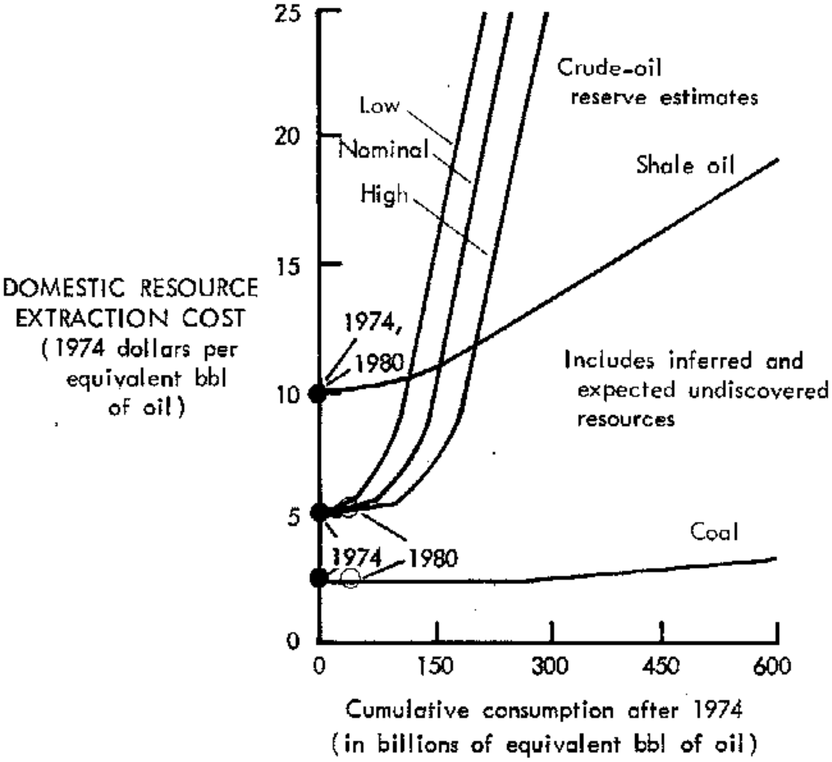
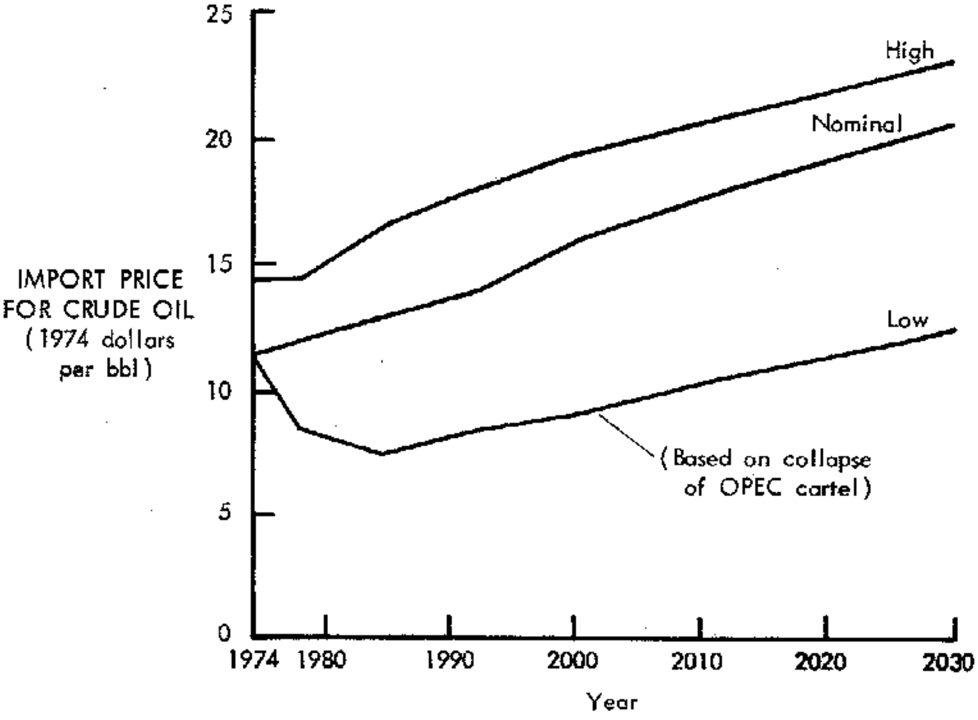
*A barrel of crude oil has an energy content of about 5.55 million Btu.



(a) Domestic resource extraction
(from Refs. 29 and 77)



(b) Import price for crude oil (from Ref. 29)

Fig. 35 — Resource assessment cases (model input)

Crude-Oil Imports. The data for crude-oil imports (Fig. 35(b)) could not be obtained on a basis comparable to that shown in Fig. 35(a) because of (1) the uncertainty about the extent of foreign reserves, (2) the extent to which nations other than the United States will deplete these reserves, and (3) the difficulty of predicting the future geopolitical conditions under which we might import crude oil. In view of these factors, we had to resort to using a range of subjective assessments of the future trend of the import price of crude oil as a function of time (see Fig. 35(b)). These assessments were formulated from the inputs of a number of government and industry experts who participated in the Synfuels Interagency Task Force study.(29) The nominal curve in Fig. 35(b), which is the basis for the jet fuel cost projections made in this section, reflects the assumption that the Organization of Petroleum Exporting Countries (OPEC) cartel remains an effective price-setting organization. The bottom, or low curve, on the other hand, reflects the price levels that might prevail if the price-setting effectiveness of the cartel were significantly weakened or collapsed. The upper curve shows the effect on the cost of oil if the price-setting effectiveness of the cartel were strengthened and could thereby extract an even higher price for crude oil.

The import price trends in Fig. 35(b) are extracted from the results of a decision analysis conducted by the SRI group which provided a principal input to the President's Synfuels Interagency Task Force Report.(34) The data in Fig. 35(b) in effect represent the spectrum of future events in terms of three scenarios: (1) an even stronger cartel; (2) survival of the current cartel's strength; and (3) a significantly weakened cartel. The experts who participated in the SRI decision analysis assessed the relative probability for these scenarios at: (1) a 0.25 probability for the first scenario (represented by the upper curve in Fig. 35(b)); (2) a 0.25 probability for the continuance of the current cartel's strength (represented by the nominal curve); and (3) a 0.5 probability for the weak cartel scenario (represented by the low curve).(34)

Projections of Resource Consumption

Given the nominal assessments of resource supply cost as a function of year in the case of imports, and as a function of cumulative consumption in the case of domestic resources, the next step is to determine the consumption patterns over time for the domestic fossil resources of interest. This was done with a model that simulates the evolution of the U.S. energy system and the consumption of our domestic fossil resources.(78) The resulting resource consumption pattern is depicted in Fig. 36, in terms of the cumulative consumption of resources after 1974 for coal, shale oil, and crude oil. (Again, the units are in terms of the equivalent energy content of a barrel of oil).

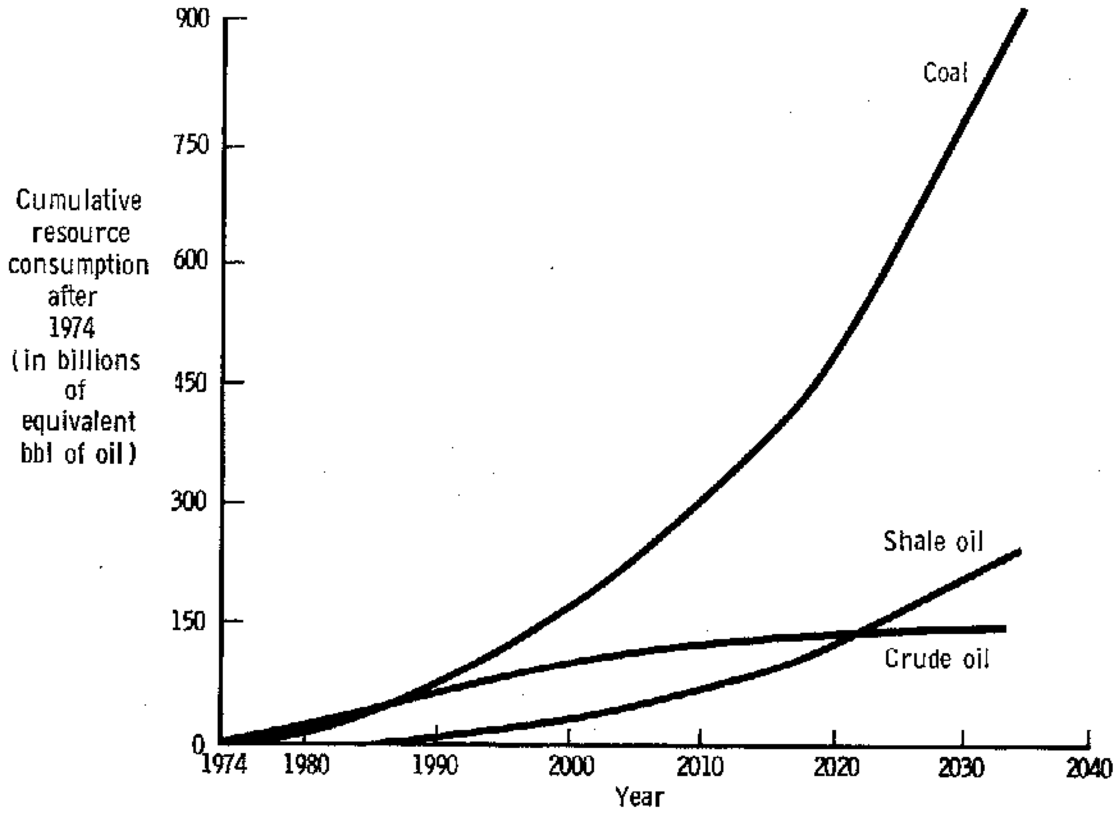


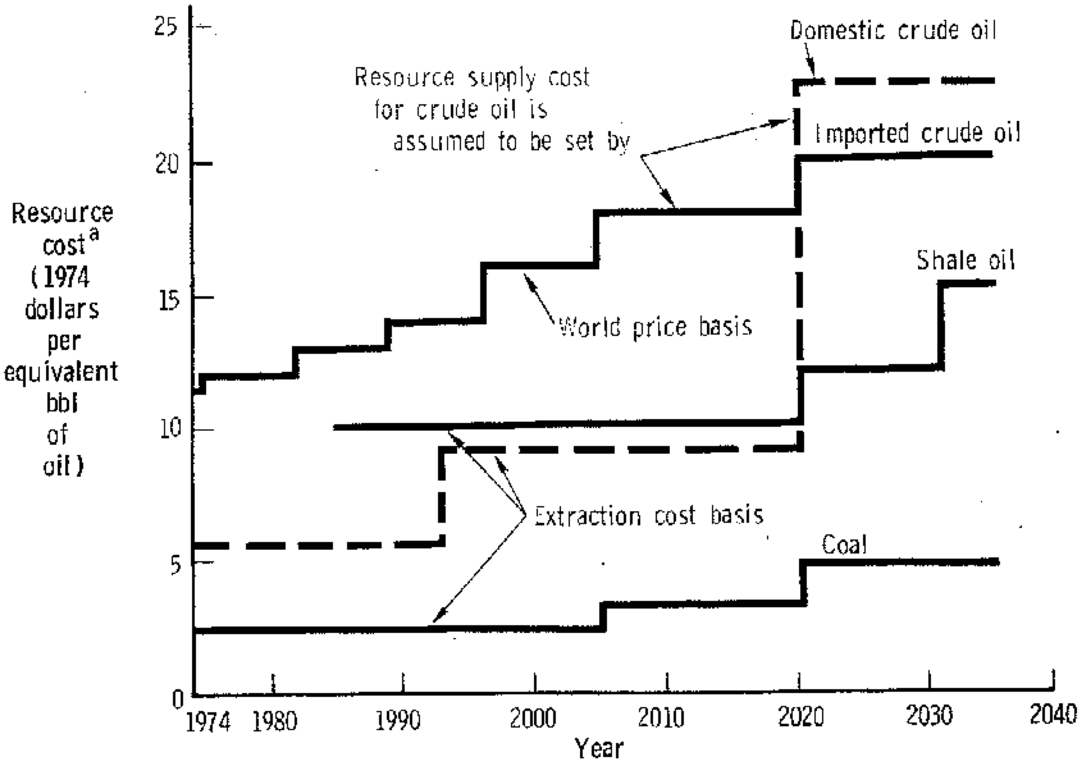
Fig. 36—Projection of cumulative consumption of domestic fossil resources

In a given year, the slope of each curve in Fig. 36 indicates the corresponding annual consumption rate. For example, the slope of the curve showing cumulative coal consumption becomes quite steep after 1990 in contrast to the slope of the crude-oil curve, which begins to flatten out. By 2020, the annual production of crude oil has become virtually nonexistent. The reason for this shift from consumption of crude oil to consumption of coal and oil shale can be discerned from Fig. 35(a) by observing the relative shapes of the curves showing domestic resource extraction costs. Once the knee in the crude-oil curve is encountered, there is significant economic pressure to replace crude oil with coal or oil shale. As the extraction costs for crude oil continue to increase, that resource becomes less and less desirable as a primary energy resource, and eventually all energy users switch to other primary energy sources, such as coal, oil shale, or uranium.

From a military point of view, it might seem beneficial if everyone else switched to coal or shale oil, simply leaving the remaining crude-oil reserves for the military to use. However, our results indicate that by the time other users shift to coal and shale oil, the crude oil in the lower extraction cost category would have been depleted, leaving only more costly crude oil for military use (see Fig. 37).

Projection of Jet Fuel Production Costs

Resource Costs for Jet Fuel Production. The primary energy resource cost projections in Fig. 37 are based on the cumulative consumption trends of Fig. 36 and the resource supply costs of Fig. 35. The imported crude-oil price curve is taken directly from Fig. 35(b). The other three curves (for domestic crude oil, shale oil, and coal) are developed from the simulation by simply combining the information in Figs. 35(a) and 36. The steps in Fig. 37 for the latter three curves represent increases in the extraction cost for the corresponding domestic resources. For example, by the early 1990s, all of the domestic oil that could be extracted for $6 per barrel will have been depleted, thus causing a shift to the extraction of oil at the $9 per barrel level. Similarly, there is another shift to the $22 per barrel



[a]Costs for domestic crude oil at the wellhead, coal at the minemouth, shale oil at the wellhead for *in situ* extraction or output from the retort facility for surface operations, imported crude oil at U.S. ports.

Fig. 37 — Resource costs for jet fuel production (data on imported crude oil from Ref. 29)

category in the year 2020. It is this latter shift that drives the remaining crude-oil users to an alternative primary energy resource, such as coal or oil shale.

Of course, actual shifts in extraction costs are more evolutionary than the discrete shifts depicted in Fig. 37. However, the figure does illustrate the two fundamental facts: (1) as resource consumption continues, extraction costs increase (especially for crude oil, since it is in much shorter supply); and (2) higher costs for crude oil drive energy users to other primary energy resources. Again, the data in Fig. 37 are presented in terms of costs per unit of equivalent energy in a barrel of oil.

Impact of Resource Costs on Production Costs. Figure 38 depicts the relationship between jet fuel production costs and the resource supply costs for the three primary energy resources of interest.(79,80) On each of the three curves, there is a benchmark (the solid circle)

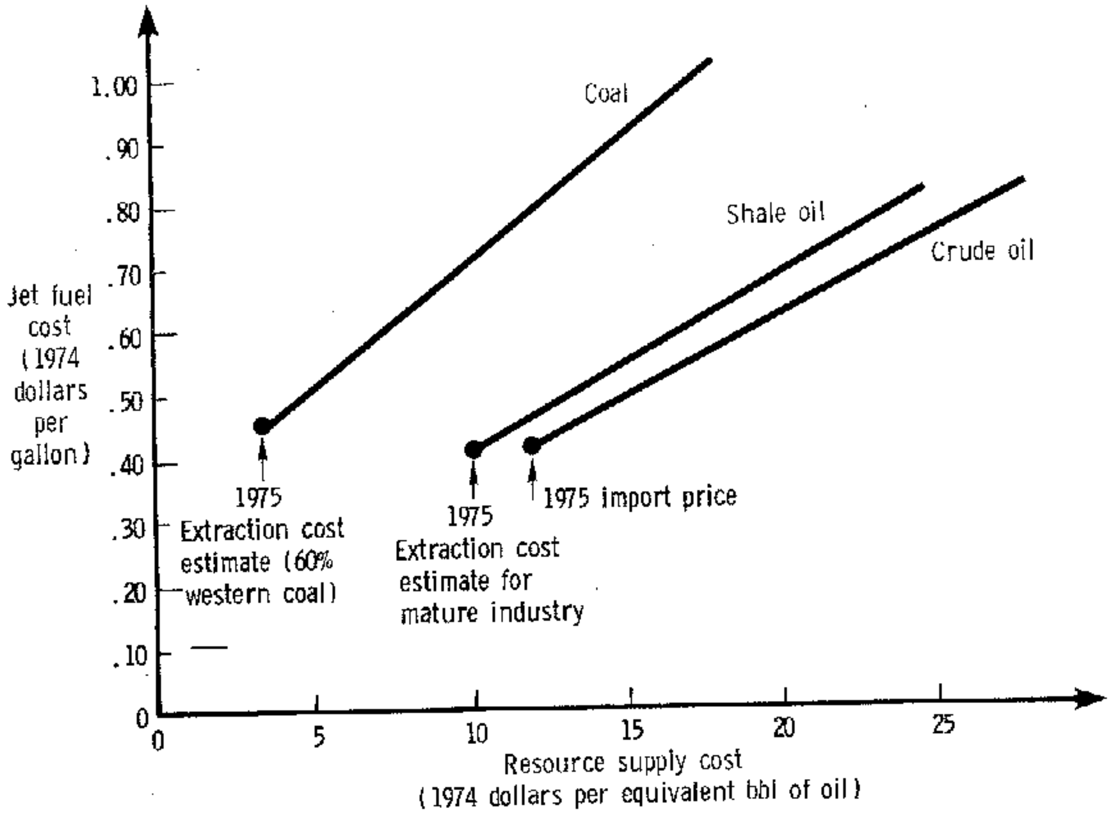


Fig. 38—Jet fuel production costs (from Refs. 79 and 80)

that indicates what the current production cost would be if the indicated primary energy resource were being used today to produce jet fuel. Since jet fuel is produced exclusively from crude oil today, the benchmarks for the coal and shale oil curves are hypothetical. Nonetheless, they indicate that at current resource supply cost levels, jet fuel could be produced for roughly the same cost from any one of the three alternatives (i.e., coal, shale oil, or crude oil). Thus, the relevant question is: *How rapidly will the resource supply cost escalate over time for the three primary energy resources*? That question was answered directly in Fig. 37 for coal and oil shale.

However, in the crude-oil case, the issue is complicated by the appearance of two resource supply cost curves in Fig. 37. In Fig. 38, we assumed that the crude-oil resource supply cost is based upon the import price for crude oil in 1975. As long as the United States requires crude-oil imports to supplement domestic crude-oil production, the marginal price of imported crude oil should set, or exert a strong influence on, the resource supply cost for jet fuel production.* Of course, strictly speaking, this is the case only for a free market, which does not wholly exist in the United States today because of price controls on domestic crude oil. However, under the current decontrol program, the government is in the process of allowing the price of domestic crude oil to rise to an uncontrolled level that will, in all likelihood, be close to the import price level. Thus, in determining the cost of producing jet fuel from crude oil, it seems reasonable to use the import price as the basis for the crude-oil resource supply cost.

Jet Fuel Production Costs. Although it is more expensive to produce jet fuel from coal than from crude oil for a given resource supply cost† (Fig. 38), we found in Fig. 37 that the resource cost for coal is much lower than that for crude oil, and therefore we find in Fig. 38 that for certain combinations of coal and crude-oil resource supply costs, jet fuel produced from coal could be less costly than a similar jet fuel produced from crude oil. Note that our results indicate that there are intervals of time (Fig. 39) during which jet fuel produced from oil shale might be less costly than that produced from coal and vice versa. Considering the level of uncertainty of the analysis, the relevant observation about Fig. 39 is not, however, that small differences in production costs may exist between jet fuels from coal and shale oil, but rather that potentially significant differences in costs may exist between jet fuels derived from crude oil and the other two competing resources.

It should be kept in perspective that as oil shale liquefaction technology (i.e., *in situ* or retort) develops and as environmental

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*As of July 1975, the Air Force was paying 42 cents per gallon for JP-4, which is essentially commensurate with jet fuel production costs at a resource supply cost equivalent to the world oil price.

†For example, if both coal and crude oil had a resource supply cost of $15 per equivalent barrel of crude oil, jet fuel produced from coal would be about twice as costly as jet fuel produced from crude oil.

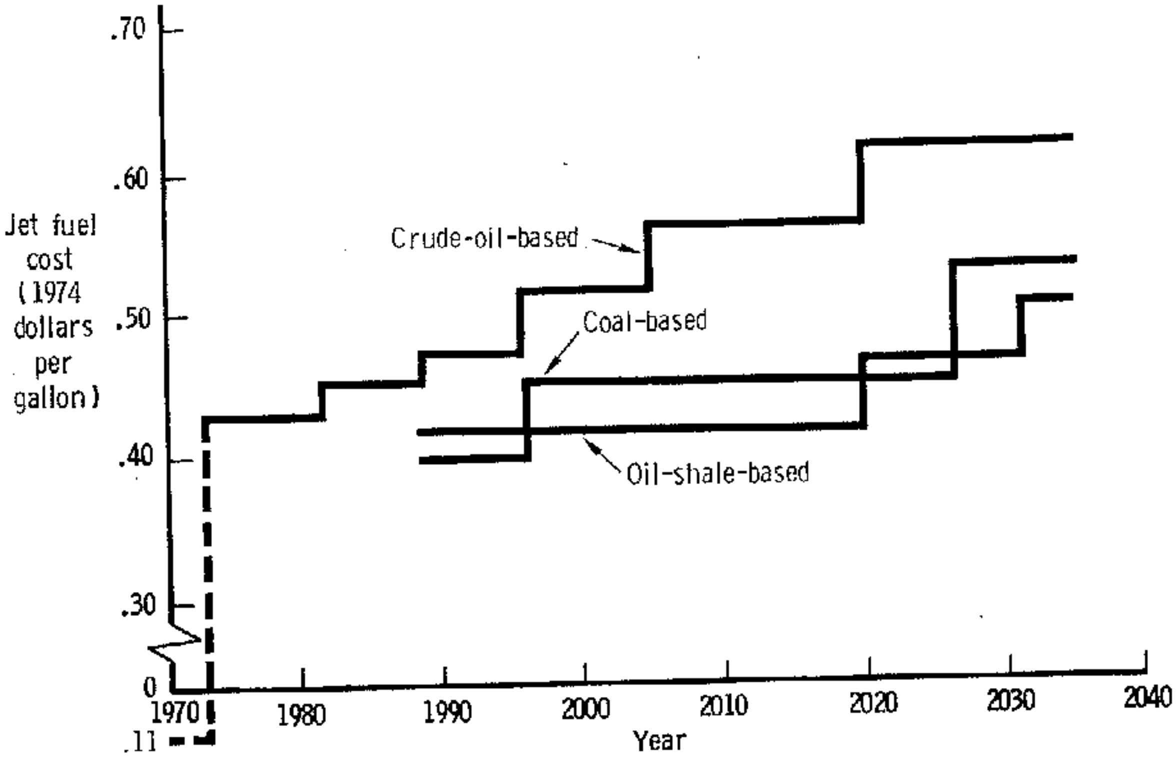

Fig. 39—Projection of jet fuel production costs (model output)

issues and reclamation costs become more certain, it is quite possible that the oil-shale alternative may lose some of its advantage over coal or even crude oil. Similarly, there are technology and cost uncertainties associated with full-scale commercialization of coal liquefaction, which could also alter the cost projection for coal-derived jet fuels. Since these uncertainties will not be resolved for some time, it seems that the development of a multifuel propulsion capability would have the distinct advantage of freeing the Air Force from reliance on just a single energy resource and associated jet fuel production technology.

<u>An Alternative View of Market Behavior</u>. Thus far, the focus has been principally on the cost of producing aviation fuel from alternative primary energy resources. With the exception of the imported oil price-setting the resource supply cost for crude oil, we have thus far purposely steered clear of any attempt to consider the marketplace price-setting mechanisms that might be in effect at the turn of the century. For the sake of completeness, however, we must acknowledge

that there is a school of thought that holds that the price that the Air Force would pay for jet fuel would not be sensitive to the primary resource used to produce that fuel, since all of the primary resources could be used to produce a similar fuel.

This argument is based on the contention that once the fuel enters the marketplace, it loses all distinction (not quite true, however)[*] concerning the source from which it was derived. That is, if there are two firms producing jet fuel, Firm A producing it from coal and Firm B producing it from crude oil, they will both end up charging the same price. Alternatively, Firm A might also be Firm B, in which case there would be little incentive to charge a different price. The argument further contends that Firm A (which uses crude oil) must charge a price that, at a minimum, covers its cost (cost including return on investment); therefore, the price that the Air Force pays for its jet fuel would follow the crude-oil projection in Fig. 39, regardless of whether the primary energy resource was crude oil, coal, or oil shale.

One fault in this argument lies in the assumption that Firm B (using coal) would be allowed to charge the same price as Firm A (using crude oil).[†] First of all, this would allow an excess profit situation to exist for Firm B, and secondly, such a situation would be counter to the stated objective of national energy policy, which is to develop secure sources of energy for the future that provide lower-cost alternatives to crude oil.(81) It does not seem credible that the public would support government investment in energy technology research, development, and demonstration (and perhaps even commercialization) and would then allow prices to be set for energy products in a manner which is in direct opposition to the objectives of the R&D investment. Thus, in the remainder of this report, we will assume that coal and oil-shale resources and the eventual end-use product of interest (i.e.,

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[*] For example, the aromatic content of jet fuels may differ, depending on the energy resource from which they are derived, and the extensiveness of the refining process.

[†] Another fault with the argument is that it assumes that there is no competition between firms of type B that use coal to produce jet fuels.