FUTURE SOURCES OF MILITARY JET FUELS

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INTRODUCTION

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 using jet fuels derived from alternative energy resources. This paper highlights some of the results of a Rand analysis for the Air Force that sought to identify (1) the most promising energy resource alternatives to crude oil for jet fuel production, (2) the most attractive military jet fuels derivable from the resource alternatives, and (3) the appropriate military R&D activities required to narrow the uncertainties associated with synthetic jet fuels.[1]

What has happened to military jet fuel prices since mid-1973 provides much of the motivation for considering alternative energy sources. The price the Air Force pays for its JP-4 jet fuel has increased by over $800 million; at present consumption rates, each penny per gallon increase in jet fuel prices translates to about a $40 million increase in annual Air Force jet fuel expenditures. Considering these increases in jet fuel costs, it seems quite possible that some time in the future, jet fuels derived from energy sources other than crude oil may become economic.

Ongoing discussions about the most appropriate future aviation fuel forms provide the motivation for evaluating more than just conventional hydrocarbon fuel types. Indeed, some have suggested that liquid hydrogen is the aviation fuel of the future, but it must be measured against the other alternatives.

The long lead times required to introduce new aviation propulsion technologies dictate that the military participate in synthetic-fuels-related research today. Our findings provide some suggestions about the appropriate research emphasis in the present environment of considerable uncertainty.

Figure 1 illustrates one of the more fundamental energy problems confronting the United States.[2] While we have a declining domestic resource base of oil and gas, we rely on imported and domestic supplies of these resources to satisfy about three-quarters of our energy needs. Fortunately, we have other resource alternatives, including abundant supplies of coal and as yet unexploited reserves of oil shale. The extent of the oil-shale resource base, and the generally favorable results of preliminary experiments conducted by the Air Force, Navy, and their contractors in the retorting and refining of oil shale to liquid military fuels, indicate that oil shale deserves serious consideration as a future energy source for jet fuels [23][26][14]. In this paper we consider a subject which has received somewhat less attention, the prospects for using coal as an energy source for jet fuels for Air Force aircraft entering the inventory in the 1985 to 2000 time period.

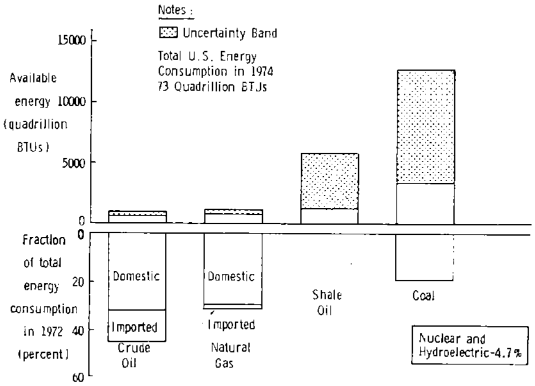


Fig. 1--U.S. Fossil Resources

SOURCES: [1][2][30][22][4].

At current rates of domestic crude-oil production, we would deplete the crude-oil reserves noted in Fig. 1 in about 40 to 60 years [18], which indicates the inevitability of some shifts in our patterns of energy resource consumption to more abundant domestic supplies of energy. Of course, if and when we begin to place greater reliance on fossil resources like oil shale and coal, we will require new processes to convert these solid fuels to liquids suitable for transportation uses.

Figure 2 illustrates a respresentative, but by no means exhaustive, set of processes for producing selected jet fuels from energy resource alternatives to crude oil and natural gas. Several of the energy resources, including coal, could, in principle, be used to produce any of the jet fuels shown in Fig. 2. Oil shale could also assume such a role, although attention thus far has mainly focused on deriving liquid distillate products from oil shale. Hydrogen has the virtue of being derivable from any of the so-called renewable or ultimate energy sources (e.g., solar energy, nuclear fusion), but the economics and energy requirements of these processes do not promise to improve upon the economics of obtaining hydrogen via coal gasification in the 1985-2000 time period. Indeed, when one considers the resource base of each of the resources shown in

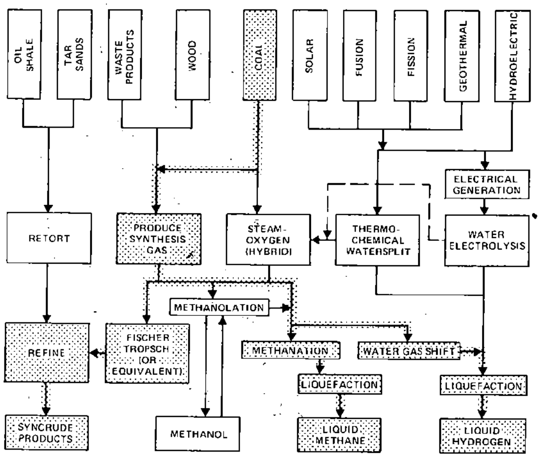


Fig. 2--Overview of Fuel Supply Processes

Fig. 2, the present and foreseeable technology for converting these resources into jet fuels of interest, and the evolving energy R&D technologies being emphasized in the United States today, one can pragmatically conclude that coal and oil shale are the most attractive resource alternatives to crude oil for jet fuel production between now and the end of the century.

COMPARISON OF ALTERNATIVES

To narrow the list of fuel candidates, we used a screening process that evaluated the difficulties in synthesizing the fuels, the comparative physical properties of the fuels in the context of aviation applications, and the performance of airplanes fueled by the various alternatives [8][17]. As a result of this exercise, we eliminated such candidates as ammonia, ethanol, methanol, etc., and concluded that two cryogenic fuels, liquid hydrogen and liquid methane, and a synthetic hydrocarbon jet fuel (or synthetic JP, to use a common military designation) held the most promise as jet fuel alternatives derivable from coal. We then compared these three alternatives in terms of the energy requirements to produce, distribute, and store the fuels, the costs associated with such fuel supply processes, the resource requirements, and some of the environmental impacts. We highlight below some of the more relevant energy and cost aspects of that analysis.

Energy

Several factors motivated our consideration of the energy expenditures required for fuel production. An understanding of the technical reasons why certain fuel production processes require more energy than others can lead to a greater understanding of why the fuel alternatives differ in cost. It can also facilitate the assessment of the total energy-intensiveness of a given aircraft and fuel combination to aid in complying with recent DoD guidelines that require considering energy effectiveness as well as cost effectiveness in evaluating future weapon systems [16][32]. Finally, it seemed prudent to identify the total energy requirements that particular fuel alternatives would impose on the nation's energy resource base, since the Air Force must compete for these supplies with many other users in the marketplace.

To measure the energy requirements for fuel production and distribution, we developed representative fuel supply systems that use surface-mined coal from Wyoming as an energy source to produce jet fuel for a West Coast air base.[3] The numbers enclosed by dashed lines above the elements of the fuel supply systems in Fig. 3 trace the flow of resource energy (energy derived from the primary resource--coal) from extraction to ultimate distribution. Liquid hydrogen production requires 289 Btu of coal resource energy to produce 100 Btu of liquid hydrogen and 35 Btu of useful by-products. Of course, fuel production also requires other energy to fuel the diesel train, build the facilities, generate electricity for liquefaction, etc. We show this process energy below the elements of the fuel supply system. The liquid hydrogen supply system requires an extremely large process-energy expenditure to generate the electricity to liquefy the gaseous hydrogen and render it suitable for storage. In fact, the process energy required is roughly equivalent to the energy content of the gaseous hydrogen entering the liquefaction plant. As a result, about 3.2 Btu of energy must be input for every Btu of liquid hydrogen and by-products output. Thus, liquid hydrogen production uses signficantly more energy than today's crude-oil supply system, which requires about 1.2 Btu of energy input for every Btu of refined products output. We shall see later how the energy-intensiveness of hydrogen liquefaction contributes significantly to the cost of liquid hydrogen.

Methane liquefaction requires only about 10 to 15 percent of the electric power required for hydrogen liquefaction [29]. Because the scale of electricity required is sufficiently low as to not preclude on-site power generation, methane liquefaction plants typically use part of the gaseous methane entering the plant to generate electricity; hence, with resource energy (the gaseous methane) supplying the energy for liquefaction, the process energy shown in Fig. 3 for methane liquefaction reflects only the energy required to build the

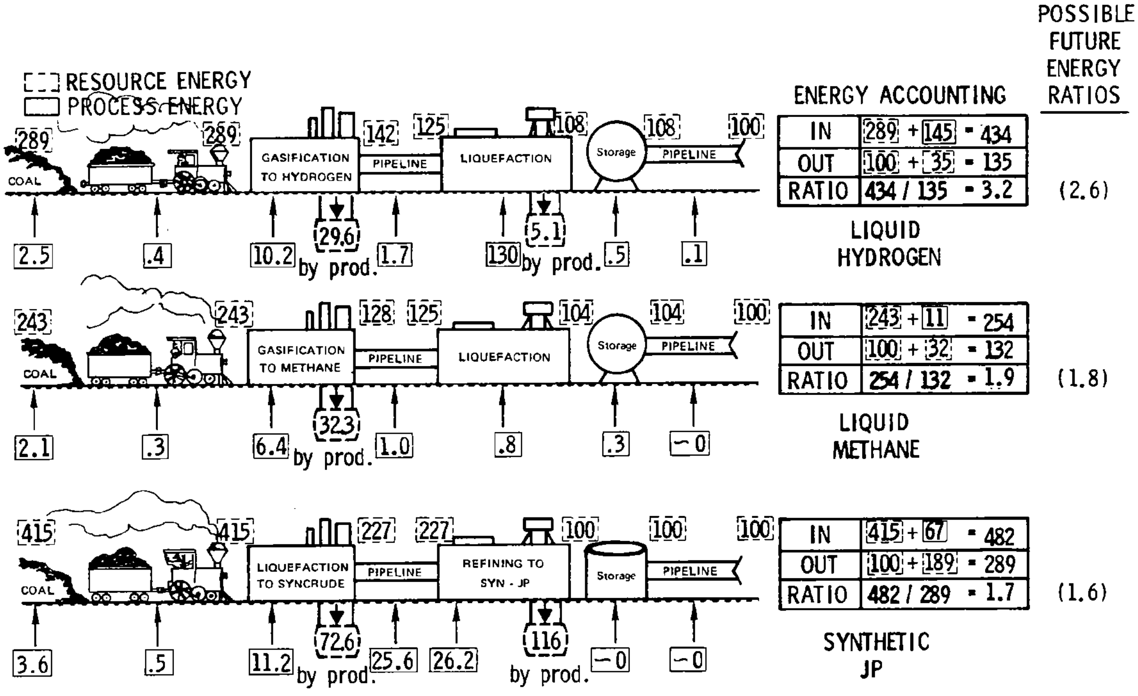


Fig. 3--Energy Needed to Produce Alternative Jet Fuels

facility [7][29][21]. The energy accounting indicates that 1.9 Btu of energy must be input for every Btu of liquid methane and by-products output.

In absolute terms, synthetic JP production requires more coal-resource energy than the other two alternatives,[4] not because the process is less efficient, but because the refinery processes less than one-half of every barrel of coal syncrude to a refined jet fuel; most of the remaining output is motor gasoline. Figure 3 indicates a comparatively large process-energy requirement for syncrude refining, which reflects the hydrogen treatment the coal syncrude must undergo to lower its characteristically high aromatic content, as well as some hydrocracking of heavier distillate fractions that maximizes the output of jet fuel. Reducing the yield of jet fuel would reduce energy requirements. Overall, the synthetic JP process requires that 1.7 Btu of energy be input for every Btu of synthetic JP and by-products output.

We have also made some plausible, but optimistic, estimates of possible future improvements in these fuel supply systems to arrive at the energy ratios shown on the right in Fig. 3. We deliberately assembled this rather optimistic set of estimates to test the hypothesis that the characteristically lighter liquid-hydrogen-fueled aircraft might use less total energy than the other alternatives. The results indicated that for a broad class of military missions, the large energy expenditures associated with liquid hydrogen production and distribution more than offset the lower on-board energy consumption of a subsonic liquid-hydrogen-transport aircraft [17]. In an energy context, the synthetic-JP-fueled aircraft proved more energy effective than the other two alternatives for almost all the missions considered.[5] We can conclude from this energy assessment that compared to the crude oil supply system, the synthetic JP alternative does not represent a means to save energy, although it does represent a possible means to save crude oil by using an alternative energy resource.

Costs

Any absolute economic assessment of alternative jet fuel costs must remain somewhat speculative until operating experience is accumulated with large synthetic fuel demonstration plants. At this writing, any such plants would appear to be at least three to five years away from operation. Nonetheless, by making consistent assumptions about the supply systems of the three fuel alternatives, we can gain some insights about the relative costs of producing and delivering the fuels. While we originally expressed the cost analysis on a 1974 dollar basis, we will translate the more relevant results to a 1978 dollar basis at the conclusion of the assessment.

We developed average fuel costs for the production and delivery of the fuels to a group of air bases, assuming a mix of underground-mined coal from the east and surface-mined coal from the west having an average price of about $9.64 per ton, or 54¢ per million Btu. Table 1 indicates the capital cost of the energy-conversion facilities per daily million Btu of fuel products, including a 28 percent "ownership" cost over and above the basic plant investment to cover interest during construction, working capital, start-up capital, etc. Because of the capital-intensiveness of these facilities, the method of financing has a strong influence on fuel costs.

Table 1

CAPITAL COSTS

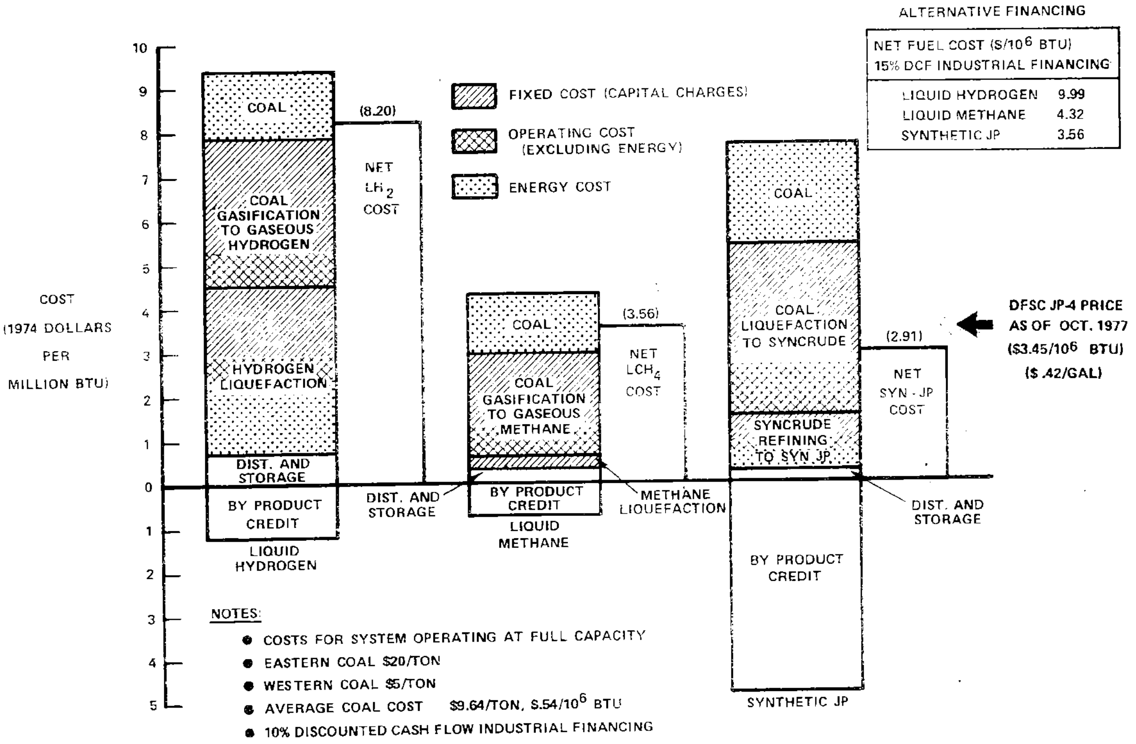
Energy Conversion Facility	Capital Cost per Daily Million Btu of Fuel Products (1974 $/$10^6$ Btu)
Coal liquefaction	1690
Syncrude refinery	490
Coal gasification to hydrogen	2590
Hydrogen liquefaction	2520
Coal gasification to methane	1730
Methane liquefaction	340

Figure 4 identifies the major cost categories for energy conversion, including the fixed (capital charges), operating (recurring labor costs, property taxes, raw materials, etc.), and energy costs. Note the large contribution of liquefaction electricity to liquid hydrogen costs. If we apply credits for the by-products, particularly the large gasoline by-product credit, we obtain costs of $8.20, $3.56, and $2.91 per million Btu for the liquid hydrogen, liquid methane, and synthetic JP, respectively. These costs assume industrial financing that yields a 10 percent discounted cash flow return-on-investment after taxes. Some have suggested that investors may very well demand returns of 15 percent or more because of the risks involved, and as a means to generate the equity for the rapid build-up of a synthetic fuels industry [25]. As a consequence, fuel costs could very well reach or exceed the values shown in the box in Fig. 4. We can conclude from this assessment that in a relative sense, synthetic JP would cost significantly less than liquid hydrogen, and modestly less than liquid methane. The fuel cost sensitivities to resource costs, financing assumptions, and plant costs shown in Figs. 5 and 6 also indicate that liquid hydrogen costs are generally more sensitive to unfavorable changes in the parameters because of the less-efficient production and distribution system.

The dramatic differences in peacetime and wartime jet fuel demands by the military (e.g., consumption changes of 100 to 300 percent) could also pose a serious problem for the particularly capital-intensive hydrogen liquefaction process. Unless a large market of interruptible users could be developed to use the excess liquid hydrogen plant capacity during peacetime, the liquefaction facility owner would have to raise fuel prices appreciably to cover his large fixed costs. In other words, there could be a large cost penalty for underutilizing the system [8]. The synthetic JP option has the apparent advantage of having a refinery product slate more amenable to assimilation into existing petroleum markets during peacetime.

A mission analysis of airplanes fueled by these three alternatives indicated that for a broad class of present and future mission applications, the synthetic-JP-fueled aircraft proved significantly more cost effective than the other alternatives, for fuel costs in the range of those cited in Fig. 4 [17]. It would seem that only major reductions in the costs of liquefying gaseous hydrogen would improve the relative attractiveness of liquid hydrogen airplanes.

Moving from relative comparisons of the fuel alternatives to absolute comparisons with present petroleum market conditions entails considerable uncertainty, but nonetheless we will do so to illustrate the presently unfavorable economics of the synthetic JP alternative. Depending on the financing, the synthetic JP cost in our example ranges from 37¢ to 45¢ per gallon in 1974 terms, or converting to 1978 terms, about 48¢ to 58¢ per gallon [6][5]. As indicated in Fig. 4, as of October 1977, the Air Force was paying the Defense Fuel Supply Center 42¢ per gallon for its JP-4 fuel, considerably less than the cost of a synthetic JP fuel [3]. Other analyses using alternative assumptions about coal conversion technology, coal costs, and financing yield a generally broad range of synthetic JP cost estimates, but virtually all of these analyses indicate that synthetic JP from coal would not be competitive under present market



NET FUEL COST ($/10⁶ BTU) 15% DCF INDUSTRIAL FINANCING	
LIQUID HYDROGEN	9.99
LIQUID METHANE	4.32
SYNTHETIC JP	3.56

NOTES:

- COSTS FOR SYSTEM OPERATING AT FULL CAPACITY
- EASTERN COAL $20/TON
- WESTERN COAL $5/TON
- AVERAGE COAL COST $9.64/TON, $.54/10⁶ BTU
- 10% DISCOUNTED CASH FLOW INDUSTRIAL FINANCING

Fig. 4--Jet Fuel Costs

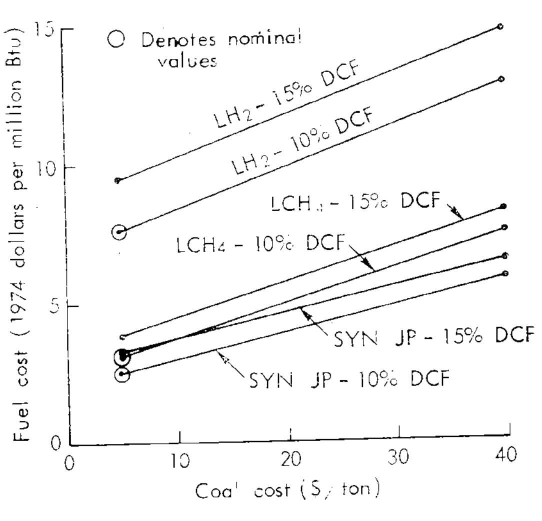


Fig. 5--Sensitivity to Coal Cost and Financing Method

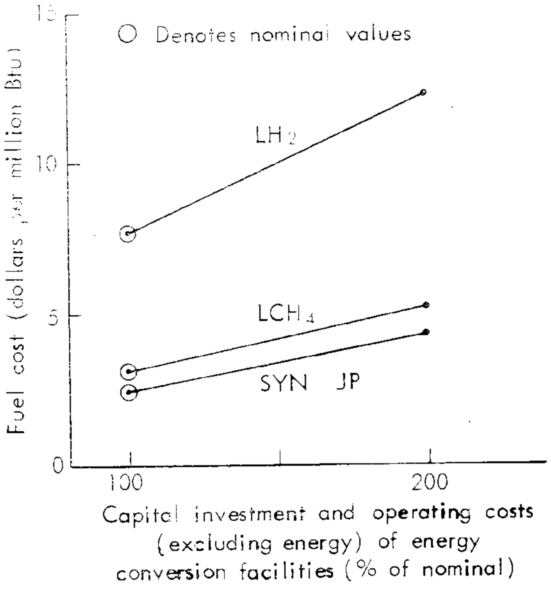


Fig. 6--Sensitivity to Facility Costs

conditions[6] [24]. The risks posed by these unfavorable economics, as well as the uncertain pricing basis of world oil, have tended to inhibit private industry from aggressively pursuing the synthetic fuel option without government assistance of some form.

RESEARCH AND DEVELOPMENT EMPHASIS

While the present world oil price does not make synthetic JP an attractive alternative in today's environment, the long lead times needed to introduce new propulsion technologies more or less require that the military participate in synthetic-fuels-related research today in order to be in a position to choose the most cost-effective synthetic JP fuel option at some future date. For the military aircraft user and developer, the primary issue concerns defining the proper technical and economic tradeoffs between engine technology and fuel processing at the refinery.

Coal-derived fuels have characteristics that can cause problems in jet engines. Their generally high aromatic content, or conversely, low hydrogen content, substantially contributes to combustion problems. Coal-derived fuels generally have higher freezing points, and when burned in jet engines, generate more smoke and increase combustor liner temperatures and infrared signatures. They have poorer thermal stability properties than petroleum fuels and pose some compatibility problems with elastomeric seals. But research already under way has demonstrated that improvements in combustor and fuel system technology can help deal with many of these problems [13]. On the other hand, at some additional cost in energy and dollars, refiners can hydrotreat coal liquids to reduce their aromatic content. Tradeoff opportunities also exist to deal with the characteristically high nitrogen content of shale liquids [14]. But the refinery-engine tradeoff interface has not yet been defined to a level of precision that could support major development decisions.

Indeed, the considerable uncertainties about synthetic JP fuel supply and utilization systems argue for a cautious and flexible R&D approach by the military. The pace and extent of oil shale and coal resource development remain uncertain. The identification of the preferred fuel-conversion technologies and their economics have yet to be defined. We still have much to learn about the effects of synthetic JP fuels on aircraft engines and fuel systems. Specifications for future jet fuels are still being discussed and debated.

The uncertainties seem to dictate a parametric approach to define fuel characteristics and the associated refinery process requirements. In other words, an R&D program structured to gain information about the spectrum of possible outcomes that might result from the present uncertain energy situation seems preferable to making an early commitment for a particular resource and fuel type. Such an R&D approach should place the military in a good position to exercise the synthetic JP fuel option when these fuels enter the marketplace as alternatives to petroleum fuels.

FOOTNOTES

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[1] This paper has been prepared for presentation at the Seventh Annual DoD Procurement/Acquisition Research Symposium, May 31-June 2, 1978, at Hershey, Pennsylvania. The views expressed in this paper are the author's own and are not necessarily shared by The Rand Corporation or its research sponsors. The paper is based on research fully reported in [8] and [17].

[2] Crude oil and natural gas estimates 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.

[3] We used a variety of sources to assemble the operating characteristics and costs for the elements of the energy distribution and conversion systems [15][19][20][9][27][12][10][21][31][11][28][7].

[4] Observe, however, that if coal is used to generate the electricity for hydrogen liquefaction, the liquid hydrogen supply process requires about as much coal as the synthetic JP alternative while delivering about half as much energy.

[5] Our energy and cost analyses did not consider hypersonic aircraft applications in which the cryogenic properties of hydrogen or methane fuels might facilitate innovative aircraft design concepts.

[6] Although in this paper we do not discuss fuels from oil shale in any detail, we believe this economic conclusion is generally extensible to synthetic JP from oil shale as well.

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