THE ENERGY DILEMMA and its Impact on Air Transportation

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The contents of this report are due to the above authors who were participants in the 1973 Summer Faculty Fellowship Program in Engineering Systems Design. The authors represent a set of diverse backgrounds who were selected from numerous universities.

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and
Its Impact on Air Transportation

Editors: **Calvin R. Dyer**
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1973 SUMMER
FACULTY FELLOWSHIP PROGRAM IN ENGINEERING SYSTEMS
DESIGN

NASA-LANGLEY RESEARCH CENTER
AMERICAN SOCIETY FOR ENGINEERING EDUCATION
OLD DOMINION UNIVERSITY RESEARCH FOUNDATION

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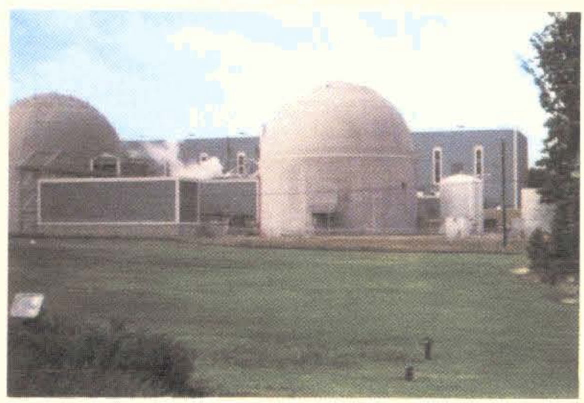

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FOREWORD

This document summarizes the results of the 1973 NASA-ASEE Summer Faculty Program in Engineering Systems Design conducted at the NASA Langley Research Center during the period June 11 through August 24. The program was jointly sponsored by the National Aeronautics and Space Administration and the American Society for Engineering Education through a contract by NASA to the Old Dominion Research Foundation of Old Dominion University.

The objectives of this systems design program included the following:

(1) To provide a useful study of a broadly based problem of society that required the coordinated efforts of a multidiciplinary team.

(2) To provide a framework for communication and collaboration between academic personnel, research engineers, and scientists in governmental agencies and private industry.

(3) To generate experience and foster interest in participation in and development of systems design activities and multidiciplinary programs at the home institutions of the participants.

These three objectives were met by an intensive systems study of the energy crisis and its effect on transportation, particularly air transportation. The report resulting from this interdisciplinary effort is intended to communicate the dimensions of the energy situation and its impact on air transportation to the general public, to governmental bodies, and to policy makers on the local, state, and federal levels. To be realistic, such a study must encompass a wide range of social, technical, legal, and economic considerations. Therefore to address this study, a group of 20 investigators, including representatives from ten different academic disciplines, was assembled. The result was a multidisciplinary team with a broad variety of expertise that could be brought to bear on one of the nation's most critical problems.

The presence of a multidisciplinary team has been essential to the success of the study, but the program has been greatly enhanced by visits from many lecturers and consultants from various industries, government agencies, and academic institutions. These individuals, who are listed in Appendices B and C, were invaluable in providing background data and information.

Particular appreciation is expressed for the excellent administrative support provided by the Co-Directors of the NASA-ASEE Summer Institute, Dr. John E. Duberg and Dr. Gene L. Goglia. The continuing assistance extended by Messrs. Pat Clark and John Witherspoon of the Personnel-Training and Education Service Branch were indispensable to the smooth functioning of the program.

Dr. Wayne D. Erickson and Dr. George F. Pezdirtz of the Langley Research Center served as technical advisors to the study program from its inception to its conclusion. For their constant encouragement, counsel, and cooperation during the entire program, the participants express their deepest appreciation.

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DIRECTORS NOTE

The contents of Chapters 2 and 3 are based on statistical data which typically show airplanes to be less energy-efficient than other modes of transportation. It should be noted that these composite statistics are gathered on a national basis and are subject to varying interpretations. Perhaps a more valid comparison would result if the various transportation modes were subject to the same groundrules, such as equal range-payload constraints. The interpretation contained within Chapters 2 and 3 may not fairly compare air transportation to that of rail and ground modes. For example, on a coast-to-coast trip, a non-stop airplane must haul a sizable amount of fuel for the journey in addition to fuel reserves, food, food preparation equipment, toilet facilities, and other such passenger comfort equipment. The aircraft structure must also have extra weight to support these amenities. The automobile, in contrast, carries fuel only for about 200 miles, has negligible food supplies, and has no toilet or other such facilities. Likewise, trains stop every few hundred miles to refuel. If automobiles and trains had to carry loads comparable tó that of the aircraft, the energy intensiveness of these ground modes would drastically increase.

Further, the bulk of the United States present domestic air transportation system consists of the 707, DC-8, 727, 737, and DC-9 type aircraft—these aircraft—the first generation jets—are based on the technology of the mid-fifties. The new wide-body aircraft, such as the 747, DC-10, and L-1011 represent very significant reductions in energy consumption relative to the early jets and are far better energy competitors relative to trains and automobiles. Anticipated payoffs from aircraft research now underway in government and industry (expected to be complete by 1978) further indicate very sizable improvements in aircraft energy-efficiency relative to the current-technology wide-bodies. These events plus the expected growth in aircraft size to potential 600-1000 passenger aircraft may well make future aircraft the most energy-efficient mode of transportation.

SUMMARY OF RECOMMENDATIONS

The seventies have thrust upon our collective responsibility the disquieting prospect of a fossil-fuel shortage. To a nation whose very functioning rests on massive amounts of such fuel this is an ominous sign. If allowed to materialize the ripples emanating from the fossil-fuel shortage can become shock waves disrupting every segment of our national life. Therein lies a challenge—and also the opportunity to test our ingenuity and will. It calls for multiple efforts aimed toward possible solutions.

The present report represents one such effort. It views our energy dilemma, not as a resource problem or an energy problem but as a national problem. Its content and form adhere to the proposition that the problem is not **mainly** technological, or economic, or political, or cultural, but all of these; and that a workable solution must take full cognizance of all of them. It suggests that new alternatives must be explored if our freedom of choice is not to be restricted; that while immediate solutions must be found to some issues, our primary concern must be with the long view.

Chapter I sets the stage for the analysis which follows by recognizing the existence of a *national energy problem caused by increasing demand in the face of dwindling supplies of con-*ventional energy sources, then invites the reader to consider the inevitable social and environmental problems attendant to any solution which attempts to meet projected energy demands. Chapter I concludes with a discussion of the possibility of an economy in which hydrogen is a principal fuel.

The scope of the study narrows in Chapter II to a consideration of energy-efficiencies and demand projections for various modes of transportation. Air transportation is investigated in detail, because of its 100% petroleum dependence and the projected exponential growth in demand for energy to power airplanes. The reasons behind these projections lead to a more detailed analysis of the social, psychological, and economic factors affecting demand for air transportation.

Chapter III investigates the present and future roles of energy efficiency in air transport systems. Methods for analyzing and controlling demand for passenger and cargo air transportation are developed. The airline system itself is then considered by evaluating the roles that competition, fuel conservation and improved systems operations play in effecting energy economy. Specific examples of the *interrelationship of these factors are given by consideration of (1) the air* terminal Hub concept, (2) capacity reduction agreements and (3) local service operations.

A brief technological assessment of fuel diversification for air transportation is developed in Chapter IV by the proposal of a demonstration project which illustrates the feasibility of a liquid-hydrogen-fueled aircraft. The technology developed with this project can provide feedback not only for the aircraft industry but for other energy-consuming sectors, and can serve as the initial step in preparation for the general use of hydrogen fuel in the economy, the importance of which lies again in the potential for decreased fossil fuel dependence and increased national energy self-sufficiency.

Chapter V summarizes the conclusions and recommendations stemming from this report. **Recommendations not receiving majority support and ideas not a direct consequence of this study but nevertheless felt to be highly significant are summarized in Appendix H.** The recommendations which are a direct consequence of investigations carried out for this report are summarized below:

A wide range national energy policy is needed now. This should include the following recommendations:

- **A national energy conservation program should be established which would include:**
  - a. **Coordination of conservation efforts and establishment of an energy conservation consciousness in the American public.**
  - b. **Institution of a penalty tax on new cars on a sliding scale in proportion to their gasoline consumption rate.**
  - c. **These plans should be implemented immediately before the energy dilemma is out of *control*.**
- **The federal government should conduct a campaign to inform the public about research-initiated technological change, and to determine the best methods for overcoming unfounded public resistance to such change.**

- An energy data bank should be established.
- Energy research should be diversified according to the following guidelines:
  a. Federal funding levels should be increased.
  b. Development of solar and geothermal energy should receive as much emphasis as nuclear energy development. The solar energy forms would include WIND, OCEAN THERMAL GRADIENTS, SOLAR THERMAL CONVERSION AND PHOTOVOLTAIC CONVERSION.
  c. Major investment should be placed in diversified research, development and production of new sources of fossil fuels.
  d. Federally-financed coal research should be continued, expanded and integrated, including conversion into clean portable fuels.
  e. Research into coal mining techniques including environmental hazards should continue and full land reclamation should be required for all surface mining operations.
  f. Federally-funded research should continue toward the development of a safe commercial breeder reactor.
  g. Fusion research should continue as a long range energy source.
  h. The conversion of solid organic waste into clean fuels should be encouraged.
- The government should sponsor an accurate reassessment of available U.S. fossil fuel reserves and production capacity.
- Public utilities should be made to pay premium rates for use of prime energy sources such as oil or natural gas so as to encourage central use of other energy sources such as coal, with the attendant pollution control investment requirements.
- Environmental, not economic, considerations should dominate the decision regarding disposal of radioactive wastes.
- A wide range national transportation policy is needed which would include the following:
  a. Government sponsored research should continue toward the development of energy-efficient subsonic aircraft for a wide range of uses, with a reduction in noise and air pollution.
  b. Modify the CAB subsidy program to force efficiency in air service to small communities.
  c. The federal government should revise the air transportation tax structure so that general tax revenues are not used to support air travel, and so that the payment of the air transportation taxes encourages energy efficiency.
  d. Encourage economy and charter flights which will fill the airplanes to capacity.
  e. To achieve economic and energy efficiency, the CAB should revise its regulatory policies so that the airlines will minimize the duplication of flights and better match aircraft to their intended mission.
  f. Provide stand-by economy ticketing for the poor and elderly.
  g. Place revenues from user taxes into a general Transportation Fund with allocations from this fund based on a national transportation plan.
- The government should establish an extensive research program leading toward the development of a hydrogen economy.
- The federal government should fund the development of economical techniques for generating hydrogen from nonfossil sources.
- Research on the use of hydrogen as an energy transmission medium should be supported.
- A demonstration project should be established to show the feasibility of using hydrogen as a regular jet fuel, with NASA in charge of the project.
- Other demonstration projects should follow which would show the feasibility of using hydrogen to power trains, buses, and cars, and as a household fuel.
- The federal government should undertake an extensive research program to resolve the present impasse between the environmentally concerned on the one hand and the nation's real energy demands on the other.

THE ENERGY SITUATION

I.A. Dimensions of the Dilemma

In undertaking an assessment of the energy dilemma, it is helpful to begin with some basic information describing the historical, current and projected production and consumption of energy. We will begin with a discussion of the demand for energy in the U.S. and compare it briefly with that of other representative countries of the world. Then U.S. energy supplies, composed almost entirely of fossil fuels, will be reviewed. Actually supply and demand depend on one another through a complex interaction in which economic, technical, environmental and institutional factors play roles of varying importance. We hope to be able to impart some of the flavor of this interaction in the more detailed and analytical look at the options for the future which follows the supply and demand assessment. We will see that attempts to project the energy situation into the future under fairly reasonable assumptions lead to enormous values of projected consumption. This suggests strongly that the system which will attempt to supply these demands may be tested rigorously. Indeed we may have to change the system so drastically that we will no longer recognize it. It is in planning for these changes that we will be called upon to use all the understanding we can muster of the factors which determine energy production, energy consumption and the effects of these variables on the quality of life. The future will be profoundly affected by the opportunities we have and the choices we make in the field of energy policy.

I.A.1. The Demand for Energy

In many ways, the energy dilemma has its roots in the enormous demand of energy in the U.S. Historically this demand has grown faster than population since the time of the industrial revolution (see Figure I-1). This is illustrated dramatically in the recent growth in the energy consumed per capita which is plotted in Figure I-2. During the period 1945-1960 the per capita use of energy grew slowly, at a rate of 1% per year on the average. However, after 1960 it dramatically increased, so that the 1960-1965 average growth in per capita consumption was 2.1%, and the 1965-1970 rate was 3.7%.

In Table I-I we compare the energy consumption figures for the U.S. in 1968 with other representative countries. Note first that the level of per capita consumption in the U.S. in 1968 was more than twice that of the United Kingdom and France and over eight times that of Chile, a typical third-world country. The growth rate for per capita consumption over the 1960-1968 period is listed in the last column. The growth in total energy consumption (4.2% for the U.S.) is composed of population growth (1.3% for the U.S.) and growth in per capita consumption. While the U.S. per capita increase of 2.9% is large compared to the comparable U.S. figures during the 1950's, we can see from the table that the per capita consumption for many other countries is growing even faster. This implies increased competition worldwide for energy resources as the rest of the world attempts to increase its standard of living.

TABLE I-I

ENERGY CONSUMPTION

	1968 Per Capita (10^6 BTU)	Growth 1960-1968 (%) Total	Population	Per Capita
U.S.	310	4.2	1.3	2.9
U.K.	150	1.4	0.6	0.8
France	110	5.0	1.1	3.9
Sweden	206	6.3	0.7	5.6
USSR	120	6.1	1.3	4.8
Japan	86	11.4	1.0	10.4
Chile	37	6.5	2.5	4.0

Source: Joel Darmstadter in **Energy, Economic Growth and the Environment,** John Hopkins Press, 1972, pp. 182-183.

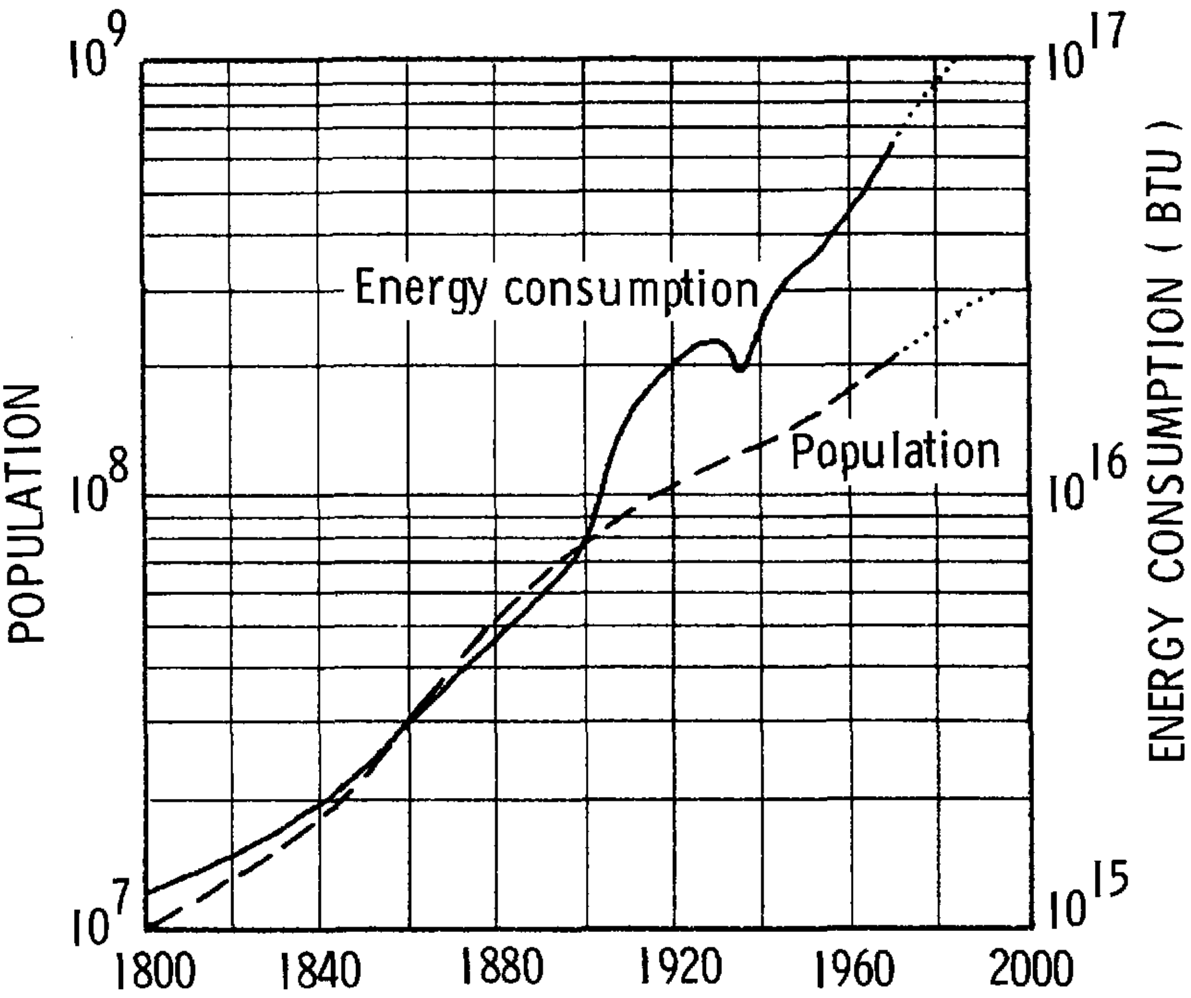


FIGURE 1.1
U. S. ENERGY CONSUMPTION AND POPULATION GROWTH
Source: **Energy and Power, 1971**
(A **Scientific American** Book)

The connection between standard of living and energy use is complicated at best, and few would argue that the gross national product (GNP) is an adequate index of living standards. Nonetheless, it is interesting to look at the variation of the energy intensiveness of GNP during the 20th century. In Figure I-3 we show the ratio of energy consumption to GNP in 1958 dollars as a function of time. Early in the century the ratio increased as the country built up its heavy industry. After 1920, however, the trend shows gradually decreasing energy cost of a dollar of GNP with fluctuations during the late 1920's, World War II, and the late 1960's. The trend reflects increasing energy efficiency in producing output in goods and services. More importantly, it shows that only really major changes in the environment in which the economy operates can separate growth in energy use from economic growth.

The increase in energy cost of GNP during the last five years of the 1960's has been the subject of some concern (1). Contributing to this rise are increased use of fossil fuels for non-energy purposes (petrochemicals) and a low GNP growth during these years. But in addition, technological factors played a role. As examples, in Figure I-4 we show the leveling off of

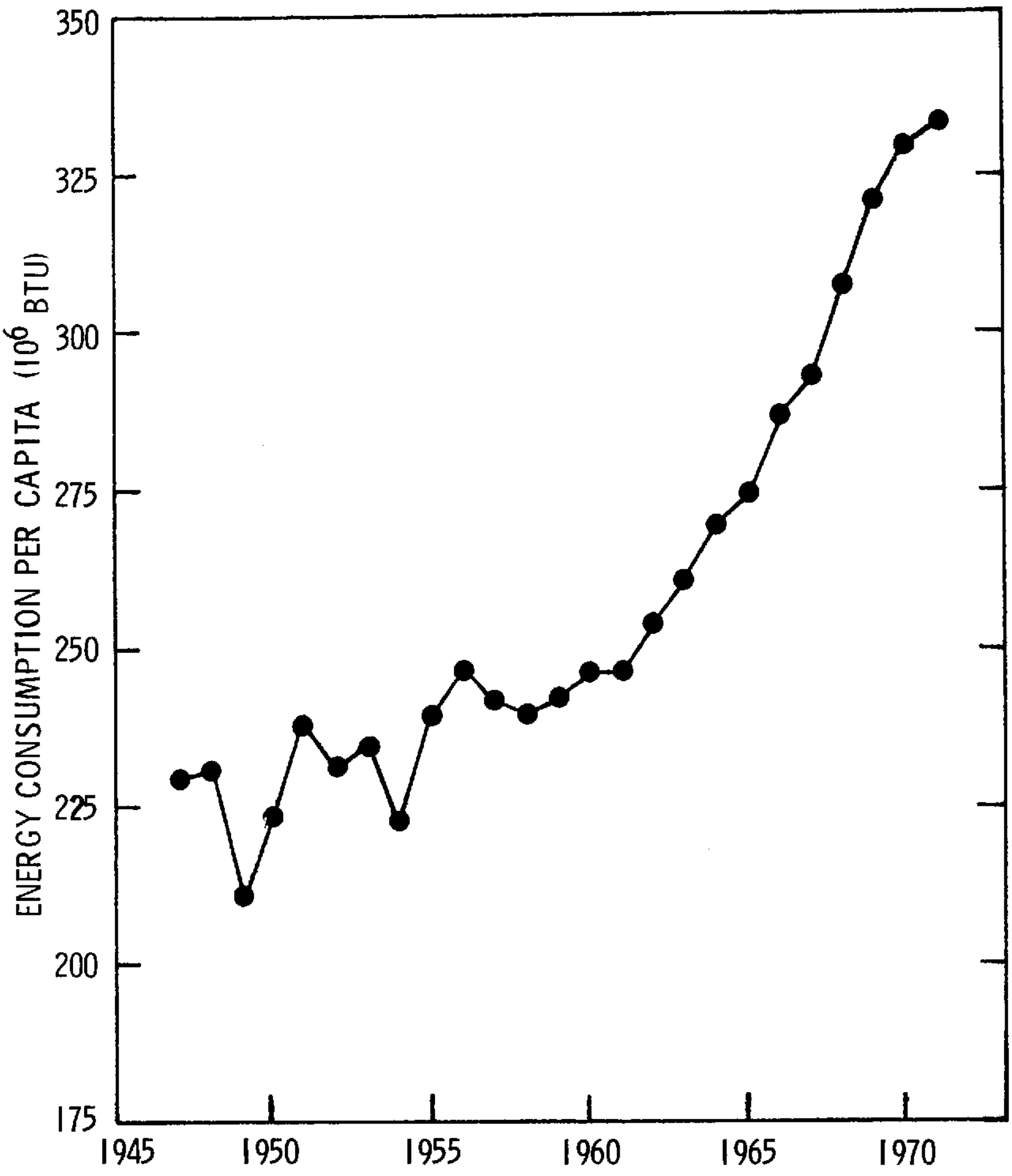


FIGURE 1.2
ANNUAL U. S. PER CAPITA
ENERGY CONSUMPTION 1947-1971

Data from Dupree, W. G. and West, J. A.,
U. S. Energy Through the Year 2000

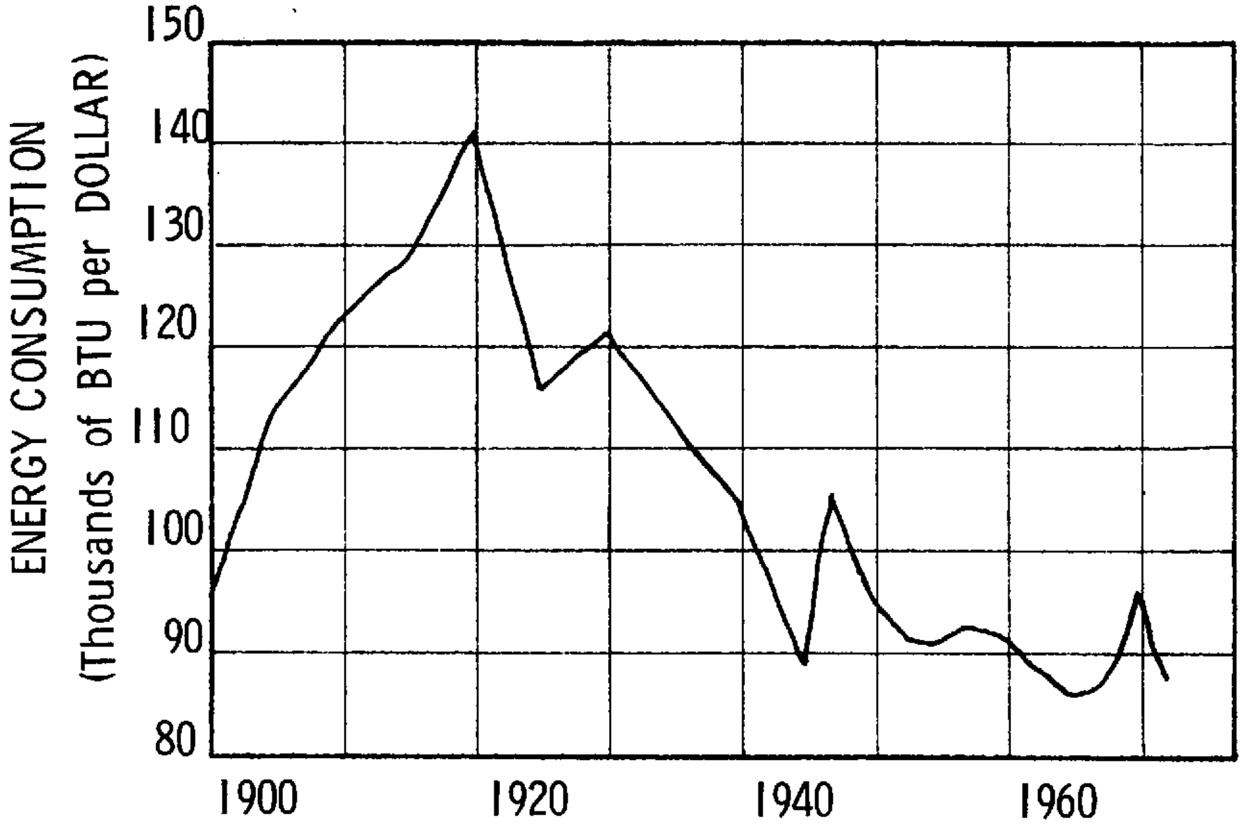


FIGURE 1.3
RATIO OF ENERGY CONSUMPTION TO GROSS NATIONAL PRODUCT
Source: **Energy and Power** (1971-2 values computed from U. S. Bureau of Mines and Survey of Current Business data)

the improvements in thermal efficiency of electric power plants during the 1960's and the decline in "efficiency" of automobiles in converting gasoline into miles traveled for this same period. Now, environmental controls are expected to cause another increase in the energy cost of GNP.

An indication of the uses to which the 1970 U.S. energy input of approximately 65×10^{15} BTU* were put is provided by Figure I-5. Notice that the overall conversion efficiency of the U.S. energy system is around 51%. The large losses come in the generation of electric power, which is limited in theoretical efficiency by the laws of thermodynamics, and in transportation. Significant losses are also produced in uses for space heating, air-conditioning, and in the industrial sector.

How is it possible for the U.S. to use so much energy while tolerating relatively high levels of waste? If one accepts the assumption that economics is the primary factor affecting our consumer behavior, then the following information will help to explain the rapid increase in U.S. energy consumption by individuals. Personal consumption expenditures for energy per capita (PCE) in 1958 dollars divided by disposable personal income per capita in 1958 dollars in recent years has varied only slightly, from 6.52% in 1955 to 7.10% in 1970. This is important because it shows that even though our "real" personal consumption expenditures have grown by 56% from 1955 to 1970, our proportion of "real" income devoted to PCE for energy has varied only slightly.

To see more clearly how this has hap-

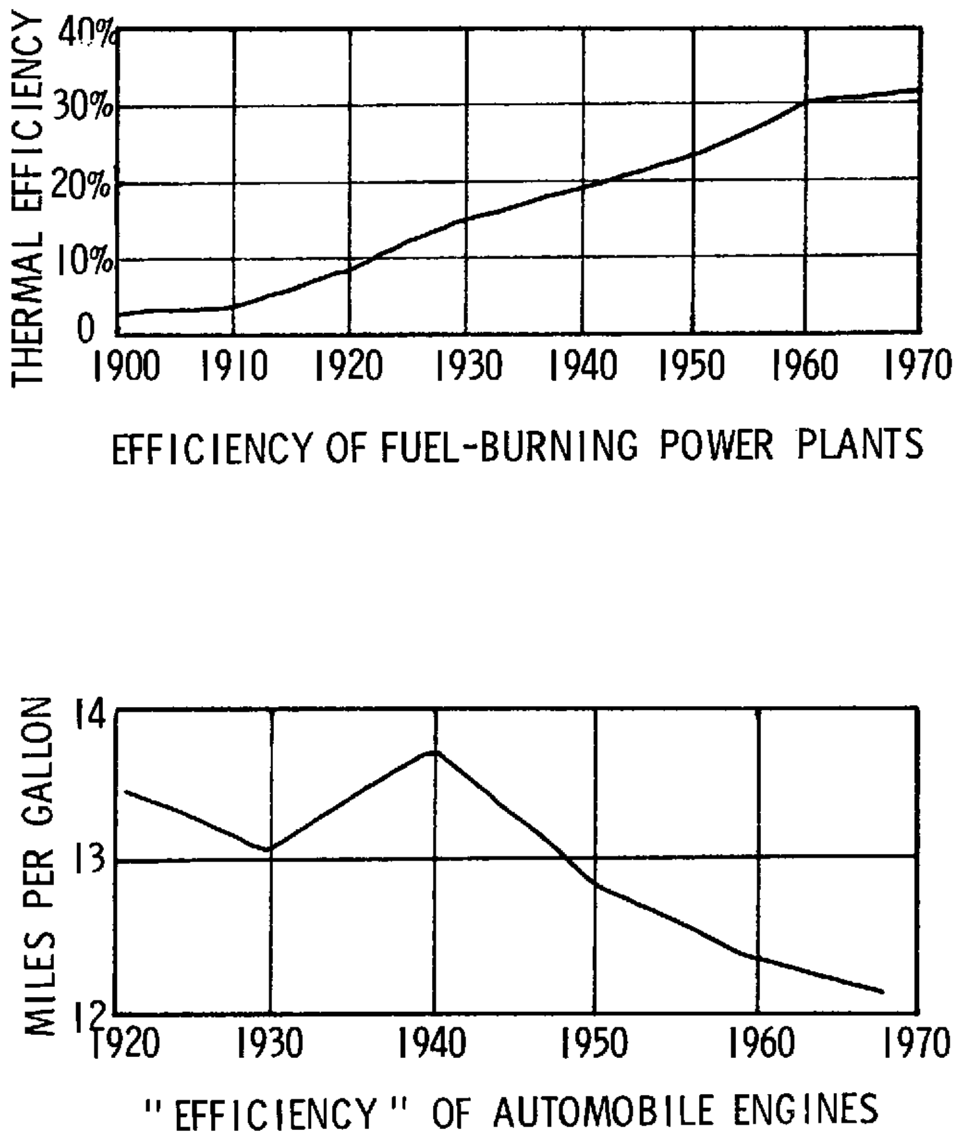


FIGURE 1.4

Source: **Energy and Power**

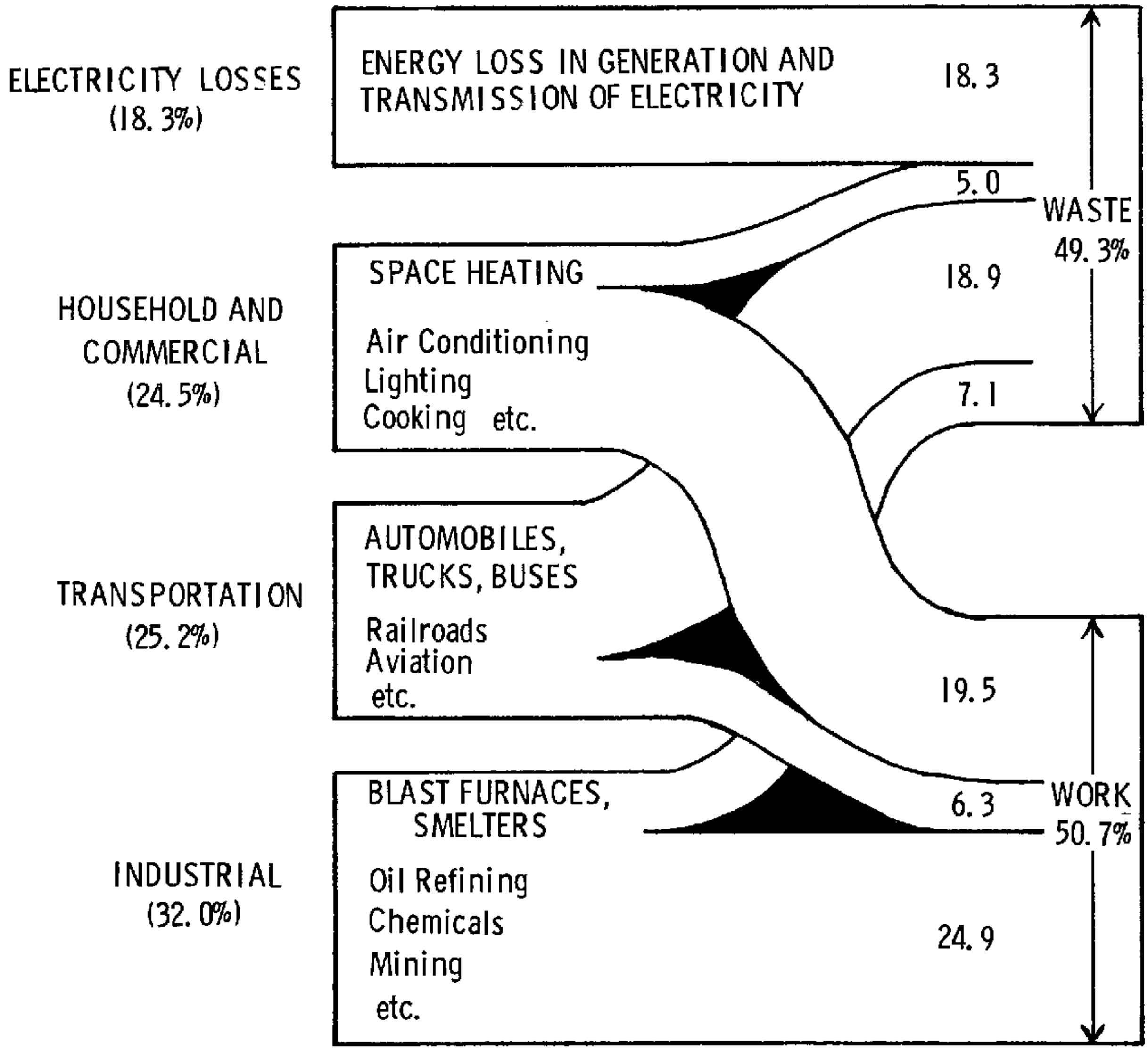


FIGURE 1.5
1970 END USE ENERGY CONSUMPTION (%)
Source: **Energy and Power**

pened, Figure I-6 shows the relative "real" price index of electricity and petroleum products. These were obtained by taking the corresponding price indices and deflating them using the decline in the purchasing power of the dollar. Between 1950 and 1970 the real price of electricity declined 27.5% while refined petroleum products (wholesale) declined 26.4%. Notice the similarity of the curves, and how both showed slight increases in 1971. Thus energy has been cheap in the past, although this era may be coming to an end.

Will the growth trends in energy consumption which we have seen in the past continue? Projections in the extensive literature forecasting energy consumption frequently predict growth rates in energy consumption of about 4% a year. These assume a population growth rate of around 1% and a hoped-for economic growth rate of near 4%. Then, if we assume that the long-term trend in the relation of energy consumption to GNP will continue to improve, a 4% growth rate in energy consumption seems not unreasonable. A 4% growth rate means U.S. energy con-

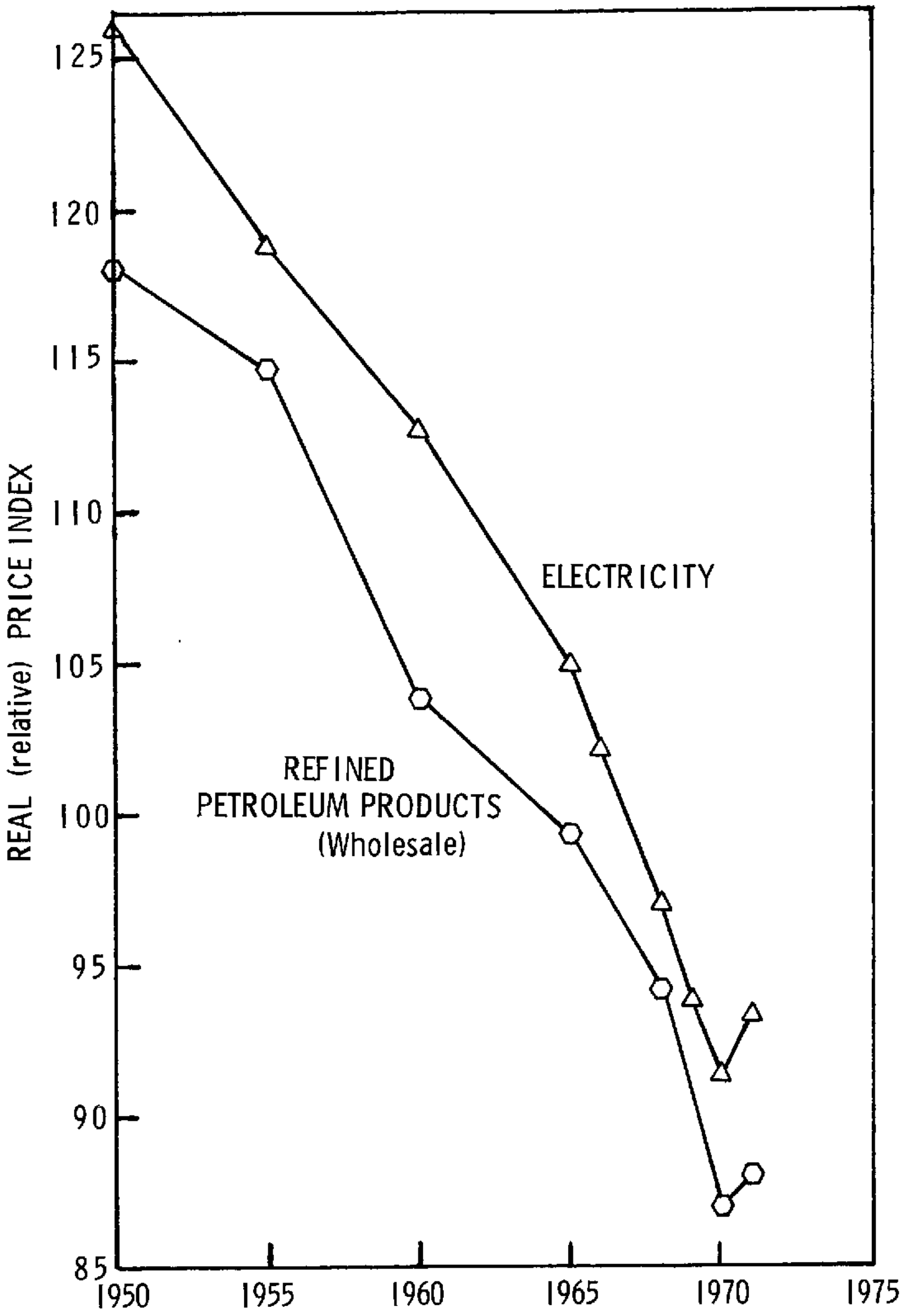


FIGURE 1.6
RELATIVE COSTS OF ELECTRICITY AND REFINED PETROLEUM PRODUCTS
Source: Statistical Abstracts of the U.S.

TABLE I-II

U.S. ENERGY PRODUCTION AND IMPORTS

(10^{15} BTU) 1970

	Production	Imports	Consumption*
Nuclear	0.2	—	0.2
Hydroelectric	2.7	—	2.7
Natural Gas**	23.4	0.9	24.3
Petroleum	17.1	6.8	23.9
Coal	15.4	-1.9	13.5
	58.8	5.8	64.6

*Excludes $4.2x10^{15}$ BTU pètroleum consumption for non-energy uses (petrochemicals, mainly)
**Includes natural gas liquids

Source: **Energy and Power,** p. 86.

sumption would double in just over 17 years and would exceed present **world** consumption by the year 2000.

If we take a more optimistic view that (1) population will approach zero growth, (2) energy efficiency will continue to improve, **and** (3) real GNP will grow about 3% per capita, then the projection of Figure I-7 appears achievable. This one exhibits a doubling time of 25 years after 1975 (2.8% growth). The projected consumption of 160 quadrillion BTU for the year 2000 would require expanding our use of fossil fuels greatly in addition to increasing the amount of nuclear power produced in order to fulfill even this projection. Such curves imply immense efforts on the part of the sectors of the economy responsible for supplying energy. In order to see what the prospects for supply are we turn to a consideration of U.S. energy resources and the prospects that the energy which forecasts predict we will need can in fact be made available.

I.A.2. U.S. Energy Supplies

The sources of the energy which the U.S. consumed in 1970 are indicated in Table I-II.

Of the total of 68.8 quadrillion BTU consumed, 96% came from fossil fuels, with natural gas and petroleum making the largest contributions to the U.S. energy mix. Coal, the only energy fuel the U.S. exports in large amounts, accounted for approximately 20% of our final consumption. Imports, principally petroleum, made up 11% of this total.

In the remainder of this section we discuss briefly the estimates of the energy resources available to the U.S. at the present time and in the near future. The results for each of the fuels are summarized in Tables I-IV, I-V and I-IX.

In general, it must be recognized that estimates of future supplies become very uncertain in the absence of a rather detailed knowledge of the interaction between the society demanding them, their costs and the technology affecting their extraction and use. For example, can we be sure that improvements in technology will not greatly increase the amount of uranium that can be extracted from known deposits at low costs? Will the requirements for reclaiming strip-mined lands placed by law reduce greatly the availability of western coal for widespread use?

The data for assessment of energy resources presented in this chapter is derived from estimates made by institutions which have a vested interest in questions of energy supply. The large, horizontally integrated energy companies are both the sources of much of the basic data concerning energy supplies and the potential subjects of energy policies which may be formulated. Similarly the AEC, which is the source of much of the

*A BTU is a British Thermal Unit, the amount of heat energy required to raise the temperature of one pound of water one degree Farenheit.

basic information on nuclear power, has an *interest as an established bureaucracy* in a strong nuclear program. It may become increasingly important in the future to have this basic supply data supplied by objective sources.

Historically, proven reserves have increased with time even though production has also expanded. We should regard these reserves as an inventory of commodity available *more or less immediately*. In the case of oil, reserves are "proven" because a well is in place. The supply of additional oil which may be available from wells as yet undrilled is much more difficult to estimate, although it is precisely this sort of number that one wishes to have available for long-term analysis of energy prospects. Throughout the section fol-

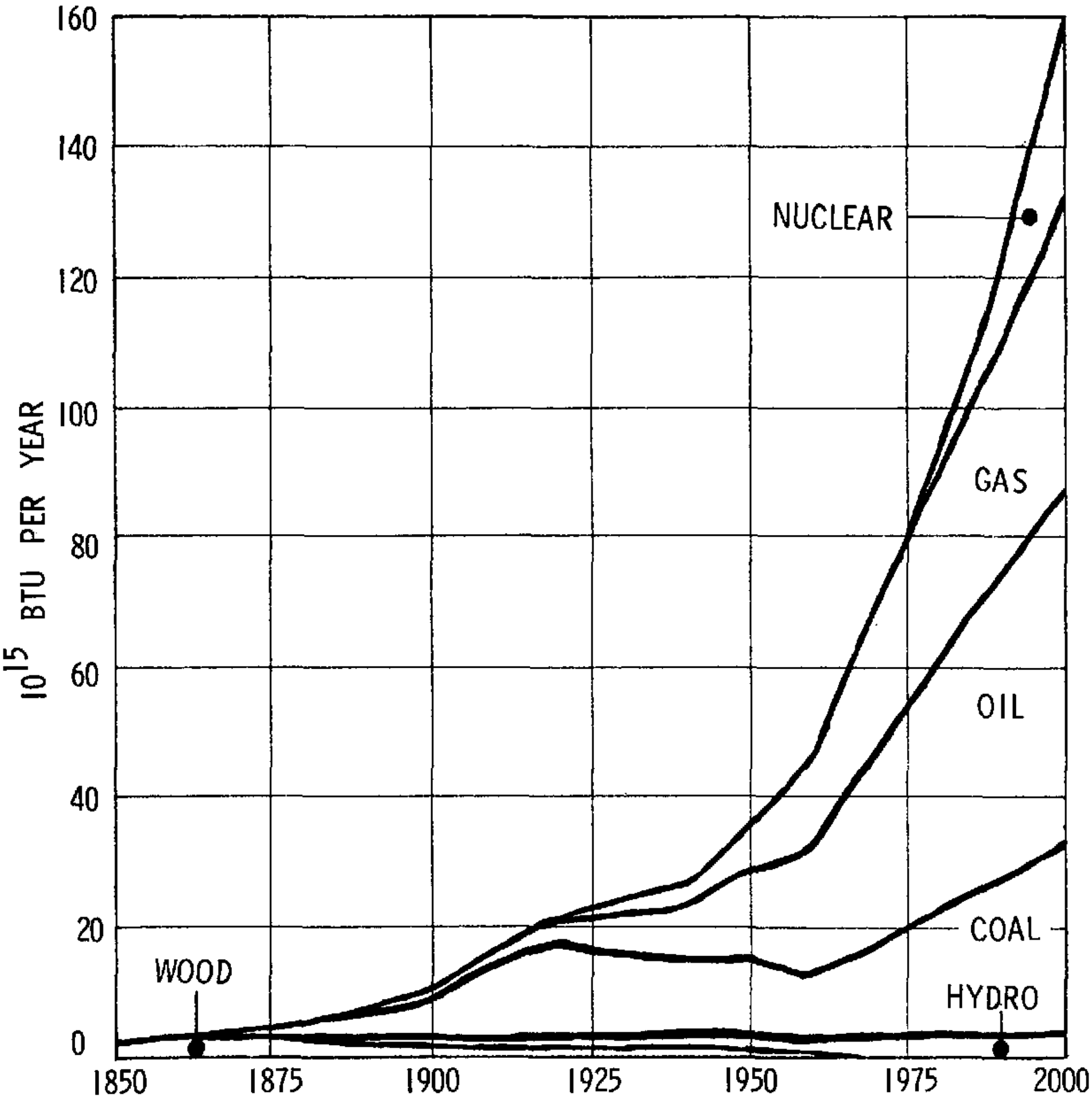


FIGURE 1.7
CLASSICAL PROJECTION OF
U. S. ENERGY CONSUMPTION BY SECTORS
Source: **Energy and Power**

lowing, we should be careful to distinguish between the accuracy with which proven reserves are known and the relative uncertainty with which we are able to estimate ultimate recoverable reserves.

The discussion which follows focuses primarily on fossil fuels, since they constitute the principal sources of primary energy for the U.S. We include a discussion of the reserves of uranium and thorium as potential nuclear fuels and an estimate of lithium resources since these are relevant to the prospects for obtaining power from thermonuclear fusion.

Energy is treated in this discussion as an input into the economy. Thus, in discussing the availability of sources of energy we make no reference to the efficiency of the systems which convert the primary resource into more usable forms of energy (i.e., electricity). Because of this, it should be realized that the inventory we present is necessarily larger than the amount of energy we could actually use. However, efficiencies vary so widely that it does not seem advisable to alter our data by incorporating assumptions about what these parameters might be.

The energy unit chosen is the British Thermal Unit (BTU). Table I-III shows how to convert to other commonly used units of energy.

In talking about energy resources it is helpful to keep some magnitudes in mind. The energy consumption of the U.S. is conveniently expressed in quadrillion (10^{15}) BTU. We call this unit Q. Consumption in the U.S. in 1970 including non-energy uses of fossil fuels was approximately 70Q. Thus, the reserve estimates which follow can be measured against this yardstick for U.S. usage.

A. Petroleum

Estimates of the petroleum which may exist in areas under U.S. jurisdiction run as high as 810 billion barrels (5, 6, 7, 8). Of this we have discovered around 450 billion barrels to date. With an average recovery efficiency of 31%, only 140 of these 450 billion barrels are recoverable under existing economic and technological conditions (7, 8). Since 103 billion barrels have been produced to date, proven reserves of crude oil in the United States amount to 37 billion barrels (215 quadrillion BTU). Included are 9.6 billion barrels of crude oil reserves on Alaskan North Slope which will not be available until adequate transportation facilities are developed (7, 8, 9).

The recovery efficiency has been improved at an average rate of 0.5% of in-place oil a year due to advancement of reservoir engineering techniques in both primary and supplementary recovery methods (8, 10). The recovery efficiency of oil-in-place is anticipated to increase from an average of 31% at present to 37% in 1985. By 1985 the ultimate recovery efficiency in **new** reservoirs discovered is expected to be about 50%, due to technological improvements (7). This implies that, in addition to the proven reserves of 37 billion barrels, some 20 billion barrels can be produced from improved recovery in reservoirs already discovered, and that 180 billion barrels will be recoverable from future discoverable reserves. Thus, crude oil totaling some 230-240 billion barrels can contribute to U.S. supplies for some 58 years at the 1970 consumption rate of 4.12 billion barrels per year, assuming no environmental restrictions.

The rate of domestic crude oil supply depends strongly upon the rate at which the potentially recoverable oil reserves are being transformed to proven reserves. During the past 15 years, total crude oil reserve additions for the United States have averaged 2.7 billion barrels per year (7). The volume added to proven reserves as a result of new oil discoveries (exclusive of 9.6 billion barrels

TABLE I-III

ENERGY CONVERSION FACTORS

1 joule (j.)	= $.95\times10^{-3}$BTU
1 kilowatt-hour (KWH)	= 3.41×10^{3}
1 cubic ft. (ft^3) natural gas	= 1.03×10^{3}
1 gallon (gal.) gasoline	= 1.36×10^{5}
1 barrel (bbl.) crude oil	= 5.80×10^{6}
1 metric ton coal equivalent (tce)	= 2.80×10^{7}

TABLE I-IV
CRUDE OIL

	(bbl.)	Energy*	Years Use**
Proven Reserves (U.S., 1970)	37	215	9
Potentially Recoverable (U.S.)	240	1392	58
Proven Reserves (Persian Gulf)	341	1978	83
Reserve Additions (U.S.)			
1956-70 avg.	2.7/yr.	15.7	0.66
1970 value	3.1	18.0	0.75
North Slope	9.6	55.7	2.30

*5.8Q/10^9 bbl.
**at U.S. 1970 consumption rate (23.9Q/yr)

Source: References 7 and 12

added by the Alaskan North Slope discovery) has decreased from over 2 billion barrels in 1955 to about 1 billion barrels in 1972. Therefore, total reserve additions have been maintained mainly through greater application of increased recovery techniques to previously discovered reserves. The finding rate of new oil reserves has decreased because drilling footage has declined at a rate of about 4% to 5% per year over the last 10 to 15 years (7).

A number of factors, all adding up to insufficient economic attractiveness of domestic oil ventures, have been cited as causes of the lack of interest in petroleum exploration and development in the United States. These include long term decline in the real price of domestic crude oil, increased tax burden, uncertainties about Federal policy on oil import controls, and, perhaps most significant of all, increasing difficulty and cost experienced by the industry in finding new oil reservoirs sufficiently large to permit economic production (5, 6, 7, 8, 11).

Production of domestic crude oil peaked in 1970 and decreased in 1972 to an average rate of 11.6 million barrels per day (bpd). In 1972, the United States reached essentially full production capacity and foreign petroleum imports totaled 4.7 million bpd or 29% of the total oil supply (6, 11). Domestic crude oil production is anticipated to increase only slightly in the future (6, 7), with approximately 20% (2 to 2.6 million bpd) coming from the Alaskan North Slope and 20% from the offshore region. Without a major change in our domestic oil finding and producing efforts, the United States will become increasingly dependent on other nations for oil supplies.

The results for petroleum supply are summarized in Table I-IV.

Total proven reserves amount to 9 years inventory at the 1970 consumption rate for petroleum of 23.9Q/yr. For comparison we indicate the Persian Gulf proven reserves, an enormous 341 billion barrels (12). Reserve additions, which represent deposits into the energy bank account, have fallen behind yearly consumption. The contribution to proven reserves from the North Slope amount to only 2.3 years inventory.

Oil shale could add several hundred billion barrels to U.S. reserves if the environmental, water supply and economic problems associated with extraction could be resolved. Estimates of reserves vary with the economic and technical assumptions made, but deposits of at least 80 billion barrels (464Q) are thought to be of economic interest before 1985 (7). Of the 11 million acres of land containing oil shale deposits considered to be of potential commercial value, some 8.3 million acres (about 72%) are public lands managed by the Federal Government (8). Therefore, future government policies will play a significant role in both the timing and magnitude of oil shale development. To stimulate commercial development on public lands, the Interior Department announced on June 29, 1971, plans for a proposed program to permit the development of a small part of the oil shale resources on public lands in

Colorado, Utah, and Wyoming. A preliminary Draft Environmental Impact Statement was also released at that time (8). Pilot programs currently under way are aiming at commercial development between 1976 and 1980 (13, 14). Methods involving surface and subsurface mining plus a retorting process have been advanced to the point that the cost of production is expected to be nearly competitive with petroleum of comparable quality (8). In this process, oil shale is processed into crude shale oil, then semi-refined into what is called syncrude. The syncrude produce is essentially free of sulfur and low in nitrogen, thus constituting a premium refinery feedstock. The in-situ method of producing shale oil (by heating underground) is in the experimental phase and commercial application of this technique cannot be expected prior to 1980 (7, 14).

Although asphalt-bearing rocks have been recognized for many years as a potential source of synthetic crude oil, tar sands deposits in the United States are quite small. Resources are estimated at 17 to 28 billion barrels (7, 8). Exploitation of the domestic tar sands deposits is expected to be limited by both physical and technological factors. Lack of water for processing, potential ecological problems, and the absence of developed exploitation technology make production unlikely before 1985 (7, 15).

In contrast to the small U.S. deposits, the heavy oil sands of northern Alberta, Canada rank as one of the world's great accumulations. The potential resources of the Athabasca tar sands are estimated to be 600 billion barrels. In addition, the amount of oil in place in Cold Lake, Peace River, and Wabasca deposits is known to be about 200 billion barrels.

Because of depth of cover, in-situ recovery methods must be used if the majority of these reserves are to be made available. Although a considerable amount of laboratory research and a fair number of field pilot tests have been conducted by several companies, oil production from these tar sands by in-situ operations cannot be anticipated before 1985 (14, 15). Reserves of oil in place in mineable areas, however, can be recovered by existing technology. The Great Canadian Oil Sands plant (42,000 barrels per day) in operation since 1967, has demonstrated that a readily marketable synthetic crude oil can be produced from the Athabasca oil sands. In the mineable area it has been estimated that about 85 billion barrels are recoverable as synthetic crude (15). Development of these tar sands deposits could make a contribution of 1.25 million barrels per day (2.6Q/yr.) to the Western Hemisphere's supply of crude oil by 1985 (7).

B. Natural Gas

The Potential Gas Committee (PGC) speculated that the total undiscovered natural gas potential of the U.S. is 1,178 trillion cubic feet (16). This estimate includes 851 trillion cubic feet for the contiguous states and 327 trillion cubic feet for Alaska. The PGC defined the undiscovered potential as reserves that will be found by test wells which can be expected to be drilled in the future under assumed conditions of adequate but reasonable prices and normal improvements in technology. The estimates are further divided into three categories: (1) probable, those reserves associated with existing fields; (2) possible, reserves in undiscovered fields in areas of established production; and, (3) speculative, potential reserves in new territories where there is no present production and the estimates are based on a minimum of information.

The PGC data indicates a major portion of this potential supply is below a depth of 15,000 feet (14%), in offshore marine areas (20%), or in Alaska (28%) (16). Thus, about 62% of the total potential is in locations which will be difficult and expensive to explore and develop. The locations of Alaskan and offshore potential will impose increased environmental, technological, and transportation costs.

Since 1968 domestic production of natural gas has exceeded additions to reserves, resulting in a decrease in proven resources. Some of the factors that have been mentioned to have caused this imbalance are: (1) an artificially low price of natural gas as compared with that of other fuels; (2) lack of economic incentives to expand exploratory efforts to increase reserves; and, (3) increasing pressure for the protection of the environment through the use of a non-polluting, clean-burning fuel (17).

In its 20-year forecast (16), the Bureau of National Gas predicted that unsatisfied demand for natural gas will be increasing over the period. However, even if these predictions are correct, part of the unsatisfied demand may be artificial. There is general agreement that the domestic market for natural gas is not in equilibrium because the Federal Power Commission (FPC) has held

TABLE I-V
NATURAL GAS

	10^{12} ft^3 (TCF)	Energy*	Years Use**
Proven Reserves	257	265	22
Potentially Recoverable	921	949	39
Reserve Additions			
1967	22	22.6	0.93
1969	7	7.2	0.30
1970	12	12.4	0.51
North Slope	26	26.8	1.10

*1.03Q/TCF
**at U.S. 1970 consumption rate (24.3Q/yr)

Source: References 7 and 16.

the field price of natural gas below the marketing clearing price. If the market price were raised to a price in equilibrium with alternate fuels, the artificial shortage might be satisfied at the higher price.

However, it is argued that the price elasticity of demand for natural gas is quite inelastic. For instance, a change in the relative price of nautral gas may not induce the consumer to revise his choice because of the high transfer costs relative to the operating costs involved in shifting to a different type of fuel. For example, once a major appliance has been installed in a house, there will be little or no substitution among different types of fuels. In the planning stage, on the other hand, the relative price of different fuels must have some effect on the decision-making process. In addition, an increase in price may cause the electric utilities to reverse the conversions to gas they have made in recent years.

One should note, however, that there may be institutional factors affecting gas supply which the ceiling price of gas simply may not be able to handle. For example, if the Department of Interior does not offer any leases for auction, or if it offers leases in areas with a low probability of finding gas, there is little that an increase in the ceiling price of offshore gas can do toward increasing the supply of gas.

The results for natural gas supply are summarized in Table I-V. In the category "potentially recoverable," we sum the "possible" and "speculative" estimates as defined above. Proven reserves, including Alaskan contributions, amount to 11 years use at the 1970 consumption rate of 24.3Q/yr. Reserve additions (7, p. 101) have declined drastically in recent years, while the contribution from the North Slope to proven reserves represented only a little over one year's use at the 1970 rate.

C. Coal

The U.S. has extensive known resources of coal. The 1970 National Power Survey estimated selective coal reserves at 220 billion tons (18). Selective reserves imply coal bed thicknesses of at least 3.5 feet for bituminous and higher grades of coal and thicknesses of at least 10 feet for sub-bituminous coal and lignite. A 50% recovery rate is assumed although it should be recognized that presently some operations are achieving 70% recovery. If we adopt 20×10^6 BTU/ton as an average value for the heat content of this coal, the energy represented by this resource is 4,400Q or 326 years of use at the 1970 consumption rate of 13.5Q/yr.

Notice that this estimate assumes particular recovery rates which are possibly minimal values if the price of coal increases enough to make profitable more thorough mining methods. Presently, the price is about $5/ton for strip-mined coal and $8/ton for coal from underground mines. Also, the heat of combustion was assumed to be 20×10^6 BTU/ton in converting from tons to BTU's, although actual heat content among various grades of coal varies from about 13.5×10^6 BTU/ton for lignite to 29×10^6 BTU/ton for the

TABLE I-VI
IMPACT OF COST OF RECLAMATION IN WESTERN UNITED STATES (Cents per ton of coal mined)

Seam Thickness (Ft.)	Approximate Recovery (Ton/Acre)	Reclamation Costs ($/Acre)		
		$ 500	$1,000	$5,000
5	9,000	5.6	11.2	16.8
10	18,000	2.8	5.6	8.4
20	36,000	1.4	2.8	4.2

best bituminous grades. Thus our reserves of coal are enormous, and the problem we face involves finding a way to utilize these resources in a manner which is acceptable economically and environmentally.

The environmental effects of coal production and its subsequent use depend upon the type of mining employed and the quality of the coal. Strip mining has inflicted severe environmental damage upon the coal bearing regions of Appalachia, the Midwest, and now somewhat in the Far West. **Congressional Quarterly** put it this way:

> Environmentally, stripping is anathema to plant life, wildlife, fish, and—ultimately—humans. Nothing and no one can live long in stripped areas where the vegetation has been denuded, the water poisoned by mine acid or thickened by silt and the soil itself rendered unstable, unproductive and ugly (19).

On the other hand, reclamation is becoming part of the business. The current average U.S. cost of reclamation is approximately $.02 per ton, but is expected to increase to $.34 per ton in 1985 (7, p. 145). Under certain conditions, this item alone can exceed $1 per ton. Some local reclamation laws are enforced and others are not, and some reclamation efforts are successful, whereas, others are not. More stringent laws are being enacted in some areas. New North Dakota strip mining laws, effective July, 1973, require salvaging topsoil to a depth of 2 feet, leveling and reseeding at an estimated cost of $1000/acre (20). Previously, only leveling and reseeding were required at about $600/acre (7). Successful reclamation has been practiced in some areas, notably by voluntary action in Wyoming by the Pacific Power and Light Company and in Pennsylvania through legislation. Cost estimates are $700/acre in Wyoming up to $5000/acre in Pennsylvania (19). The effects of these costs on coal prices are shown in Table I-VI. Presently, the total purchase cost of strip-mined coal is typically $5/ton.

Another serious environmental hazard associated with mining is the acid mine waste. The sulfur from the coal combines with atmospheric oxygen and water to form sulfuric acid. Coal seams exposed to the atmosphere accelerate this process.

Atmospheric environmental hazards due to coal usage result mainly from sulfur content, although particulates in stack gases are also of concern.

Existing and projected SO_2 emission regulations would preclude use of even the lowest sulfur coals from substantial areas of the U.S. (7, p. 158). Ninety-three percent of low-sulfur U.S. coal is west of the Mississippi River and, therefore, distant from the major demand centers in the East. Eleven percent of eastern coal is low in sulfur, but it is a low volatile coal and not well suited for most existing power generation plants.

We should note that according to Karel A. Weits, President of the Industrial Gas Cleaning Institute, equipment is available to reduce particulate emissions from industrial sources to acceptable levels (19, p. 70).

D. Hydroelectric Power

Hydorelectric power provided less than 3% of U.S. energy consumption in 1970. The problem with hydropower is not that it is finite, because it is indeed as infinite a source as the sun, but that there is a small quantity available in the places where it can be most

TABLE I-VII
WORLD WATER-POWER CAPACITY

Region	Potential (10^3 Mw)	Percent of total	Development (10^3 Mw)	Percent developed
North America	313	11	59	19
South America	577	20	5	
Western Europe	158	6	47	30
Africa	780	27	2	
Middle East	21	1	—	
Southeast Asia	455	16	2	
Far East	42	1	19	
Australasia	45	2	2	
U.S.S.R., China and satellites	466	16	16	3
TOTAL	2,857	100	152	

Source: Reference 21, p. 209.

easily used. For example, Table I-VII shows that the third world actually has the largest hydro potential (21, p. 209).

The world potential of 2,857x10^3 Mw is equivalent to approximately 85Q per year. Translated into equivalent fossil fuel input, this potential exceeds the world's gross energy input in 1971.* Although hydro power could theoretically satisfy those needs, there are restrictions which make it unfeasible. The basic problem in inaccessibility, not only on a world basis, but also within the U.S.

The heavily industrialized regions do not necessarily coincide with the regions of greatest hydro potential. Even on a local scale, industrial plants are not located, generally, at the hydro power site.

If the assumption can be made that the world's development of hydro power will peak at about 30% of maximum potential (the U.S. and Western Europe are currently at this figure), then the world's hydro power will be approximately 25.5Q. If the same assumption is made concerning tidal power, which has a maximum potential of approximately 1.9Q (21, p. 212), then the future development will be approximately 26.2Q.

In short, hydro power shows limited potential for providing any significant additions to U.S. power supply beyond the present 29 million kilowatts.

*Fossil fuel conversion to electricity involves the inefficiencies of thermal power plants. If we divide 85Q by 0.32, an average efficiency for thermal plants, we see that the hydro potential of 85Q actually could replace a fossil input of 266Q.

E. Nuclear Power

Energy from nuclear sources is only a small part of U.S. consumption at present, but its development is being pushed strongly by the Atomic Energy Commission (AEC) and to a lesser extent by private industry. We briefly discuss the current situation with respect to nuclear power.

Conventional fission reactors employ U^{235}, (0.7% of uranium in ores) the only naturally occurring isotope which fissions spontaneously following capture of a slow neutron. Each fission event produces on the average 200 million electron volts in kinetic energy, so that a gram of U^{235} potentially can produce 77.6x10^6 BTU, or about the thermal energy equivalent of 13.4 barrels of crude oil.

The reactor fuel is uranium dioxide, UO_2, which is the final product of a time-consuming and relatively expensive diffusion process designed to increase the percentage of U^{235} present in the uranium fuel with respect to U^{238}. Over 99% of natural uranium is U^{238} which does not fission in reactor environments.

Heat from the nuclear reaction is absorbed by water, pressurized water, or helium gas coolant which additionally acts to slow down the neutrons produced by fission which keep the reaction going. This heated material is used to run a conventional turbine to produce electric power. Efficiencies for water reactors are low (around 33%) while for the high-temperature gas reactor 40% efficiencies are possible (22, 23).

In all reactors some of the U^{238} present in the fuel elements is converted by neutron capture into plutonium (Pu^{239}) which can also fission. Plutonium has a half-life of $2.4x10^4$ years, and so does not occur naturally. However, its presence as a by-product of the fission of U^{235} increases the fuel value of the UO_2 inserted into the reactor. This idea, called "breeding," permits the conversion of more than 0.7% of natural uranium which is U^{235} into useful energy. For conventional reactors one actually finds that 1.5-2% of the enriched uranium used can be converted.

If the energy of the neutrons in a reactor is permitted to increase from thermal values (around 0.025 electron volts) to the 100,000 electron-volt region, breeding gains become dramatic, and one can look for conversion of up to 70% of the energy stored in natural uranium (23). Because the probability of fission decreases with increasing neutron energy (24) breeding reactors involve larger critical masses, and, because moderation of the neutrons is not desired, they tend to require exotic coolants, such as molten sodium in the liquid metal fast breeder reactor (LMFBR). In addition, breeder reactors produce much more fissionable plutonium by converting large fractions of U^{238}. Hence, the world's stock of uranium is used far more efficiently (a factor of 30-50). This means the cost of nuclear-generated electric power could become nearly insensitive to the cost of uranium ores for the foreseeable future (23).

The feasibility of water-cooled conventional reactors is well established. Twenty-five water-cooled reactors producing 12,840 megawatts (electric) are operating in the U.S. along with a single high-temperature gas reactor producing 40 megawatts (25). Breeder reactors, on the other hand, are very much in the development stage. The U.S. effort has concentrated on developing the components of a breeder program while European countries have emphasized development of actual demonstration plants. France, Britain and the Soviet Union expect to have plants operating at a few hundred megawatts within a year of this writing.

Estimates of uranium resources rely on data supplied by the AEC (7, 26-29). In Table I-VIII we list the proven and potential reserves at various prices per pound of U_3O_8, the naturally-occurring oxide of uranium.

Potential reserves are presumed to occur in extensions of known deposits and undiscovered deposits in known districts. Nearly all these reserves are located in less than 10% of the regions in which uranium is known to occur (7).

The thermal energy available from one million tons of U_3O_8 depends on the percentage of uranium converted in reactors. For conventional reactors this number is of the order of 1.5%. This assumption leads to an energy production of 895Q/10^6 tons U_3O_8, which is equivalent to 29,800 million kilowatt years. Dividing by the 1970 generating capacity of nearly 350 million kilowatts we find that a million tons of U_3O_8 would supply nearly 85 years of power in conventional reactors at this production rate. Proven reserves under $10/lb. U_3O_8 are 0.423 million tons, so that these reserves can only supply power at current use rates for approximately 36 years.

For a system involving breeder reactors this number is multiplied by a factor of 30 to 50, and the supply of fuel in this case is not a source of concern for the forseeable future.

The urgency of the AEC program to develop the breeder reactor stems from the short lifetime predicted for fuel supplies burned in conventional reactors. AEC publications combine this relative scarcity of uranium with projections of rapidly growing electricity demand to emphasize the need for the rapid development of breeder capability

TABLE I-VIII
DOMESTIC SOURCES OF URANIUM

Production Cost ($/lb)	Proven Reserves	Potential Reserves
	1(10^6 tons U_3O_8)	
8	0.273	0.460
10	0.423	0.650
15	0.625	1.000

(28, 29). Energy companies, on the other hand, stress the need to provide economic incentives for further exploration and the reasonable prospects that incentives will lead to discoveries (7, p. 185). Figure I-8 illustrates industry response in the past to market incentive. Both production and reserve additions fell drastically when the AEC announced that ore discovered after 1958 would no longer be purchased at prices which had encouraged exploration during early phases of the development of commercial reactors (26, p. 457). By the late 60's predictions of future demand for nuclear power stimulated renewed exploration. Recent fall-off in reserve additions may be due to the slow down in plant sitings due to environmental objections and industry uneasiness about the future disposition of the 50,000 tons of U_3O_8 held in AEC stockpiles.

It is probable that strong efforts will be made to expand nuclear capacity involving conventional reactors in view of the relatively plentiful supply of uranium currently available and the reasonable prospects that additional amounts can be supplied. In addition, the increase in the cost of electricity due to a doubling of uranium costs is expected to be small, less than 10% (7, p. 182; 22, pp. 30-31).

A breeding cycle which converts naturally occurring thorium (Th^{232}) to the fissionable uranium isotope U^{233} has been proposed for use in the helium-cooled high temperature gas reactor (HTGR). Like plutonium, U^{233} does not occur in nature, so breeding is the only source of this potential reactor fuel. Thorium has not been subject to great demand in the past, so that estimates of reserves available are meaningless at this time (7, 26, 27). Rapid expansion of the HTGR capacity could generate increased interest in thorium supply.

F. Fusion

The fuel for a thermonuclear fusion reactor will most likely include lithium (30). The proven reserves of lithium in the U.S. are around one million tons (26, p. 372). Moreover, these reserves exist primarily in two locations in the U.S. The known reserves would undoubtedly go much higher if extensive exploration were undertaken, so that if thermonuclear reactors are to be employed in the future it is not expected that supplies of lithium will limit their potential (26, p. 375).

G. Other Elements

Inventories of known world resources and projected discoveries of metals indicate an adequate supply of most metals into the next century (31, p. 58). A few elements appear to be in short supply with mercury and helium leading this list. Within the United States the natural resources have been heavily mined, and a long term capability for self-sufficiency does not exist. Some metals critical to the manufacture of airplane engines (columbium, nickel, chromium, and cobalt) are available in sufficient supply only through importing.

More ore deposits will be found. Large areas of the earth including the ocean floors have not been explored. Known lower grade ore deposits will become economic to mine with rising prices and improved technology, but this will be accomplished only at a price of increasing energy consumption. The availability of energy may be the ultimate limit to the development of these resources.

H. Summary

Energy reserves from the principal energy sources other than petroleum and natural gas are summarized in Table I-IX.

(The data in this table combined with those in Tables I-IV and I-V illustrate an important feature of the energy dilemma.) The energy resources we are accustomed to using are being consumed at rates which exceed our ability to replace them through new discoveries and improvements in technology. To expand our consumption of these fuels we must pay higher costs—to develop marginal resources within the U.S. or import in a world market for energy which is characterized by rapidly increasing competition for sources of supply.

The alternate energy sources which we possess in large amounts (coal) or which we show promise of developing because of our relatively high level of technical ability (nuclear) are under increasing challenge because of their costs and their implications for the environment. (It would seem that we have no choice but to press the development of these sources, but the extent to which they will become acceptable in the future is difficult to forecast.) Even if these additional sources are developed we must face the fact that we currently require petroleum and natural gas as **transportable** energy sources. Thus the prospects for developing alternate fuels as well as alternate sources of primary energy must be assessed.

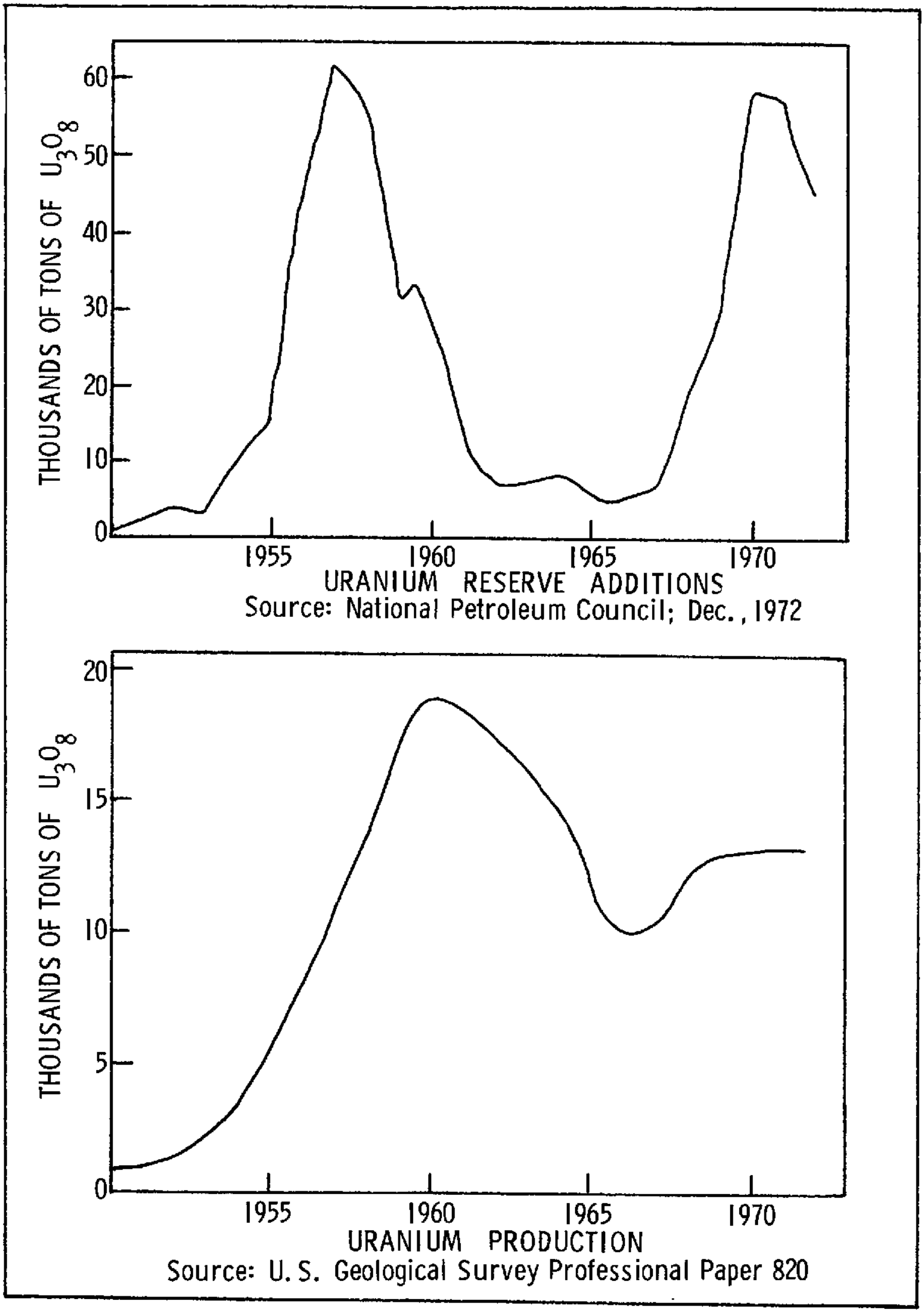

THOUSANDS OF TONS OF U_3O_8
0
10
20
30
40
50
60
1955
1960
1965
1970
URANIUM RESERVE ADDITIONS
Source: National Petroleum Council; Dec., 1972
THOUSANDS OF TONS OF U_3O_8
0
5
10
15
20
1955
1960
1965
1970
URANIUM PRODUCTION
Source: U. S. Geological Survey Professional Paper 820

FIGURE 1.8

TABLE I-IX

RESERVES OF COAL, HYDROELECTRIC POWER AND NUCLEAR FUELS

Source	Proven Reserves	Years use at 1970 Consumption Rates
Coal	220 billion tons	326
Hydro	29 million kilowatts	effectively infinite
Nuclear		
Conventional	423 million tons U_3O_8	36
Breeder	423 million tons U_3O_8	over 1000

	Oil and Gas	Coal	Synthetic	Nuclear
Case I	drilling up 5.5% per year, high discoveries per foot drilled	production up 5% per year	maximum development possible, no constraints	till 1985 all new baseload plants nuclear
Case II	3.5% growth rate, high discoveries	3.5% growth rate	moderate development	current problems solved quickly
Case III	3.5% growth rate, discoveries equivalent to present experience	3.5% growth rate	moderate development	less than Case II, equivalent to AEC optimistic forecast
Case IV	rates and discoveries equivalent to present	current problems continue	current problems continue	current problems continue

The data for assessment of energy resources presented in this chapter is derived from estimates made by institutions which have a vested interest in questions of energy supply. The large, horizontally integrated energy companies are both the sources of much of the basic data concerning energy supplies and the potential subjects of energy policies which may be formulated. Similarly the AEC, which is the source of the basic information on nuclear power, has an interest as an established bureaucracy in a strong nuclear program. It may become increasingly important in the future to have this basic supply data also supplied by other objective sources.

Finally we may ask whether the standard consumption projections (of which Figure I-7 is a conservative example) are inevitable. The wastage of energy in the U.S. is enormous. On the other hand, the means of achieving the needed efficiencies in energy use lie largely in our social institutions, for the necessary technology is largely extant. If we are to maintain a national social policy of material well-being and gradual improvement in the lot of our disadvantaged, it is essential that our social processes, attitudes, and institutions evolve from historically reckless energy consumption to a practice of energy conservation.

A more difficult problem is presented by attempts to decouple increasing energy consumption from economic growth. There have been few periods in history during which economic growth proceeded at a rate significantly larger than the growth in energy consumption. We may be called upon to produce the conditions for such a period in the near future and to attempt to accelerate dramatically the rate at which the energy cost of economic growth declines.

I. B. The Future: Some Alternatives

The exponentially rising demand for energy in the United States coupled with our growing inability to fulfill that demand has created a situation that cries for a strategy of solution before desperate measures are forced upon us.

Within the confines of current trends in technology, the first part of this section deals with some economic and political considerations related to oil imports. Some resource and technological alternatives to this scenario are offered in the second part. Some institutional constraints to solution are discussed in the third.

The fourth part presents an outline of various policy measures that could be taken to bring energy demand in line with supply.

I. B. 1. Portents of the Future: Oil Imports

No solution to this nation's energy problems will come through exclusive attention to either demand for energy or the supply of energy; realistic solutions will not be possible until the relationships between supply and demand are recognized and factored into solution strategies. These interactions may be as obvious as new cars needing more fuel than older cars, or as subtle as the politics of national and international oil markets. In today's world oil plays a unique role: it serves as the energy currency because all other energy is judged relative to it and because it can be easily substituted for most other fuels. Therefore, what follows is a discussion of oil, with the emphasis on oil imports.

The historical trend in U.S. oil production and net imports since 1945 are indicated in Figure I-9 (7, 32, 33). It can be seen that 1947 was the last year in which the United States exported more petroleum than it imported. Of course we do export oil—85 million barrels in 1968—but the net balance is a deficit. The figures on future oil imports are subject to significant variations. President Nixon's Task Force on oil imports predicted in February, 1970 that not until 1980 would oil imports reach the level of 5 million barrels per day. Yet already in 1972 imports had climbed to 4.75 MMB/D.

In December, 1972 the National Petroleum Council's Committee on U.S. Energy Outlook issued a report which presents detailed projections through 1985 of energy supply and demand (7). Their estimates of imported oil were based on permutations of various values for three factors concerned with fuel supply and demand.

First, four supply cases were postulated for each of the primary fuels with the following assumptions defining each case for a particular fuel:

Second, total energy demand was projected by NPC for three levels of demand considered reasonable:

In connection with these figures, it may be noted that this report earlier forecast 4%.

Third, considerations of fuel mix for electric utilities generated six different possible conditions affecting projected oil imports. They ranged from a prediction that oil consumption would equal 5% of total utitlity fuel needs by 1985 (assuming coal and oil at 1970 levels, gas one-half of 1970, and nuclear carrying all growth) to a prediction that oil consumption would represent 36% of utility fuel if coal and nuclear use are restricted. Their most likely case predicts oil will be 10% of utility fuel by 1985 versus 12% in 1970.

Combinations of these factors led NPC to predictions of the following range of oil import needs (Table I-XI):

TABLE I-X

ENERGY DEMAND GROWTH RATES, % PER YEAR

	1970-81	1981-85	1971-85
High	4.5	4.3	4.4
Intermediate	4.2	4.0	4.2
Low	3.5	3.3	3.4

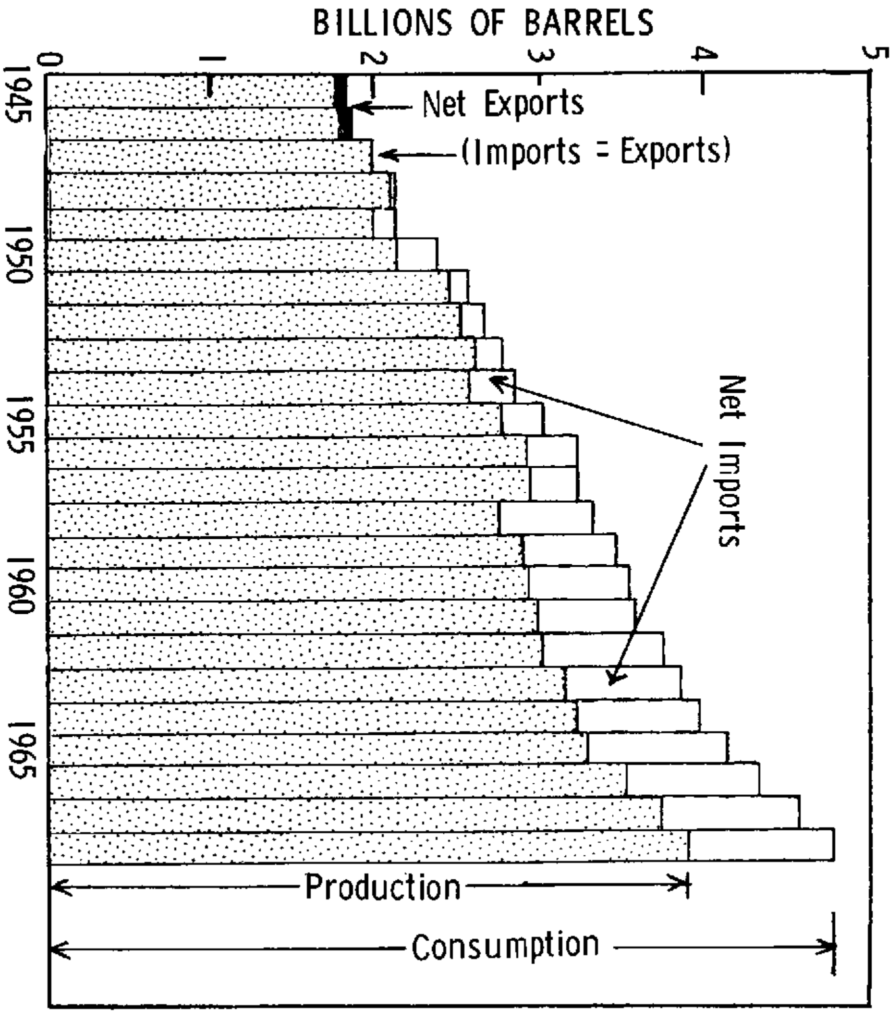


FIGURE 1.9
U. S. PRODUCTION, NET IMPORTS, AND CONSUMPTION OF LIQUID PETROLEUM
Data from U. S. Bureau of Mines

TABLE I-XI
PREDICTED OIL IMPORTS

Energy Demand	Oil Demand for Electricity	Fuel Supply	Oil 1975	Imports 1980	(MMB/D) 1985
1. low	expected	II	7.4	4.2	2.8
2. intermediate	expected	I	7.2	5.8	3.6
3. intermediate	expected	II	7.4	7.5	8.7
4. intermediate	expected	III	8.5	10.6	13.5
5. intermediate	expected	IV	9.7	16.4	19.2
6. intermediate	high	III	9.0	13.7	17.1
7. high	expected	II	7.4	8.8	11.1
8. high	expected	III	8.5	11.9	15.9

The first alternative is not deemed realistic; the demand seems too low. Alternatives 2, 3, and 4 involve the development of synthetic and nuclear energy at rates higher than those supported by this study. If alternatives 4, 5, and 8 are accepted as reasonable, imports in 1985 would range between 13.5 and 19.2 MMB/D.

From data contained in the NPC Report a rough estimate shows oil imports of 24.6 MMB/D by 1985 for the "worst possible" case—high energy demand, high oil requirements for utilities, and an extension of today's fuel supply situation (Case IV). At the other extreme, total national independence from imported energy could be achieved by 1985 if the electric utilities were to engage in a large shift toward coal and/or nuclear energy.

In past years the United States has depended primarily on Western Hemisphere nations, particularly Venezuela and Canada, for imported petroleum. Now oil also comes in increasing quantities from Africa and the Persian Gulf states, or more importantly, from the members of the Organization of Petroleum Exporting Countries (OPEC). The OPEC countries' control of free-world reserves is demonstrated by Figure I-10 (34, p. 25).

Saudi Arabia has increased its capacity to 9 MMB/D in 1973 compared to 6.5 MMB/D in 1972 and will reach 11.7 MMB/D by late 1975. Sometime in 1974 Saudi Arabia will probably be producing more than either the U.S. or the U.S.S.R. and thereby become the world's number one producer. The Saudi Arabian minister of petroleum, Ahmad Zaki Yamani, has announced a goal of 20 MMB/D by 1980, a goal that "already seems improbably high" (35). Based on reserves and other considerations, the principal long-term supply sources for the U.S. are Iran and Saudi Arabia.

Economic and Political Implications of Oil Imports

Given the need for the U.S. to import oil, the presence of foreign reserves, and the installed capacity to produce the oil, two other basic criteria must be met: (1) our willingness to buy, and (2) the willingness of the country-of-origin to sell to us.

Our willingness to buy will be primarily an economic, not a political decision, presuming no major change in current world relationships. Our willingness to buy will depend on the options open to us. It is true that the price of alternative energy represents a lid on the

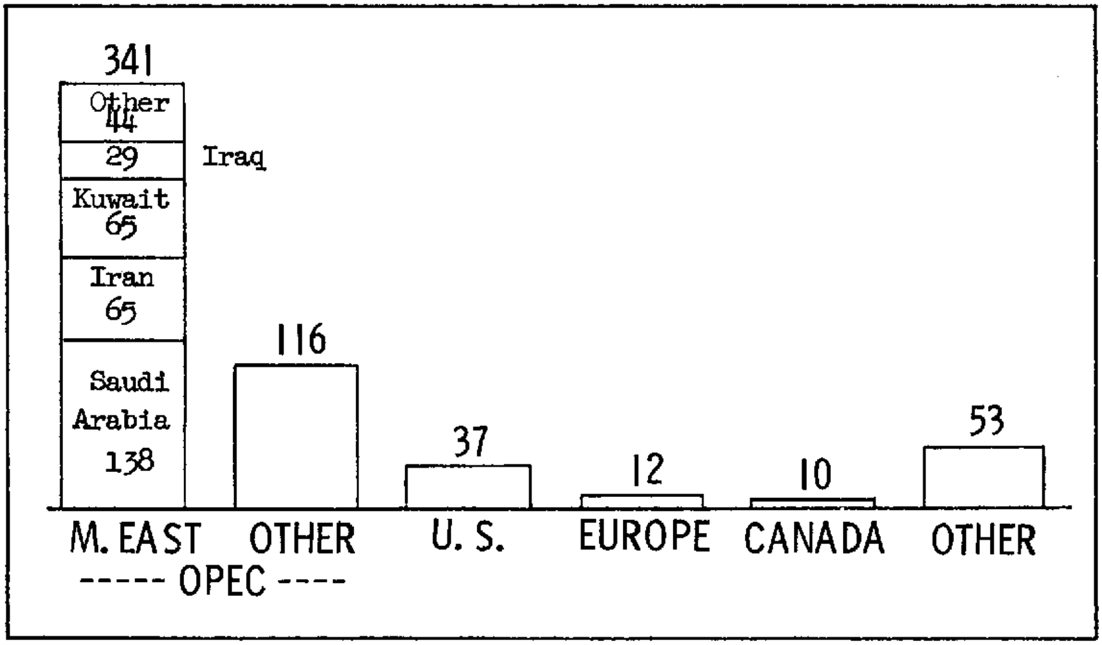


FIGURE 1.10

FREE WORLD CRUDE OIL RESERVES, END 1972 (Billions of bbls.)

Source: **Oil and Gas Journal**

cost of imported oil—but it may well be a flexible, porous lid. Flexible because the price of alternative sources also continue to rise; porous because even a national decision to develop alternate sources would involve a considerable time lag.

The U.S. will be competing in the international oil market against countries experiencing greater growth rates in energy demand. This can have diverse effects. On one side we (and others) will be able to outbid many under-developed countries. India, for instance, has already reduced outside fuel purchases (35, p. 462). At the other extreme the U.S. now is facing competition from other industrialized nations. Europe and Japan are the primary competitors: Europe imports 90% of its oil (13 MMB/D), Japan nearly 100% (4.6 MMB/D). By 1985 U.S. consumption may double but in the same period Japan expects a 156% rise in imports (36, p. 676)

A producing country seemingly bases its willingness to sell on the choice between current and future production and income. At present there appears to be a conscious effort by some countries to defer production at the expense of current income. Libya instituted production restrictions in 1970; in 1972 Kuwait limited production to 3 MMB/D, and Iran is planning not to exceed 8 MMB/D. These measures have been taken for many reasons. One is that it will lengthen the time period that those countries will have use of a finite resource base of consequence to the world. This presumes no significant substitute for a petroleum economy will be found that would devalue the **in situ** oil. In thus acting to limit their production, the producing countries are simultaneously depending on increases in price to raise their total income and admitting that current and projected income levels are more than sufficient for their purposes. Projected incomes are large, though estimates vary widely. One source (12) suggests a cumulative income total for the 11 OPEC countries of $500 billion for 1971-1985, with $27 billion expected in 1975 and $45 billion in 1985. Another (36, p. 676) mentions an OPEC income in 1980 between $40 and $80 billion, cumulatively $250 to $360 billion. Akins (35) predicts for Middle East and African countries $19.1 billion in 1975 and $63.4 billion in 1980 (35).

Notwithstanding the variation in the estimates and the fact that not all of these sums would turn into excess liquidity, there is the possibility that this liquidity would be used as a destabilizing force. Some countries (e.g., Iran) have large absorptive capacity (multiple investment outlets); others, particularly those with small populations, do not. The suggestion is made that the oil-producing countries should be encouraged to undertake investments in the oil-consuming countries. An initial move in this direction has already taken place with the agreement between the government of Iran and Ashland Oil to establish a joint producing-marketing organization. Of course profitable investments will become additional sources of revenue. Adelman argues that the best policy is to maximize production and income; he postulates that excess income, if invested, will show greater growth in value than oil **in situ** (37).

Whatever assessment one makes of the long-term strength of OPEC and of the need of a countervailing force in the form of a block of importing countries, one fact seems inescapable—the days when the oil companies could set the posted price of oil at $1.80 per barrel are over. A spokesman for one of OPEC's members has made this painfully clear (36, pp. 680, 682-84, 686). An irreplaceable and important resource such as oil must be priced at its true (scarcity) value. Not only does economics dictate this but it is also a question of equity. The oil-producing countries demand what they consider a just price for a resource that one day will no longer be in existence. OPEC's success in its dealings with the oil companies has caused steep rises in oil prices. No attempt is made here to detail the conflict or to dwell on the question of justice. Simplistically, the world wants oil, OPEC has it, and this in essence determines whose "best interests" prevail (38, p. 273).

I. B. 2. Alternate Energy Sources

Demand is rapidly burgeoning and will continue to do so while domestic supplies are leveling or declining; but all is not hopeless. There are alternate sources and technologies that can be applied to bring supply into better balance with the human and environmental needs of this nation. These needs will be summarized before developing the means.

A. Why Diversify?

Six percent of BTU consumption for the United States in 1970 went for non-energy uses such as petrochemicals (7, p. 16). This use is projected to increase to 7% of total

BTU consumption or 9.2Q (quadrillion BTU) by 1985 (7, p. 16). For comparison, this would consume the oil on the Alaskan North Slope in 15 years (7, p. 72).

The non-energy users of fossil fuels cannot substitute energy sources such as solar but need the chemical structures found in fossil fuels for their basic building blocks. Because countless products made from fossil fuels, such as plastics, are used extensively in the United States economy, a large future potential exists in non-energy uses of fossil fuels. Switching to alternate energy sources will help ensure a supply of non-substitutable fossil fuel chemical building blocks for future generations (39).

The desirability of the United States becoming dependent on the Middle East for a large portion of its crude oil supplies has already been shown to be suspect; but of greater importance is the impact on the American people of the $20 billion trade deficit in oil purchases predicted by Lichtblau to occur in 1980 (40). The impact of dollar devaluation on food exports is already being felt in the food budgets of American families. How much food and fiber, basic necessities of life, will $20 billion in oil cost in 1980? Without major alterations in our economic system and international eco-political policy, it is not feasible to buy that much oil in 1980 and more in 1985 and more in 1990. The economic impact of reduced demand will fall on the American people.

Related to the potential impact of foreign trade is the socio-economic impact of the domestic energy industry. In the United States it is only necessary to enumerate the ten or twenty largest corporations and then to identify the energy oriented corporations in order to realize the enormity of their power and the profitability of the industry. In the general energy industry the glamour has centered on petroleum. In very recent years the insatiable demand for petroleum has outstripped even the considerable ability of the major oil companies to provide the required products. Recognizing the dwindling reserves and production in both oil and gas, the major oil companies used their large cash flows to become major coal and uranium concerns (as documented in the next section on institutional factors). Thus, the majors have earned the right to call themselves "Energy Companies." It is interesting to note that the National Petroleum Council is now "encouraging" Congress to divert irrigation water from food to coal gasification for the production of synthetic natural gas (7, p. 11).

Because of the dominance the major oil companies have in energy exploitation technology, it is postulated that the development of alternate technologies, by others, might provide healthy competition of benefit to the American consumer.

Today's technology of fossil fuel exploitation, leads beyond present and potential socio-economic problems. Environmental problems exist in nearly every phase of the energy cycle—extraction, transport of primary fuel, conversion of useful work, and electrical transmission. Each of the present major sources of primary energy has its own unique problems which will increase in complexity as the nation's appetite for more and more energy continues to grow. In the latter part of this century, we will probably be forced to considerably reduce the use of fossil fuel.

During the employment of fossil fuels, the high temperatures of combustion and the requirement for certain stoichiometric ratios cause atmospheric nitrogen to combine with oxygen to form nitrogen oxides. The sulfur content results in sulfur oxides. The incomplete burning of the fuel also causes the emission of carbon monoxide and unburned hydrocarbons. Fuel additives which improve the burning characteristics of the fuel are also significant sources of pollution. Spills of the petroleum fuels can cause severe environmental damage as well as being extremely dangerous to life and property in the event of ignition. Reforming of hydrocarbons during combustion can also result in the emission of carcinogenic compounds.

Natural processes can to a limited degree remove or modify many of the emissions from the combustion and petroleum spills. In many areas, however, these processes are overwhelmed by the high concentrations encountered, and the concentration of emissions and the number of spills will become greater as population centralization continues and usage increases.

There are a number of alternative courses that can be pursued at this time. One course of action would be to do nothing and accept the consequences. Another would be to restrict growth and redistribute population, which is highly unlikely. A third alternative is the development of cleaner engines and desulfurization, which has not been accomplished. The most desirable alternative would be to use a substitute fuel that has all the advantages of petroleum fuels and none of the disadvantages. Hydrogen may be that fuel. Its development should be encouraged in the light of (1) the environmental impact of fossil fuels and (2) the finite capability of petroleum fuels.

B. Hydrogen: The Nexus of Energy

In order to satisfy the energy demands of the future, alternate sources of energy must be developed and new methods of energy conversion must be devised. A twentieth century primary source which would be developed is coal, which can be gasified into an easily transportable clean-burning fuel; but to satisfy our twenty-first century needs for primary energy, we must rely on nuclear, solar and geothermal energy. These are intrinsically sources of energy that can be transmitted to the consumer in the form of electricity; but when storage, transmission and distribution costs are considered, the need for another energy carrier becomes apparent.

According to Gregory hydrogen is the ideal medium for storing and carrying energy (41). It is one of the most abundant elements on this planet since it is a component of water (H_2O), and when burned, it reverts to water. Under proper conditions its burning cycle is almost pollution-free.

The major cost advantage of hydrogen over electricity comes in the transmission and distribution costs, especially when one considers that future environmental demands will force electric transmission lines underground. Wische gives these costs as follows (42, p. 1325):

TRANSMISSION COSTS	$1 100 MM BTU MILES
Hydrogen	.02-.04
Electric (underground)	.20
DISTRIBUTION COSTS	**$/MM BTU**
Hydrogen	0.66
Electric (overhead wires)	2.55

If the hydrogen transmitted had to be converted into electricity before final distribution with an efficiency of 30%, the above hydrogen costs for transmission would have to be multiplied by 3.33 before making the comparisons with electricity. Fortunately, however, hydrogen is a useful fuel which could eventually find direct application in transportation, space heating, cooking and refrigeration, as well as electrical generation.

There have been several suggestions for using present natural gas pipelines for hydrogen (43, 44). Martin points out that, although hydrogen leaks more readily than natural gas the energy loss may be about the same for both gases (45).

Cost studies by Marchetti provide a base for cost comparison of natural gas and hydrogen gas pipelines (45, p. 1325). To deliver energy at the same rate, the capital costs and transportation costs for hydrogen are 40-50% greater for hydrogen than for natural gas. The increased costs reflect the larger pipelines required by the comparatively low density hydrogen.

If conversion from existing natural gas lines to hydrogen gas delivery is considered it is necessary to increase the pumping power by a factor of roughly three in order to deliver equivalent amounts of energy (46, p. 23). This factor results from assuming equal pressure drops in both systems and reflects the larger volumetric flow rates required.

In addition to its cost advantages, hydrogen has significant environmental advantages in transmission. While today's technology of electric transmission requires unsightly towers on rights-of-way up to 200 feet wide, gas lines use under 20 feet. The 300,000 miles of electric lines extant in 1970 occupied an area approaching the size of Connecticut. The 500,000 miles predicted for 1990 are expected to consume over 11,000 square miles, or the equivalent of Massachusetts, Connecticut, and Rhode Island (47, p. 116). Hydrogen transmission would require one-tenth this much land. To this may be added the aesthetic purity of underground lines.

Pipeline transmission also has some long-term economic and environmental advantages relative to the fabrication of facilities. Copper is in short supply. Its competitor in electric transmission, aluminum, consumes vast amounts of power in refining. The problems attendant to both copper and aluminum would be alleviated by substituting pipeline transmission.

The economics of hydrogen transmission enable the production of power at remote locations where the earth offers heat sink capabilities sufficient to absorb waste heat without thermal pollution.

Hydrogen is also an ideal energy storage medium. Well-developed natural gas technology may be applied to store hydrogen underground or in tanks, pressure or cryogenic. In addition, pressure-balanced storage in the ocean depths has been proposed for offshore facilities. Wherever it is stored, hydrogen would enable leveling the peaks and filling the valleys of daily and seasonal load on generating facilities. Similarly, it would enable storing energy produced from variable sources (e.g., wind to be discussed later).

But above all, hydrogen is the one energy carrying medium that inter-connects all potential forms of energy—fossil, nuclear, solar, and geothermal and offers the means of orderly transition to new energy sources.

To reiterate, hydrogen is the clean fuel. It may be produced, stored and transmitted with a minimum of environmental impact, and reverts to water when burned. Cleanliness, potential economics, and the infinite nature of hydrogen favor conclusion that hydrogen should replace petroleum as the fuel against which all others are measured. But the hydrogen ecomony is still in the future, especially if huge quantities of hydrogen must be produced by electrolysis via solar or nuclear sources. In the interim, we must turn to our abundant supplies of coal from which we may synthesize substitutes for petroleum.

C. Coal: The Twentieth Century Primary Fuel

Coal is an underdeveloped energy source that has the potential to supplement and replace dwindling energy sources such as petroleum. Coal-oil gas refineries currently being designed will produce LPG, pipeline gas (natural gas), "light refinery liquid", a clean burning coal for plant utility fuel, and electrical power (see Figure I-II). By-products of these conversion plants can be processed for their chemical content and also provide basic construction material. Additionally, coal conversion plants produce hydrogen gas, currently used in processing, that could be used directly as a fuel for transportation, industry, and the home.

This is an integrated, synthetic concept in resource employment which contrasts markedly with the fragmented, parochial approach so typical of our technological society. Ecah constituent of the coal is put to its optimum chemical, physical or energy use and the product is cleaned in the process. The process can even employ the by-product

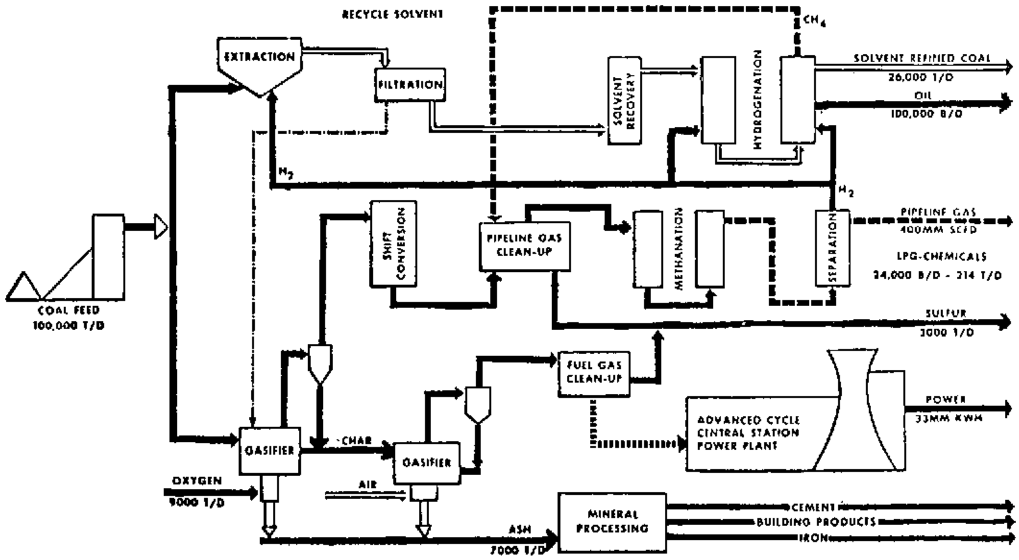


FIGURE 1.11
MULTIPRODUCT COAL CONVERSION PLANT
Source: Office of Coal Research

oxygen if some of its electric power is used to electrolyze water to secure hydrogen.

Coal conversion is one energy area that enables an orderly national redirection from petroleum fuels to hydrogen fuel. Conversion plants would initially produce "light refinery liquids" that can be converted into JP-4 and gasoline. As hydrogen fueled equipment is developed, coal conversion plants can be switched to hydrogen gas. This flexibility coupled with large reserves makes coal the most favorable intermediate energy source while solar and fusion systems are being developed. This process could allow the nation to become energy self-sufficient in the eighties and start on the road to the clean fuel economy.

But all is not ideal, for the major reserves of coal in this country are found in the western states, remote from eastern demand centers. These coals are shallow, suitable for strip mining on a large scale, and low in sulfur content, but a major drawback to their utilization in coal conversion plants is available water resources.

The environmental degradation problems associated with large strip mines need additional study. The problems appear less in the western states where the low sulfur content, more level terrain, and low amounts of precipitation do not aggravate the situation compared to the eastern coals. An in-depth look at the strip mining procedures and locations is required by an independent group to determine critical environmental factors and suggest modifications of present strip mining procedures to reduce environmental impact.

The Task Force on Energy listed the following goals for coal research and development (92, p. 93).

1. Mine and process coal without unacceptable environmental effects
2. Use coal for generation of electricity without unacceptable pollution of air or water
3. Convert coal to clean gaseous and liquid fuels
   —find most economical means
   —methanation (conversion of fuel-gas to high BTU pipeline gas)
4. Design and build multiproduct coal refineries
   —low BTU fuel gas
   —high BTU pipeline gas
   —high quality metallurgical coke
   —liquid fuels
   —byproduct chemicals

Research in coal production methods and conversion of coal to other fuels has been funded at a comparatively low level. The research funding request for fiscal year 1973 was $94.4 million. As a comparison, $65.4 million was requested for the AEC fusion program whose technology is not foreseen to be useful until about the year 2000, and $356.4 million was requested for the further development of nuclear power. Nuclear power is presently viewed as applicable only to the generation of electricity, whereas coal research could result in broadly useful, clean fuels.

D. Primary Energy for the Next Millennium

Due to the ultimate depletion of fossil fuels, future primary energy must be developed from nuclear, solar and geothermal sources. This section will discuss the potential and problems of developing these forms of energy.

Nuclear

This energy constitutes one of the possible alternatives to fossil fuels. Today's fission reactor has a finite life ending sometime in the next century. The breeder reactor would extend the technological life of fission greatly but magnifies already monumental environmental and social problems. Thermonuclear fusion is a longer range possibility but is still very much in the theoretical stage.

Several series of reactions have been proposed for extracting nuclear energy through fusion. The deuterium (H^2) cycle

$$H^2 + H^2 \rightarrow He^3 + n$$
$$H^2 + H^2 \rightarrow H^3 + H^1$$
$$H^2 + H^3 \rightarrow He^4 + n$$
$$H^2 + He^3 \rightarrow He^4 + H^1$$

is exothermic and requires an ignition temperature of several hundred million degrees. The lithium deuterium cycle

$$Li^6 + n \rightarrow He^4 + H^3$$
$$H^2 + H^3 \rightarrow He^4 + n$$

has a lower ignition temperature, some forty million degrees, but ties power production to the world's lithium supply.

The extreme temperatures involved in fusion (comparable to the solar central temperature) impose formidable technological obstacles to extracting nuclear energy in a practical manner in a habitable power plant. Thus, current research is directed at demonstrating the **feasibility** of fusion reactors; the costs of systems engineering and economic analysis to which fission reactors are subjected has not even begun in the case of fusion power. Thus, although the potential for fusion may be great, prediction of its lead time for significant contributions to energy use must remain vague.

The following questions which dominate prospects for expansion of nuclear capacity deserve comment:

(a) Thermal Pollution: The thermal pollution problem exists for both the conventional fossil fuel plant and the nuclear plant. The important fact is, however, that ecological damage is not caused by the quantity of heat dispersed, but by the temperature increase resulting from this added heat. The question to be asked then is how can heat be dissipated and absorbed by the surroundings so that there is a negligible temperature rise and, therefore, no thermal pollution? Various options are available to insure negligible thermal pollution, ranging from the actual diffuser design to the use of cooling towers. Ultimately, because U.S. rivers and lakes have a limited capacity to absorb this heat, nuclear plants must use the cooling capacity of the sea.

The nuclear power development scheme of ocean shore front plants and neutrally buoyant underwater plants could be built to have negligible thermal effects. Ocean based nuclear plants could provide direct current power for the production of hydrogen from sea water. Land based plants would be best sited on oceanfront locations rather than estuaries, due to the delicate nature of marine life found in coastal inlets.

(b) Accidents: The safety record of nuclear reactors has been exemplary, yet the fear of accidents has made siting additional plants a major problem. Safety research has allegedly not kept pace with technical research in the U.S. breeder reactor program (48); the AEC now faces the task of producing a long overdue environmental impact statement for its entire program.

(c) Low-level radioactivity: An unresolved controversy exists as to the extent of the potential for genetic damage and/or carcinogenesis in large populations as a result of a gradual raising of the level of background radiation (49). The effects of sustained low dosage radiation are not known, because sufficiently large populations (animal or human) have not been tested at these levels. Critics of the proliferation of reactors (and hence the inevitable raising of background radiation levels) stress the possibility that we may discover harmful effects too late to counter them.

(d) Radiation damage to materials: In breeder reactors the structural degradation of stainless steel from high energy neutrons has been found to be considerable.

(e) Diversion of fuel: Fuel in breeder reactors is the same grade material that is used in nuclear explosive devices. The major obstacle to the construction of a nuclear explosive device is the difficulty in obtaining such material. In a large breeder program, it seems very difficult to rule out the development of a black market in plutonium which could affect national and international stability.

(f) Waste disposal: Perhaps the crucial objection to a strong nuclear development program concerns the radioactive wastes generated. Wastes from conventional fission reactors have half-lives of 30 years and require storage (or isolated disposal) for about 500 years. Present techniques for storage range from above-ground tanks containing liquid wastes, which require cooling, to solidification and storage in underground bins. Neither method has been established as entirely reliable. It is estimated that the total accumulated solid wastes associated with a program of continuing nuclear reactor development will amount to a half million cubic feet by the end of the century, at a time when nuclear reactor development will be only in its growth stage as compared to its current stage of infancy. If such a program is undertaken, this lethal legacy will be left for future generations to "sit on" for their entire lifetimes.

Breeder reactors compound the problem by several orders of magnitude. The radioactive wastes from breeder reactors include large amounts of plutonium, which has a half-life of 24,000 years and would therefore require isolation from man and man's environment for several hundred thousand years (50). Even if the technology of isolation can be resolved, the morality of assigning this responsibility to future generations is suspect.

The end products of the fusion reaction are almost entirely benign. But some of the intermediates and the equipment in which they are used present a modest radiological hazard (51, p. 12).

(g) Economics: The information available is sketchy and sometimes contradictory, but there is evidence that nuclear power is far from economically competitive. Costs of construction per KWH are rising to multiples of fossil fueled plants; nuclear fuel appears to be uneconomic without the indirect Federal subsidy of its refinement. Cheap, limitless nuclear power in the future may be a myth.

Nonetheless, William R. Gould, Chairman of the Atomic Industrial Forum, told the National Science Teachers Convention:

> Nuclear power appeared on the scene at the precise moment in human history when it was desperately needed to solve an otherwise impossible dilemma. It is as though Providence had laid out a path for man to follow.

Proponents have argued that, in spite of the environmental problems associated with nuclear energy, it is a much too valuable source of needed reliable energy not to develop. But these environmental problems extend beyond technology into moral issues that must be resolved before nuclear power is allowed to burgeon. Nuclear energy is not the only solution to the energy problem.

2. Solar Energy

This nation must learn to effectively utilize energy from the sun. There is no pollution problem connected with the generation of solar energy and, uniquely, no heat is added to the global thermal balance. Solar energy appears naturally in several forms, and includes:

(a) Wind
(b) Ocean Thermal Gradients
(c) Photosynthesis
(d) Solar Thermal Conversion
(e) Photovoltaic Generation

These energy conversion methods will now be considered individually.

(i) Wind: One direct form of solar energy is wind caused by solar-induced atmospheric and oceanic processes. Energy from wind has been estimated as averaging 80 billion megawatts over the northern hemisphere, increasing to 800 billion in the winter and decreasing to 60 billion in the late summer and early fall (52, p. 3). (Current U.S. electric capacity is about 400,000 megawatts.) An estimate attributed to Hewson indicated that, if properly recovered, wind could supply approximately 10-15% of the United States' power needs (53). Heronemus appears to have been more conservative in his estimate that, by the year 2000, wind could contribute 6% and 7% of the projected U.S. needs (54, p. 18). A potential energy supply of this magnitude deserves further research and development.

The advantages of using the energy in wind power include (52, p. 3):

1. infinite resource availability
2. zero pollution
3. zero fuel cost and overall economy
4. available technology of exploitation
5. zero addition to the global heat balance.

The primary disadvantage of wind power is that it is a random source of energy that is not directly storable (55, p. 103). The technology has been demonstrated, however, for storing wind energy as hydrogen gas and then transporting it as a gas either for direct use or conversion to electricity (Figure 1-2). Simple wind energy water pumping and storage and charging D.C. batteries has been used in agricultural regions for many years (56).

Many schemes for the harnessing of wind energy have been proposed. Four schemes have been propounded in detail by Professor William Heronemus of the University of Massachusetts (57). The ideas range from private ownership for small home heating systems to public utility companies operating large numbers of wind towers for general distribution networks.

If the thorough research of Heronemus is accepted as valid, multiple uses of wind power appear highly probable and highly feasible, given appropriate funding and testing of his ideas.

(ii) Ocean Thermal Gradients: A number of investigators have suggested using the energy stored in the oceans for power generation (54, 58, 59, 60, 61). The oceans of the world are one of the natural storage reservoirs for solar energy. They are as nearly an infinite energy storehouse as can be found on earth since the energy they lose is constantly being replenished by the sun, directly by surface absoption of photons, and indirectly through melting of ice which "slides" under the warmer surface water and maintains the low equilibrium temperature of the bottom.

The temperature differential between upper and lower layers of the oceans provides the "hot" and "cold" reservoirs needed for operation of a heat cycle engine. In a closed cycle system, surface water would give up its energy to vaporize a volatile liquid like propane, ammonia, or a Freon. This gas would then expand through a turbine driving a

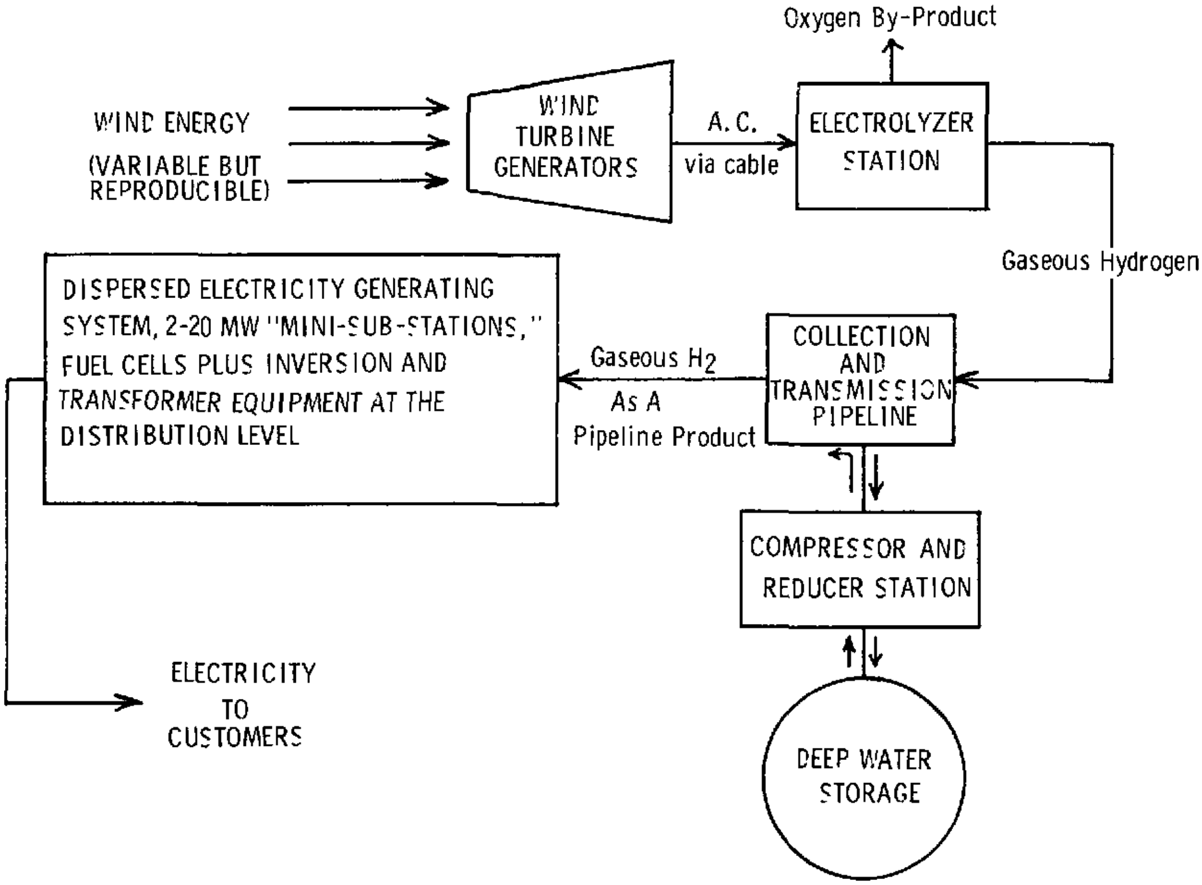


FIGURE 1.12
BASIC SYSTEM DIAGRAM FOR WIND POWER
Source: Heronemus, W. E., "Pollution-Free Energy from Offshore Wind."

generator. The lower pressure exhaust gas would finally be liquified by condensers cooled by bottom water.

Criteria for ocean sites are a maximum temperature difference between upper and lower levels and a reasonable current to avoid exhausting a local area. A prime candidate for U.S. operation is the Gulf Stream. It is typically 25°C at the surface and 5°C at a depth of 1,000 meters. The ideal Carnot efficiency operating between temperatures of this magnitude is about 7% of which perhaps half is physically realizable. The Gulf Stream alone could provide about 75 times the 1980 electric demand with less than a 1° drop in temperature.

The typical thermal gradient unit is expected to be sized in the 100-400 MW range and to cost less than nuclear, particularly if mariculture is included. The main structure would be neutrally buoyant at about 200 feet and at this depth would be cheap to build because the zero pressure differential between the inside of the system and the ocean would not require pressure vessel construction. An additional advantage would accrue if an electrolysis unit were added that could produce hydrogen and oxygen. If they were stored at this depth and their containers towed to shore, they could be used directly as high pressure feed for gas turbines. Alternately, the gases could be piped ashore.

Heronemus suggests placing fifteen power stations in a row one mile apart with 500 such rows placed along the Gulf Stream (54.) This system would provide 750,000 MW or about twice our current electrical generating capability. Surely, this energy form deserves considerable attention and Federal support.

(iii) Photosynthesis: Solar energy may be converted into chemical energy in the form of trees and grasses by photosynthesis. The organic products of photosynthesis may then be converted directly into heat through combustion, or the organic plant material may be processed into an economically transportable fuel. One of the problems with photosynthesis as a converter of solar energy is the low conversion efficiency associated with the process, which ranges from 0.3% to 3% in natural ecosystems (62, p. 22). The reasons for these low values are discussed in detail by Schneider who predicts a theoretical upper bound of about 11%, with 5% as a possible attainment in future systems (2).

Figure I-13 shows a summary of typical processes for producing stored energy from organic wastes as well as from organics grown for fuel (62, p. 23). It is estimated that an annual energy supply amounting to 10^{15} BTU is available as organic wastes under conditions not involving prohibitively high collection costs and perhaps 50 times this amount total (62, p. 26). The economics of converting this waste into energy are not now competitive with fossil fuels, but the ecological benefits of recycling and the continually increasing cost of solid waste disposal make this process appear more palatable. The main technical problems in using this energy source are the variable composition and tendency towards degradation of the wastes. The three processes of

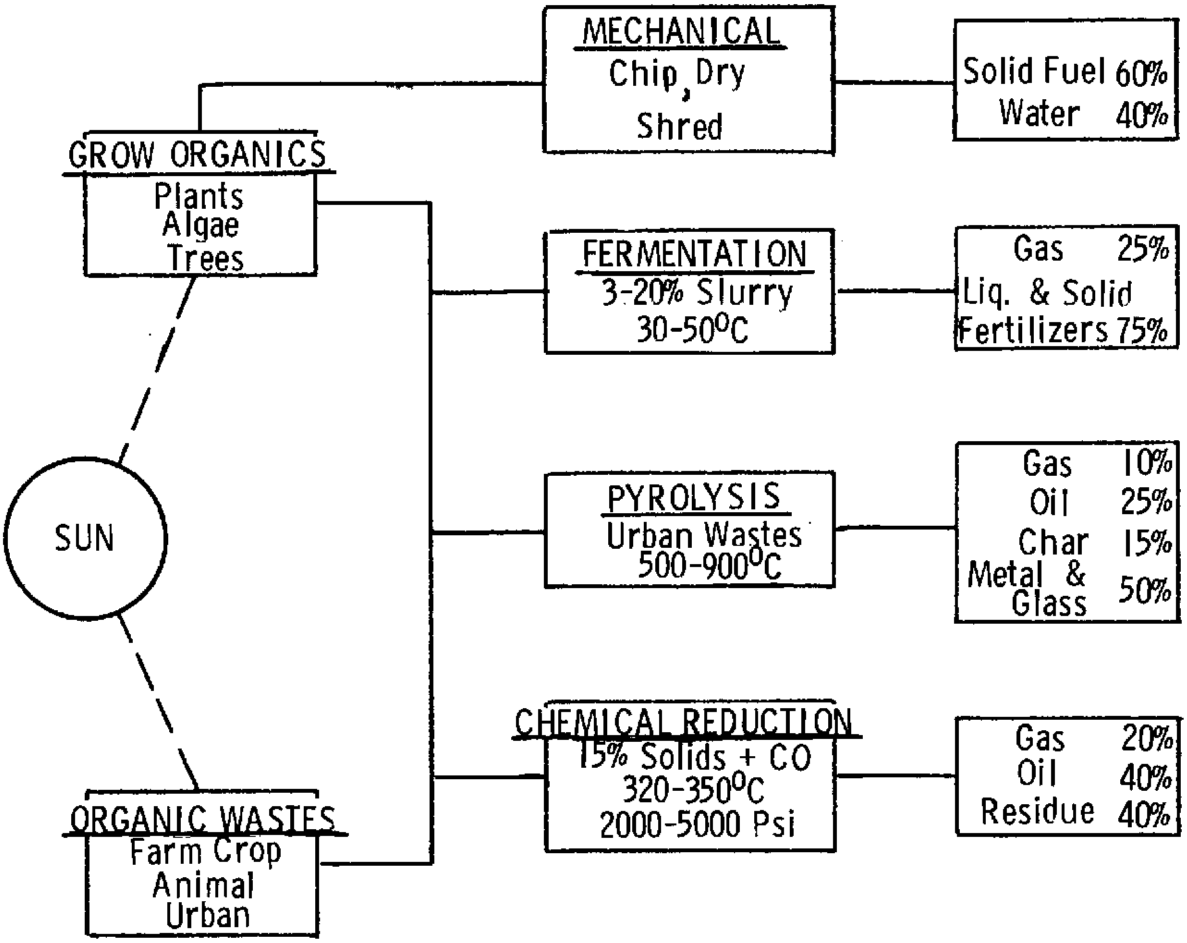


FIGURE 1.13

PRODUCTION OF FUELS FROM PHOTOSYNTHESIS

Source: NSF/NASA Solar Energy Panel; Dec., 1972 treating solid organic wastes to produce clean fuel are technically feasible, with similar economics.

The economics of using land to grow fuel is very dependent upon the cost of that land. This is pointed up in Szego's analysis of his solar plantation—a tree farm grown for the purpose of generating power by burning wood (64). A 1,000MW power plant of this type would require about 400-500 square miles of land and would be economical only if land were available for less than $250/acre.

Other possibilities for using photosynthesis to produce power include growing algae or floating water plants to produce methane, or growing cereal crops or corn to produce fermentation alcohol. The former uses the fermentation process shown in Figure I-13 and appears most economical when the algae are grown on sewage ponds. Reduction in the overall cost below $2/MM BTU though would require substantial improvements in harvesting techniques. Growing corn to produce fermentation alcohol does not appear to have any promise. The farm surplus that gave birth to this idea is no longer a surplus and will likely be a deficit in the future.

This last factor may inhibit using arable land for energy production. Growing algae on sewage ponds and processing solid organic wastes into fuel both still offer attractive possibilities as supplemental energy sources.

(iv) Solar Thermal Conversion: Amidst all of the conversation about the possibility of solar thermal conversion it is interesting to note that an operational steam-driven water pump was built at Meadi, Egypt, in 1913-1914. "With a parabolic trough reflector with cylindrical symmetry and a pipe receiver in its focal line sufficient steam was generated to operate a 50 hp steam engine" (62, p. 48).

In short, the technology for successful solar thermal conversion has existed for some time, and has been improved markedly by recent technology, particularly in the development of high temperature selective solar absorber coatings, which permit the use of low precision optics to concentrate solar energy (62, p. 48).

The NSF/NASA Solar Energy Panel, convened at the University of Maryland in December, 1972, describes the following thermal conversion system (62): (see Figure I-14)

> One of the current concepts consists of five major elements: (1) a solar concentrator to concentrate the sun's energy; (2) a receiver to absorb the concentrated energy; (3) means to transfer the heat to the thermal storage facility or to the turbo-generator; (4) a thermal storage element to store thermal energy for use at night and on cloudy days; and (5) a turbo-generator to produce electrical energy.

The Maryland panel, whose comments warrant serious study, has emphasized the availability of solar thermal conversion

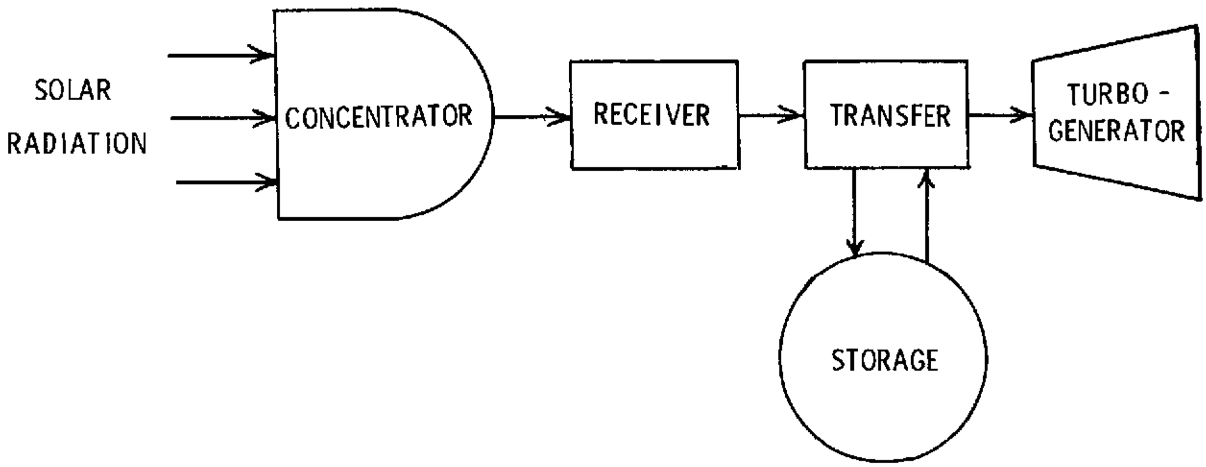


FIGURE 1.14
SOLAR THERMAL CONVERSION CONCEPT
Source: NSF/NASA Energy Panel; Dec., 1972

technology, and recommends a comprehensive $1.13 billion R & D funding plan over the next 15 years which will be used (a) to conduct a feasibility study, (b) to construct a pilot and demonstration plant, and (c) to contribute to an overall solar thermal development plan which will permit commercial availability of electricity from solar thermal conversion by 1990, with the limited goal of providing "5% of the Nation's generating capacity in the year 2020" (62, p. 51).

While not a part of this study, it is noted that solar thermal conversion has great potential for home and commercial building heating and air-conditioning.

(v) Photovoltaic Generation: The photovoltaic process takes sunlight into a solar cell array and converts it directly to electricity. The technology for this process is well established, and has been used successfully in several space projects. However, the solar cells have always been assembled by hand, up to 75% of the silicon crystal has been wasted (because the crystal is basically round, but has been cut into rectangles to minimize weight and intersticial space between cells) and total costs range from $200-$1,000/watt, which is about three orders of magnitude greater than commercial electricity ($100/KW) (65, p. 5).

Photovoltaic systems have been divided by Berman into three basic types of units (65:

a. Satellite Solar Power Station (satellite station)
b. Rooftop Solar Generator (rooftop array)
c. Large-area Photovoltaic Solar Generator (solar farm).

Theoretically, the extra terrestrial solar-arrays would be in synchronous orbit (always in the sunlight), would escape the effects of earthly dirt and atmospheric erosion, and would beam their collected energy back to earth via microwave transmission. The microwave power could then be converted into usable electricity. The pivotal problem here, of course, is the enormous cost of assembling a huge array in space. NASA has estimated that "eighty large stations, each 13 square miles in size, might satisfy the United States mainland electric power needs in 1985, or more than 3 times our present requirements" (66, p. 28). Attendant problems are that currently we cannot launch sufficiently heavy payloads (total weight of the system is 40-100 million lbs.) into space to make the scheme practicable, and our microwave technology needs refinement (66, pp. 27-29; 65 p. 2).

As Berman has pointed out, the difference between rooftop and ground-based arrays is mostly a matter of scale, although the rooftop, or individual dwelling array would have to be almost maintenance-free, whereas a commercial power-plant solar array some several miles square would have a built-in maintenance team (65). Common to any ground-based system is the problem of intermittent sunlight and the consequent need for either advanced methods of storing energy or a dual system of solar and conventional power which can work together without requiring two complete systems.

Throughout the rapidly expanding literature on photovoltaic conversion of sunlight there is the theme so lucidly expressed by Berman: central to all kinds of arrays, whether earth-bound or extraterrestrial, is the need to reduce the cost of the individual solar cell by roughly three orders of magnitude. Meinel and others have been funded by NSF to study a variety of solar cell designs, some of which use thin layers of gallium-arsenide and other highly selective materials instead of the common silicon crystals. The most practical approach for earth-based solar stations seems to be to concentrate on developing commercial technology which will reduce the cost of silicon crystals, principally because silicon is readily available in essentially unlimited quantities (66, p. 52).

(vi) Regional Modes: In contrast to our commitment, the potential for domestic application of solar energy is enormous. It is interesting to note that although annual isolation of earth's surface is "28 times the world's total supply of fossil fuel energy," only 3/100 of one percent of our Federal R & D budget is devoted to terrestrial applications of solar energy (66, p. 15 & 17). The area of the continental United States intercepts 500 times the year 2000 projected energy requirements (67, p. 1). The economics for many of the techniques for concentrating a portion of this energy are today nearly competitive with energy obtained from fossil fuels. With increasing costs of fossil fuels, the economics of solar energy utilization will undoubtedly dictate its use in the near future.

The tendency to select one technique for solar energy conversion as the best one is to be discouraged. The available resources and relative economics vary from region to region across the United States. Accordingly, it is recommended that R & D proceed along several paths simultaneously and that solar energy development be accomplished to best suit each region. A map illustrating a possible solar energy development program is shown in Figure I-15. Regions are shown there for photovoltaic and solar thermal conversion systems, ocean thermal gradient heat engines, and windmills.

Photovoltaic and solar thermal conversion power systems operate best in areas with high direct radiation, the Southwestern states. In addition, solar thermal collectors for heat and photovoltaic arrays for electricity may be placed on buildings for use within those buildings. Such applications could substantially reduce the requirements for central electric generation facilities.

As mentioned previously, ocean thermal gradient power systems placed along the Florida-Georgia coast have been suggested by Heronemus in order to take advantage of the flow of the Gulf Stream which amounts to 7.45×10^{10} lbs. of tropical water per second (54, p. 33). The potential electrical power to be obtained from the Gulf Stream in this manner amounts to 1.6 million megawatts (four times today's installed capacity).

The location of wind towers in the Great Plains Region and the Green and White Mountains of the Northeast was also suggested by Heronemus who estimates the potential electrical power output as 189,000 megawatts for the Great Plains and 5,000 megawatts for New England (54, p. 9). In addition, Heronemus suggests an Offshore Wind Power System in the Gulf of Main-Georges Bank area of the continental shelf to produce an additional 18,000 megawatts of electrical power (57). The potential of windpower is also being investigated along the Oregon coast (68).

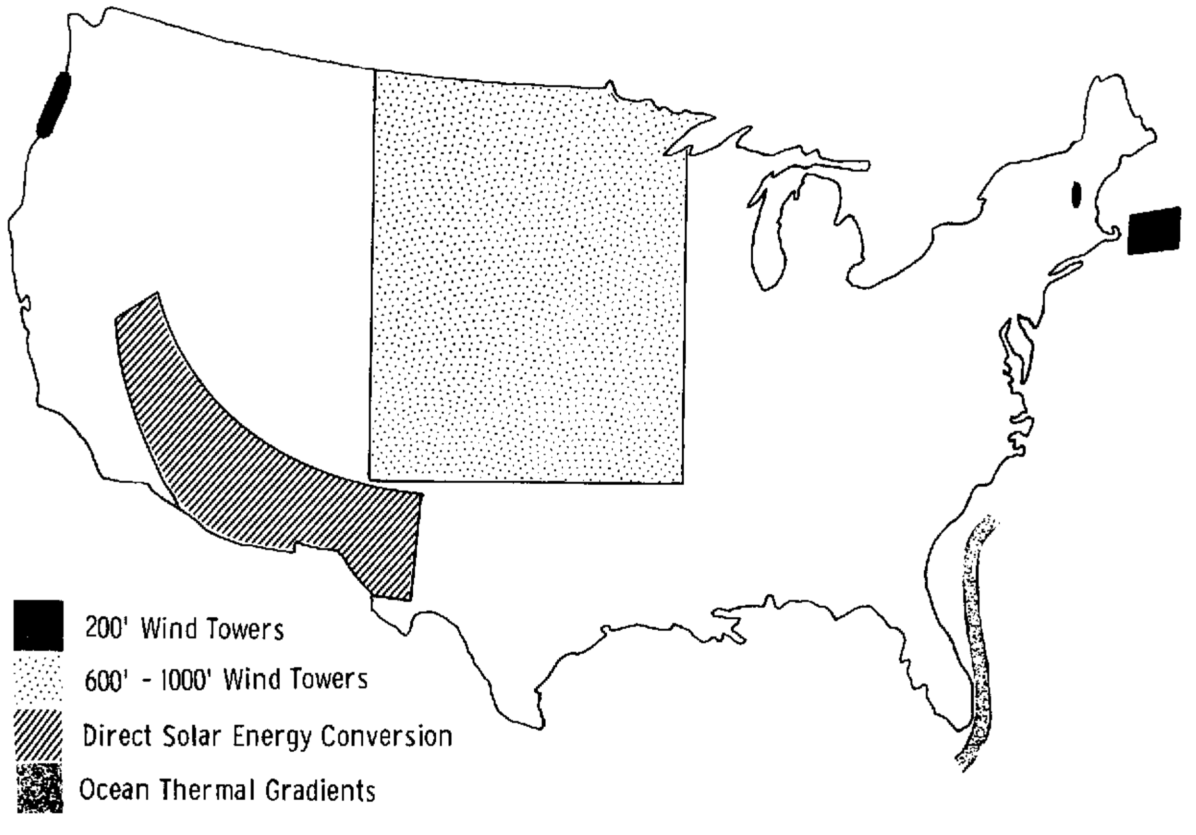


FIGURE 1.15
REGIONAL SOLAR ENERGY DEVELOPMENT CONCEPT

(3) Geothermal: The potential useful heat in the earth is enormous, though estimates vary widely, but only 1085 MW of world capacity existed in 1972 including 184 MW of Geysers, California (69, 70).

The various technologies current and proposed, use water as the heat transfer medium to generate electricity. The operational technology is available from the petroleum and electrical generating industries, but for major exploitation to occur, *there must be extensive research into the* techniques of finding promising sources.

A number of environmental problems must also be resolved: brine solutions, *noxious gases, thermal pollution, subsidence,* and possibly earthquake precipitation. Federal policy will be central to geothermal development not only through environmental regulation but also through leasing public land where a major portion of the apparent geothermal sites are located (71).

E. Conclusions

There are a number of feasible ways to supplement United States energy resources *and relieve our dependence on imports.* These technologies, listed by the time to exploitation deemed to be practical are:

- 1980's — coal refining, central wind power systems, and solar thermal for homes and buildings, geothermal;
- 1990's — central solar thermal and ocean thermal gradient systems, plus breeder reactors at sea, all generating, storing, and transmitting hydrogen;
- 2000+ — central photovoltaic systems and, possibly, thermonuclear fusion reactors.

The key technology needed to exploit these technologies is economic hydrogen generation. When compared with the current natural gas cost of 40c per million BTU, the following current costs of hydrogen show the need for improvement (92):

Water Electrolysis	**c/10⁶ BTU**
—Power at 8 mills/KWH	368
—Advanced Tech at 8 mills/KWH	233
—Advanced Tech + By-Product Credits at 8 mills/KWH	174
—Off-Peak Power at 2.5 mills/KWH	155
Fossil Based Processes	
—Natural Gas at $.40/10^3 ft^3	97
—Coal at $7/ton	132
—Lignite at $2/ton	78

The economics of electrolysis would be measureably enhanced by finding an economic use for large volumes of by-product oxygen and by generating DC power (half the present investment cost is due to converting DC to AC) (73, p. 1329). In the case of nuclear power, there is promise in a number of proposed thermochemical decomposition proposals (74, 75, 76, 77).

In summary, the authors recommend a major national commitment to a comprehensive, coherent research, development, and implementation program in new, clean, safe sources of energy according to the following guidelines:

1. Recognize that political quagmire, shortage of gasoline and heating oil, is *simply the result of the failure* to build sufficient refining capacity in recent years.
2. Recognize that nuclear fusion, present or breeder, is not the panacea to our energy shortage. In fact, if continued research, which is recommended, cannot resolve the safety, maintenance, disposal diversion, and thermal pollution questions, it may be an ecological catastrophe. Finally, all the nation's lakes and rivers are insufficient to cool the nuclear plant program being *espoused much beyond a decade.* It appears the thermal pollution problem will be insurmountable except for deep sea sited plants.
3. *Interim* relief of the energy shortage appears to center on multiproduct coal conversion technology currently in the prototype stage under the auspices of the Office of Coal Research. Its rapid development is recommended. Conversely, coal gasification appears to require too much water in the arid location of the coal and serves only a narrow, parochial purpose. In addition, extensive research is needed in mining techniques to develop methods with minimal environmental impact.
4. *Hydrogen is the key to long-term,* clean, energy development. Thus, initiation of a comprehensive research program leading to cheap means of gener-

ating hydrogen is crucial.

5. Solar energy warrants a vast increase in the funds devoted to developing the essentially completed research into an operating technology. Some suggested guidelines, listed according to the probable rapidity to large scale utilization, are:
   a) Wind. Prototype/demonstration unit on Grand Banks.
   b) Photosynthesis. Prototype/demonstration plans for converting urban waste and sewerage grown algae into gas, oil, and recyclable materials.
   c) Solar thermal. Motivation of a component industry for home and building units through demonstrations, tax incentives, etc. Central prototype/demonstration plant to pick up summer peaking load due to air conditioning. (Large scale use awaits H_2 generation economics.)
   d) Ocean thermal gradient. Prototype generation plant in Gulf Stream off Miami (54).
   e) Photovoltaic. Research into economic solar cell production techniques.
6. Geothermal energy is potentially an attractive source of electric energy. Its large scale utilization is as yet speculative. Extensive research is needed in the techniques of locating geothermal resources and in the conversion of those resources into energy.
7. Thermonuclear fusion research should be expedited, because of its enormous potential for the twenty-first and following centuries.
8. Fuel research must not be overlooked. Although physically possible, ultimately becoming entirely dependent on electricity and hydrogen is suspect. It is felt that there will always be a need for fossil fuels. Thus, in addition to coal, research should be encouraged in ecologically compatible development and utilization of oil and shale recovery techniques.

I.B.3. Constraints to Equitable Solutions

For society to ignore economical, productive, and positive uses of technology and social science is absurd. Yet, this is precisely what we are doing today in the United States, and it will have global consequences. We are quite liable to exhaust our primary fossil fuels and possibly degrade our environment, while we have the technological ability and organizational skills to improve fuel efficiency, reduce consumption and to harness new, ecologically gentle, energy sources. The question remains, do we have the social capability?

The intent of this section is to examine psychological, social, and political obstacles to achieving a balanced resolution of our economic, human, and environmental needs as they affect reflected in energy consumption.

A. Social Resistance To Technological Change

Critics of technological advancement argue that social and humanistic values have been subjugated in America and that technology and its mystique, not man, have become the goal of life. MacLeish has argued that during the past century, America has shifted to a society built not with human purposes in mind but for the sake of technology. The process of change took over, leaving the reason for change to follow. We as managers of the process ceased to exist and we became its dependents. In accepting change and automation we lost our human purpose. Historically, new ideas and products were uncritically accepted; we no longer thought of whether this new idea or product, this new invention, somehow matched human purpose (78, p. 13). There is an American sense of frustration, a numb, uninformed persistent sense, like the hinting pinch of pain which is not yet brutal hurt but will be, that we, as Americans, we perhaps as members of our generation on this earth, have somehow lost control of the management of our human affairs, of the direction of our lives of what our ancestors would have called our destiny (78, p. 12).

Technology can help abate human shortsightedness; however, social invention and change will be necessary. For example, recent Environmental Protection Agency standards on automobile exhaust emissions have reduced pollutants with a resultant loss of fuel economy in the automobile. Only a change in consumer travel patterns (reduced travel) or social acceptance of an available clean-burning fuel source will resolve this apparent zero-sum balance.

As we move in the direction of an homogenized American culture, we will come to realize, as Baram has pointed out, that

> "many of our problems labeled technology-induced or environmental are, in reality, the behavioral problems of a materialistic society. . . . How much longer can these absurd ratios [e.g., annually three new cars to each new American] and harmful effects be tolerated, despite the importance of the [automobile] industry of the economy?" (79, p. 536)

To obviate a social barrier, one must recognize that he is attempting to change the complex behavior of people; that while materials, money, and machines are easily manipulable, man is not. Social change, to be induced, must overcome behaviors and attitudes learned and experienced since birth. To modify basic human motivation is a task considerably more difficult than mobilizing an assault on a particular technology.

Weinberg has pointed out the obvious to any social scientist:

> [It] is a long, hard business to persuade individuals to forego immediate personal gain or pleasure, as seen by the indivdual, in favor of longer-term social gain" (80, p. 5).

We must seek ways of modifying social behavior for everyone's benefit. **Business Week** stressed the importance of the need for a shift in the outlook toward social change: ". . .new attitudes toward congestion, economic growth, and life style may eventually prove as important as new technology" (81).

How much and to what extent are we willing to alter our life-styles? Our life-style shift could range from no change to energy conservation to transition toward alternate and multi-modal non-petroleum based energy sources—or, for that matter, to any of the multitudinous alternatives or combinations thereof, that man's ingenuity can suggest. But, Berry has warned that:

> We know from some of our present dilemmas how massive the difficulties can be in trying to adopt multiple means, once we have locked ourselves and our life-style into a single one. It is pathetic to look back and realize that the problems we now have with automobiles—traffic, pollution, disposal—were entirely predictable 20 years ago, and that in every way, except one, it would have been much easier to develop multiple means of transportation in 1950 than in 1970. The one exception that might make it easier now is, of course, our motivation (82, p. 26).

The thrust of this discussion is that society's mind must be changed, with a change in resultant behavior, from a belief that its problems are primarily technological to a realization that social abdication of control is equally at fault. According to Dubos.

> We must not ask where science and technology are taking us, but rather how we can manage science and technology so that they can help us get where we want to go (78, p. 16).

Baram has suggested that since two-thirds of the funds spent on research are Federal funds, this

> provides even further justification for public interest in the social control of science and technology (79, p. 535).

B. Public Attitude And Awareness

Social attitudes are often formed by limited individual experience and group pressures. These result in selective perceptions.

For example, the majority perceive only the immediate symptoms of our energy problems, such as brown-outs and closed gas stations, and do not become concerned about social problems until there is a crisis. Consequently, energy shortages of great significance for human survival or for the maintenance of existing life styles which will not have catastrophic consequences for 20 to 30 years do not generate public concern (83, p. 16). This public short-sightedness is a significant obstacle to solutions of the energy dilemma, because an immediate large-scale assault is necessary if the projected energy requirements for 1995 are to be met.

In recent years, public attitude has shifted strongly toward examination of environmental problems (e.g., air and water pollution regulations, wilderness legislation, etc.) A recent DOT-NASA study has reported that "Public pressures can easily constrain or even prevent the introduction of new [technological] systems or can be equally effective in curtailing the use of existing systems" (84, p. 6-4). As an example of such curtailment, Stans has estimated that "from $5 billion to $10 billion worth of public and private [power generation] construction projects are now being held up by environmental actions" (85).

Symptomatic of the more general resistance, and certainly far more pervasive among lay individuals would be the sort of curtailment policy bred by such illogical statements as "better health care is more important than new aircraft." Such statements often stop both programs by inferring that they are mutually exclusive. This attitude, often abetted by media over-simplification, only adds to the difficulty of resolving social problems.

Unfortunately, the "two cultures" popularized by C.P. Snow is a reality. The *manifestation of this is the attitude often held* by the technological community that there are political solutions to society's problems, while some social scientists have a corresponding faith that new technology will eventually provide the tools to solve society's problems. The danger is that the possible solution will *"fall between two schools," i.e., the social* scientists will defer to the social scientists.

Whether myth or fact, it is widely held that the following values dominate the technological establishment:

1. The belief that technological progress is both desirable and inevitable; that what can be made, should be, and will be.
2. The belief that "nature" exists to be conquered.
3. The belief that ultimately there are no unsolvable technological problems. Barriers to "progress" that now exist will be overcome if we throw enough money at them.

This latter myth often leads to the popular misconception that poverty and war are the same as moon exploration and are equally subject to solutions if we only apply *technological know-how*.

There are also socio-political myths that lead to ineffective action.:

1. The myth of government omnipotence: For generations "conventional wisdom" has maintained that the state enjoys a monopoly on the use of coercion; and that this monopoly enables the state to enforce its decisions effectively. Therefore, the often repeated *demand* "Pass a law." Witness the War on Poverty that now expends more per poor family than a middle class family income.
2. The myth of administrative efficacy and independence: A second myth is the belief that administrative agencies can *be established to regulate vital in*dustries in the public interest in a manner that will be efficacious in enabling new technological advancement to be rapidly put into practice and at the same time act as a public safeguard against raids by private interests on the national resources.

A recent study of Theodore Lowi, **The End of Liberalism,** documents with great detail the fact that the delegation of power to administrative agencies creates a pattern that inhibits both planning and justice. **In the Symbolic Uses of Power,** Murry Edelmann further documents that in numerous cases the only intended effect of governmental action is one of symbolic reassurance rather than substantive change. It may well be argued that the nomination of an "energy Tsar" will do little more than falsely reassure the public about the energy crisis.

Murray adequately summarized when he wrote "I am pessimistic about the future—not because the problems we face are technically or economically insurmountable but because they seem humanly insurmountable" (86, p. 70).

C. Vested Interests

In contrast to other societies, America has given great significance to the values of individuals. Paradoxically, as the complexities of our technological society increase, the power of individuals and groups located in strategic positions also increases.

The final and most pervasive myth is the belief that the American political system can be best described as "Pluralism;" but Political pluralism, critics contend, leads to larger monopolies of political power.

A "Power Elite" model would appear the more accurate description in the energy area. Of the world's twenty largest corporations, seven are oil companies. Further, a subcommittee on special small business problems of the House Select Committee on Small Business found that major American oil companies account for: (87, p. 38)

—approximately 84% of U.S. refining capacity

—about 72% of natural gas production and ownership of reserves
—30% of domestic coal reserves
—more than 20% of domestic coal production capacity
—more than 50% of uranium reserves
—25% of uranium milling capacity

The following items (88, p. 207) indicate the extent of conglomerate mergers in the energy industry.

—Since 1963, 5 oil companies have purchased 9 coal companies.
—Since 1959, 6 large industrials have purchased 7 coal companies.
—Three major coal companies, two of them oil company subsidiaries control 27% of all coat production.
—Seven of largest 15 coal producers are oil companies.

It should be obvious that the politics of the energy crisis is the politics of the most powerful corporations in the world. It would be naive to assume that political actions can be taken without a considerable compromise in the direction of the interests of these corporations.

Ridgeway has documented the manipulation of local and state laws by the energy companies (88). Ridgeway also suggests that companies which operate in several counties appear to avoid personal property taxes by convenient transfers of equipment. The return to the indigenous population of the coal producing areas, of the monies extracted in resources, is minimal and contributes to the economic deprivation of Appalachia.

Most of the western coal states have small amounts of precipitation in the coal field areas. The construction of numerous mine-mouth plants would require the diversion of water flow from the major through-flowing rivers. The waters of many of these rivers have been allocated to irrigation and other purposes. The National Petroleum Council (7, p. 11) suggests the Federal Government resolve the water allocation problem in favor of the coal utilization thereby stripping irrigation of its water. This is a conflict that should be presented for full and open discussion by the public to determine the best use of this water.

D. Decision Making

A plausible scenario might be

Thesis: Awareness of the energy crisis demands conservation of energy and exploration of new resources. Citizens complain to Congressmen about fuel shortages - brown-outs, high prices of gasoline, increased transportation costs.

Antithesis: Backlash develops —The energy crisis affects powerful groups, such as oil, automobile, aviation industries and the scientific community. Many assume an ostrich posture. The U.S. imports more oil.

Synthesis: Energy conservation fails as impact of reduced consumption on life patterns becomes apparent. People pay the high prices for fuels while the increased rate of consumption continues. Pessimistic predictions are ignored. A hedonistic philosophy takes over in a society which is using up its energy resources at an ever increasing rate while surrendering to every increasing ecological danger.

Must the nation follow this path with new agencies designed for symbolic reassurance rather than substantive change?

A less pessimistic argument can be made that the ideological and political environment in which an energy policy could be hammered out would almost certainly necessitate that any changes from existing policy would be characterized as "incrementalism" in spite of what might be seen as the vital need for drastic and comprehensive changes in policy. This merely summarizes what many students of modern bureaucracy have been saying for some time: that only incremental change is possible and that this may not be sufficient to avoid a catastrophe in the not too distant future. Must this be so?

Given the status of public awareness and attitudes, the power of vested interests, and the pervasive resistance to comprehensive change, it will take a major national effort to avoid the traditional pitfalls and to achieve a coherent resolution of our energy-related problems.

Hopefully the trend toward self-education in implications of this ecological/sociological/technological problem will continue among our political, business, and academic leaders. This education may offset the sometimes biased information being distributed by vested interests.

There is an acute need for a national effort to create a public awareness of the energy problem, the transportation problem, and the advantages of the hydrogen economy. Discussion must be generated, ideas propounded, and end results of technological change forecast with greater clarity. Public involvement must be elicited along with that of special interest groups and research and development decisions must take into account as many points of view as possible.

The Office of Technological Assessment has the opportunity to make an outstanding contribution and will receive increasing public support provided, as Hardin has argued:

> The public interests in every proposal will in the future weigh more and more heavily in reaching decisions on the expenditure of public moneys. Cost-benefit analysis [and environmental impact statements] must be carried out within an intellectual framework that comes closer to incorporating the total system . . . (89, p. 20).

In addition, the growing science of systems analysis and computer simulation will be applied to assess the effects of proposed decisions. A number of large studies have proven the technique effective in the analysis of complex socio/technological systems.

Despite the national uproar over the need for environmental protection and for solving problems of air and water pollution, waste disposal, urban decay, and mass transportation, to say nothing of an attack on our energy problem, a clear-cut objective has not been delineated nor has a systematic approach been planned (90). At best, efforts to solve such problems have been shotgun in nature with no coherent national commitment and with inconsistent funding. The Federal Government must assemble a unified package—a national commitment, a well defined goal, and adequate funding to carry out an assault on domestic problems (90).

Our task is clear, for

> the question is not of survival, [says Feinberg] but of survival in what form. We are now in a period in which our social institutions are being strenously questioned. It may well be that a continuation of the life mankind has had in the past and has in the present is neither possible nor desirable, compared to some of the alternatives that we could construct for ourselves (91, p. 27).

I.B.4. Toward A National Energy Policy

Today's energy problem is a function of a rapidly accelerating demand for energy and the depletion of the supply of conventional sources of fossil fuels. An interim policy which can bridge this gap is needed to provide time for a long term policy to effect the development of pollution-free and economically-feasible new sources of energy. In the absence of forethought haphazard policies may have to be followed by default. The following alternatives are suggested as a means of narrowing the gap between energy supply and demand.

One innocuous policy is to call upon the American people for voluntary restrictions in energy consumption. President Nixon has already urged the nation to restrict consumption and has asked the Federal Government to reduce by 7% its use of energy in nonessential government business. The Federal Government's voluntary cutback might serve as a model for similar moves by state and local agencies. This in turn may have an impact on industrial and private consumers.

A. Energy Rationing

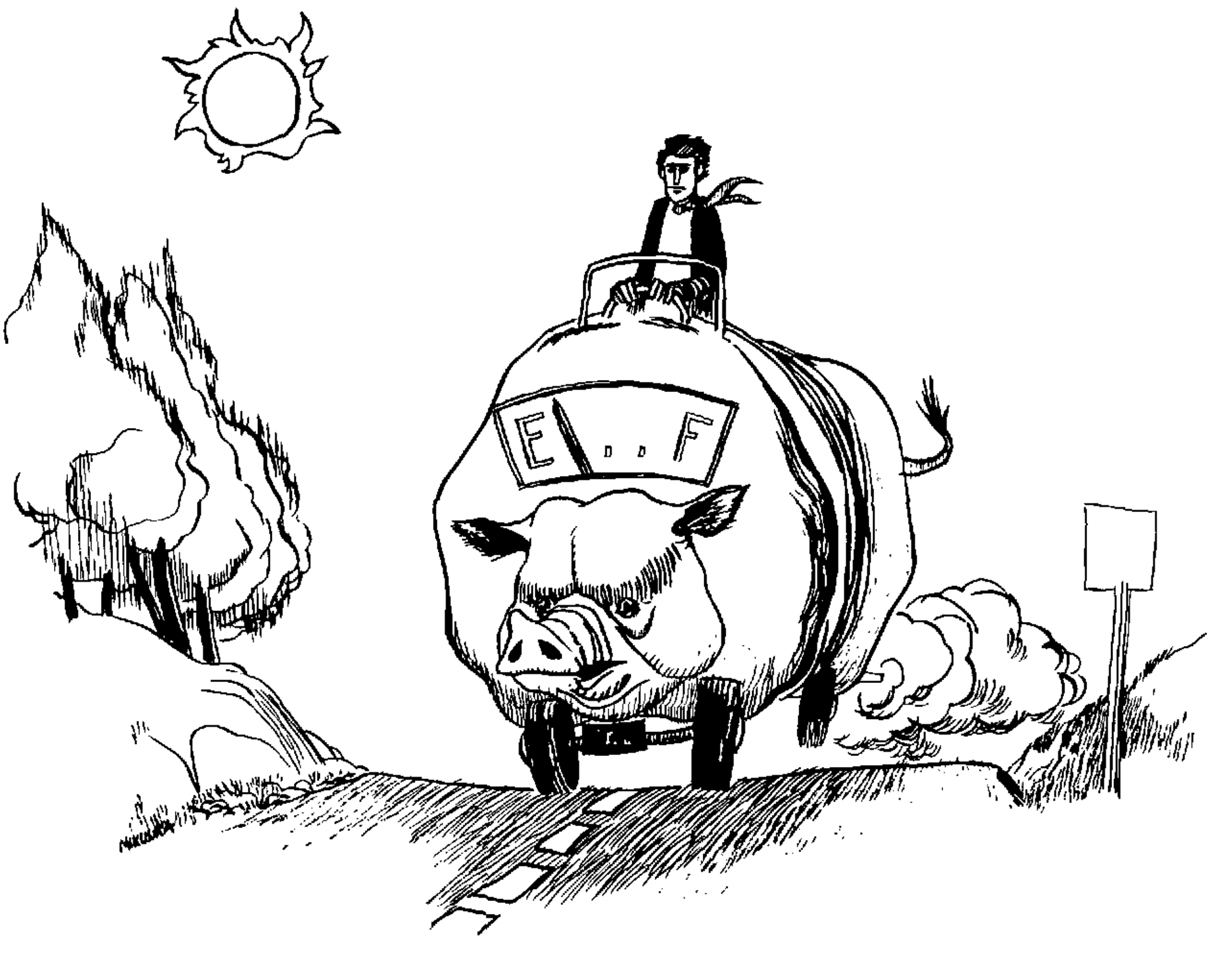
A more drastic measure of immediate impact would be a mandatory energy conservation program supported by rationing. The defense of rationing derives from the proposition that fossil energy sources are a national resource and belong to all the people of the United States. Therefore, individuals or industries no longer have the right to waste a limited resource to the detriment of the American people and future generations. The means of implementing such a policy are as follows:

1. BTU allotments could be issued, based on a formula which considers the current U.S. continental supply of fossil fuels and the personal consumption habits of U.S. citizens. Adjustments could be made for age, occupations, location and other factors. Provisions could entitle each American enough energy to heat his home, get to work, and enjoy some pleasure. This system should not be considered a "crisis" program but a regulatory one. Provisions should be made for monthly adjustments. If the system were put into operation early enough, there would be

time for adjustments in the system. A BTU credit card system would enable people to have choices on how to use energy.

2. Implementation of an energy rationing policy is much more practical today with our computer technology than during WWII. Each household could be issued a national energy card, probably identified by social security number. The card would be used in addition to national credit cards or money when making energy purchases such as gasoline, coal, and fuel oil. Each month the responsible government agency would forward energy statements describing the debit or credit in the various energy forms. Monthly energy debits would be taxed in increasing amounts as a function of the quantity of excess energy usage. This method would allow the individual who wishes to buy additional energy to operate essentially in a non-rationed market—if he is willing to pay excess usage taxation penalties. These additional tax funds could then be utilized to support government sponsored energy research. Year-end credits could be either accumulated or sold back to the government as a conservation incentive. Hopefully, this method would allow control of black market activities while still maintaining desirable conservation and free market place characteristics. The monthly computer printout would allow rapid adjustment of the minimum energy levels as they are effected by seasonal weather conditions, regional location, and national energy availability.

One might ask what effect energy rationing would have on the economy. Certainly, there would be demand for more energy efficient appliances, vehicles and building construction. American technology would be redirected to include energy efficiency along with cost and quality in design.



B. Energy Taxation

As an alternative to rationing, the power to tax could also be used. For example, the government could simply levy excise taxes to drive the cost of fuels to a point where the market mechanism would reduce demand. However, a just and equitable distribution of energy will not necessarily come about. Probably such a system would severely penalize the poorer sector of our economy. To avoid this problem, selective taxes could be levied on new automobiles, air-conditioners, and luxury appliances in proportion to energy consumption.

The power to regulate may be used to encourage conservation or discourage fuel diversions considered socially undesirable. For example,

1. The Federal Housing Authority could require heavier insulation in new homes;
2. The Federal Price Commission could restrict gas-fired power plants; or
3. The Interstate Commerce Commission and the Civil Aeronautics Board could effect fuel efficiency in air transportation through their regulatory powers.

C. Energy Conservation

Beyond the obvious short-term methods of limited effectiveness in slowing demand growth, the nation desperately needs a comprehensive program of research in energy conservation. There are a great number of promising proposals in the literature that warrant investigation and, if effective, implementation. The proposals span the major energy consumers—homes, apartments, buildings, industry and transportation. Many overlap with supply of new energy in that they propose using energy naturally and locally availalbe.

D. New Energy Sources

Despite all efforts to reduce demand for energy, there will be considerable need for new energy if the nation is to continue the policy of improving well-being, cleaning the effluents of man and his transportation and industry, and providing for the growth in our number. Acquiescing to the proposals made by the major oil companies that Federal lands and offshore areas be opened to drilling may alleviate the supply problem for a while (the "fabulous" proven reserves in the Alaskan North Slope amount to about two years' supply), but inevitably the nation must turn to new, clean sources. It is almost too late to start their development, for, in reality, the need for those sources exists NOW.

E. Energy And The Environment

Lest the development and utilization of new energy resources repeat the shortsighted evolutionary process that accompanied the development of the fossil fuel era and resulted in the current environmental dilemma, a carefully planned "energy-environment-society" must be the goal as the United States enters the "clean fuel" era. Points of view are needed from both environmentally-conscious and energy-conscious groups. The two cannot expect to continue functioning independently but must couple their efforts for the general good. The nation cannot afford zero-sum games involving energy and environment. Environmentalists need to realize that it is impossible to absolutely eliminate the risk factor in the design and implementation of energy projects. Technology can reduce the risk to an acceptable level but the demand for **absolute** safety is never going to be satisfied.

Experience also proves that the present system of proposal, preliminary design, environmental objections, and lengthy litigation will not work. Although demand for energy can be reduced, it appears that environmental problems can be solved more realistically by improved energy efficiency, pollution control, recycling, and the development of naturally clean energy sources. But to achieve this goal the nation desperately needs a faster method of resolving energy-environment matters.

F. Energy Administration

President Nixon has proposed a Department of Energy and Natural Resources and other plans for dealing with the energy situation. It is imperative that the DENR actually fulfill the role that is embodied in the spirit of its creation, and not become victim to narrow interests. Without subscribing to xenophobia, on long-range goal of the government should be to minimize the U.S. dependence on foreign sources can make the U.S. vulnerable to threatened or actual economic sanctions by other countries, restrict American international policies, and adversely affect the U.S. economy.

This report has alluded frequently to the petroleum-dependent transportation sector of the economy. One energy-consuming sector requires a great deal of attention: air transportation. In terms of its expected growth, its enormous fuel requirements and the inefficiencies that beset it, it portends serious difficulties in the years ahead. Therefore, it should be brought into the limelight. What is *its nature? How does it operate?* What does its history reveal? What are its prospects? These and other questions need examination. The reason is obvious. If a transporation mode *is expected to play a larger and larger role* in the future lacks viability our problems will be compounded. An attempt is made to search for answers to the questions posed. Hence, the following three chapters focus on air transporation.

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2

THE AIR TRANSPORTATION/ ENERGY SYSTEM

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Introduction

Chapter I developed the nature of the energy problem; the function of this chapter is to examine the air transportation system and its relationship to energy consumption. The chapter is organized as follows:

Section A contains data on the changing pattern of transportation; **Section B** analyzes the energy intensiveness of various modes of transportation; **Section C** discusses socio-psychological data affecting why people travel by air; **Section D** presents governmental regulation and air transportation economics; and finally, **Section E** draws some conclusions regarding the existing status of the air transportation system.

II. A. Changing Patterns of Transportation

II. A. 1. Historical Trends in Transportation

The transportation sector in the United States accounts for a major percentage of total energy consumption averaging around 24% since 1950 as shown in Table II-I. However, transportation energy requirement almost doubled from 1950 to 1970 (i.e., from 8,724 x 10^{12} BTU in 1950 to 16,445 x 10^{12} BTU in 1970) (1, p. 3). This increase was due to increasing levels of traffic and shifts to less energy-efficient transportation modes.

Table II-II shows the distribution of energy within the transportation sector for 1960 and 1970. Automobiles consumed more than 50% of the transportation energy during both years. The percentage of energy devoted to automobiles and trucks increased slightly from 1960 to 1970, whereas the increase in aircraft usage was substantial, jumping from 4.1% in 1960 to 7.5% in 1970. For railroads, there was a decline in the percentage for the same time period.

These significant changes in modes of travel can also be demonstrated by comparing transportation by various modes in terms of passenger-miles and ton-miles as shown in Tables II-III and II-IV.

One can see in Table II-III that over the past twenty years automobile traffic has held its own, accounting for 86.8% of the total passenger miles in 1950 and 87.0% of the total passenger-miles in 1970; however, during this period, railroads have declined from 6.4% to less than 1% of the total passenger-miles and most interesting for the present study is the fact that the airplane has made nearly a five-fold increase in its share of total passenger-miles during the past two decades. In 1970 it accounted for nearly 10% of total passenger-miles.

In terms of freight traffic Table II-IV shows the change in transportation mode has not been nearly so dramatic, although it does represent the same tendency, e.g., railroads carry a smaller percentage of total ton-miles

TABLE II-I

ENERGY CONSUMPTION IN THE U.S. TOTAL AND TRANSPORTATION[a]

Year	Total (10^{12} BTU)	Transportation (10^{12}) BTU)	Percent to Transportation
1950	34,154	8,724	25.5
1955	39,956	9,904	24.8
1960	44,960	10,881	24.2
1965	53,785	12,771	23.7
1970	68,810	16,495	24.0

Data from Bureau of Mines (1968, 1971)

Source: Eric Hirst, **Energy Consumption for Transportation** (1, 3)

TABLE II-II
DISTRIBUTION OF ENERGY WITHIN THE TRANSPORTATION SECTOR

	% of Total Transportation Energy	
	1960	1970
1. Automobiles		
urban	25.2	28.9
intercity	27.6	26.4
	(52.8)	(55.3)
2. Aircraft (Commercial only)		
freight	0.3	0.8
passenger	3.8	6.7
	(4.1)	(7.5)
3. Railroads		
freight	3.7	3.2
passenger	0.3	0.1
	(4.0)	(3.3)
4. Trucks		
inter-city freight	6.1	5.8
other uses	13.8	15.3
	(19.9)	(21.1)
5. Waterways, freight	1.1	1.0
6. Pipelines	0.9	1.2
7. Buses	0.2	1.2
8. Other[a]	17.0	10.4
TOTAL	100.00	100.0
Total Transportation Energy Consumption (10^{15})	10.9	16.5 BTU

[a]Includes passenger traffic by boat, general aviation, pleasure boating, and non-bus urban mass transit, as well as the effects of historical variations in modal energy-efficiencies.

Source: Eric Hirst, **Energy Consumption for Transportation in the U.S.,** ORNL-NSF Environmental Program, Oak Ridge, Tennessee, March, 1972, (1, p. 27).

while all other modes carry a larger percentage than they did in 1950. However, air freight remains relatively insignificant in that it carries only 0.18% of total ton-miles.

II. A. 2. Future Trends in Transportation

The art of predicting future demand trends is a most difficult one. Although many "experts" in this field appear to have developed a science from this art, there are too many undefined variables and any results should be accepted with some reservations. With this thought in mind, projections of future transportation energy demands are analyzed.

The Office of Science and Technology (OST), in response to the request in the President's Energy Message to Congress on

TABLE II-III
INTER-CITY PASSENGER TRAFFIC[a]

Year	Total Passenger-Miles (10^9)	Percent of Total Passenger-Miles Automobile	Airplane	Bus	Railroad
1950	510	86.8	2.0	5.2	6.4
1955	720	89.5	3.2	3.6	4.0
1960	780	90.1	4.3	2.5	2.8
1965	920	88.8	6.3	2.6	1.9
1970	1,180	87.0	9.7	2.1	0.9

[a]Data from Statistical Abstract (1970) and from Transportation Facts and Trends (1971).

Source: Eric Hirst, **Energy Consumption for Transportation** (1, p. 10).

TABLE II-IV
INTER-CITY FREIGHT TRAFFIC[a]

Year	Ton-Miles Freight (10^9)	Percent of Total Ton-Miles Railroads	Trucks	Waterways	Pipelines	Airways
1950	1090	57.4	15.8	14.9	11.8	0.03
1955	1300	50.4	17.2	16.7	15.7	0.04
1960	1330	44.7	21.5	16.6	17.2	0.06
1965	1650	43.7	21.8	15.9	18.6	0.12
1970	1930	40.1	21.4	15.9	22.4	0.18

[a]Data from Statistical Abstract (1970) and from Transportation Facts and Trends (1971).

Source: Eric Hirst, **Energy Consumption for Transportation** (1, p. 6).

June 4, 1971, designed and organized a study to assess promising technologies. The basic plan was developed by Associated Universities, Inc. (AUI) on the basis of consultations with OST, other government agencies, and knowledgeable experts from outside the government (2).

The first phase of the study involved the preparation of a common framework in which to evaluate energy technologies. The AUI transportation projection was taken from study which was also the springboard for the Transportation Energy Panel (TEP) projections of September, 1972 (3). The primary effect of the TEP study was to confirm and add information to the AUI Reference Study.

Figure II-1 illustrates both the AUI and TEP fuel consumption projections. The projections do not include military consumption and are based on 1.1% population growth and 4.2% GNP growth.

The basic differences between the two projections are in the air, bus, and rail modes. Concerning air mode consumption, the AUI projection shows a sharper increase that the TEP projection up to about 1990. This is due to an optimistic outlook on the introduction of the SST. Beyond 1990 the AUI projection proceeds at a slower rate than TEP, and they converge at about 2020. This vigorous air travel growth is due mainly to saturation-effects in the automotive mode. Saturation of automobile expenses leaves an excess for family travel by other modes. Regarding bus and rail mode consumption, the TEP projections incorporate smaller growth in both modes than does the AUI study. Although buses are highly efficient modes of travel both

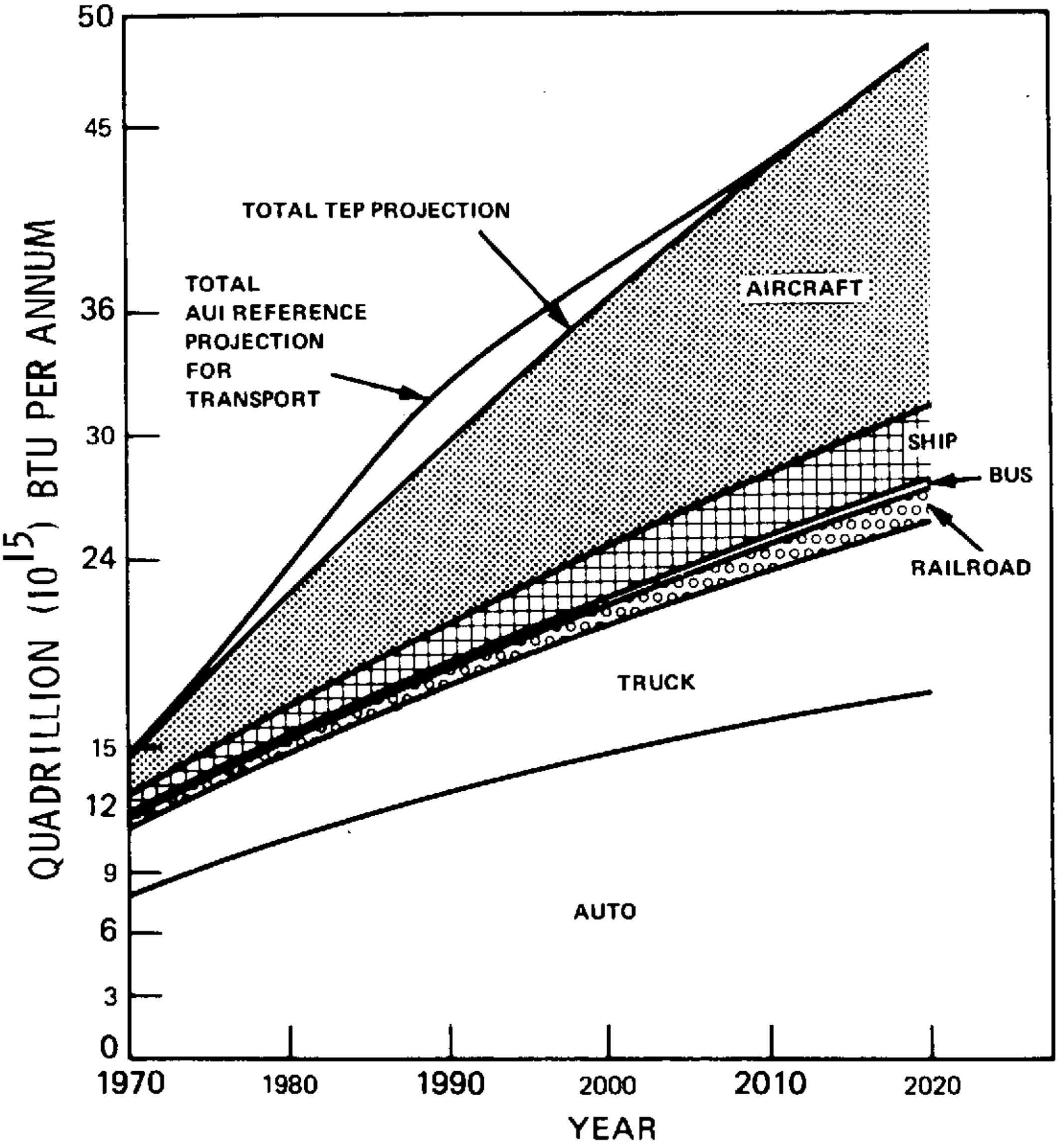

FIGURE 2.1
PROJECTED TRANSPORTATION ENERGY CONSUMPTION
Source: **Transportation Energy Panel,** Sept. 1972

in terms of energy and economics, they cannot compete effectively with either air or personal automobiles.

In summary, the projections of transportation energy demand to 1990 by TEP indicated that (1) transportation will continue to account for 25% of the total energy consumption; (2) the highway share of transportation energy consumption will drop from 82% to 65%; and, (3) the aviation share will increase to 26%. Simple projections to 1990 indicated the highway vehicles will still dominate total transportation energy consumption (see Figure II-2).

A recent study by the Department of Transportation—Transportation Needs Study (TNS)—projected a breakdown of air transportation energy demands (5). This study projected passenger demand at an average growth rate of 8.6% to 1990. The projection assumed this growth rate could not be sustained beyond 1990; subsequent growth rate was taken to equal 3% corresponding to the projected growth in per capita GNP.

The Transportation Needs Study projected cargo demand at an average growth rate of 11.6% to 1990. Since increased market penetration in this area is anticipated, this growth rate was assumed to continue until cargo demand equals one-half of passenger energy demand. From that point, growth is projected to be tied to GNP.

The projected 8.6% rate of increase in passenger demand for air travel means that this demand will double every eight years. Furthermore, the 11.6% rate of increase in air cargo will provide a doubling of cargo demand every six years.

While passenger and cargo demand is increasing with such rapidity, energy consumption by the airplane will increase more rapidly because of the energy-intensiveness of the airplane.

Although there is difficulty determining which of the many energy demand projections is most accurate, one general opinion may be drawn. Air transportation energy demand is increasing at an alarming rate and could well be five to nine times present consumption by 2000.

The next section demonstrates why, if unabated, the fuel consumption demand for air travel will equal the automobile. This is so because the airplane, relative to other modes of travel, is highly energy-intensive.

II. B. Energy-Intensiveness of Various Modes of Transportation

The consumption of fuel through the use of a particular mode of transportation is directly proportional to the energy-intensiveness of that mode. Energy-intensiveness is the

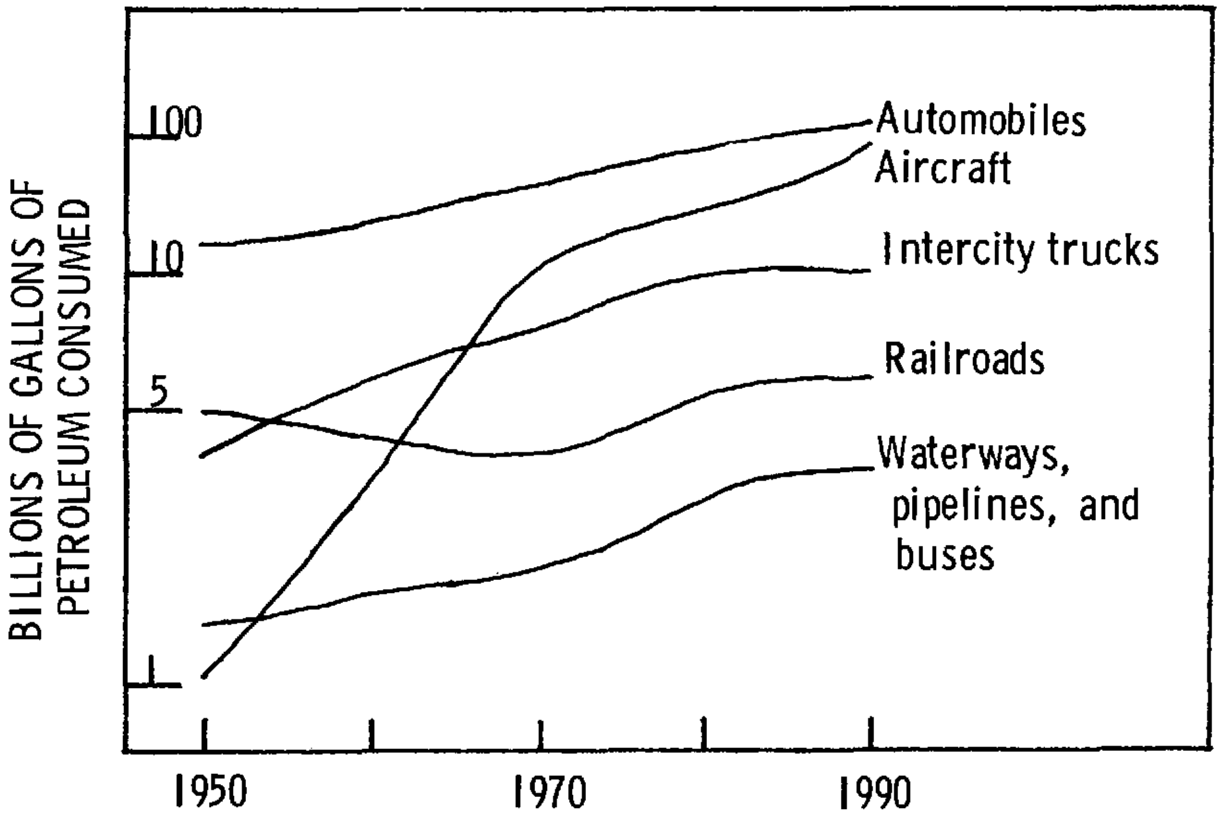

FIGURE 2.2
PROJECTED FUEL CONSUMPTION BY TRANSPORTATION MODE
Source: Rice, R., **Technology Review**, Jan. 1972

amount of energy required to move one unit (one passenger or one ton of cargo) a distance of one mile, and is expressed as BTU/PM or BTU/TM, where PM stands for passenger-mile and TM for ton-mile. A comparison of the energy-intensiveness for various modes of transport indicates which modes are energy-efficient and should be stressed in a national energy conservation effort. Table II-V shows energy-intensiveness values for various forms of freight transport. The inefficiency of moving freight by air is shown, but as was shown earlier in Table II-IV, the air freight represents an insignificant portion of total freight traffic. Of the ground transport modes, rail is more than four times as efficient as truck transport.

Table II-VI and Figure II-3 provide a similar comparison of energy-intensiveness for passenger traffic. Here, passenger train (with the exception of pullman) is shown to be more efficient than aircraft and the automobile.

Particularly alarming in terms of energy-intensiveness is the increase since 1950 of the airplane as shown in Figure 11-3.

If one considers only fuel consumption, and disregards speed, comfort, and convenience, then aviation is a relatively inefficient mode of transportation. Nevertheless, the demand for air travel, as has been noted, continues to increase. The next section

TABLE II-V

ENERGY-INTENSIVENESS FOR FREIGHT TRAFFIC

Mode	**EI, BTU/TM**[1]
Aircraft	42,000
Trucks	2,800
Intercity, Average	1,100
Waterway	700
Rail	650
Pipeline	450
Supertanker	150

[1] Assuming 136,000 BTU/gal.

Source: E. Hirst and J. C. Moyers, "Potential for Energy Conservation," March 1973 (6).

TABLE II-VI

ENERGY-INTENSIVENESS FOR INTER-CITY PASSENGER TRAVEL

Mode	**BTU/PM**
Pullman Train	10,460
Aircraft	8,400
Automobile	3,400
Bus	1,600

Source: E. Hirst and J. C. Moyer, "Potential for Energy Conservation," March, 1973, (6).

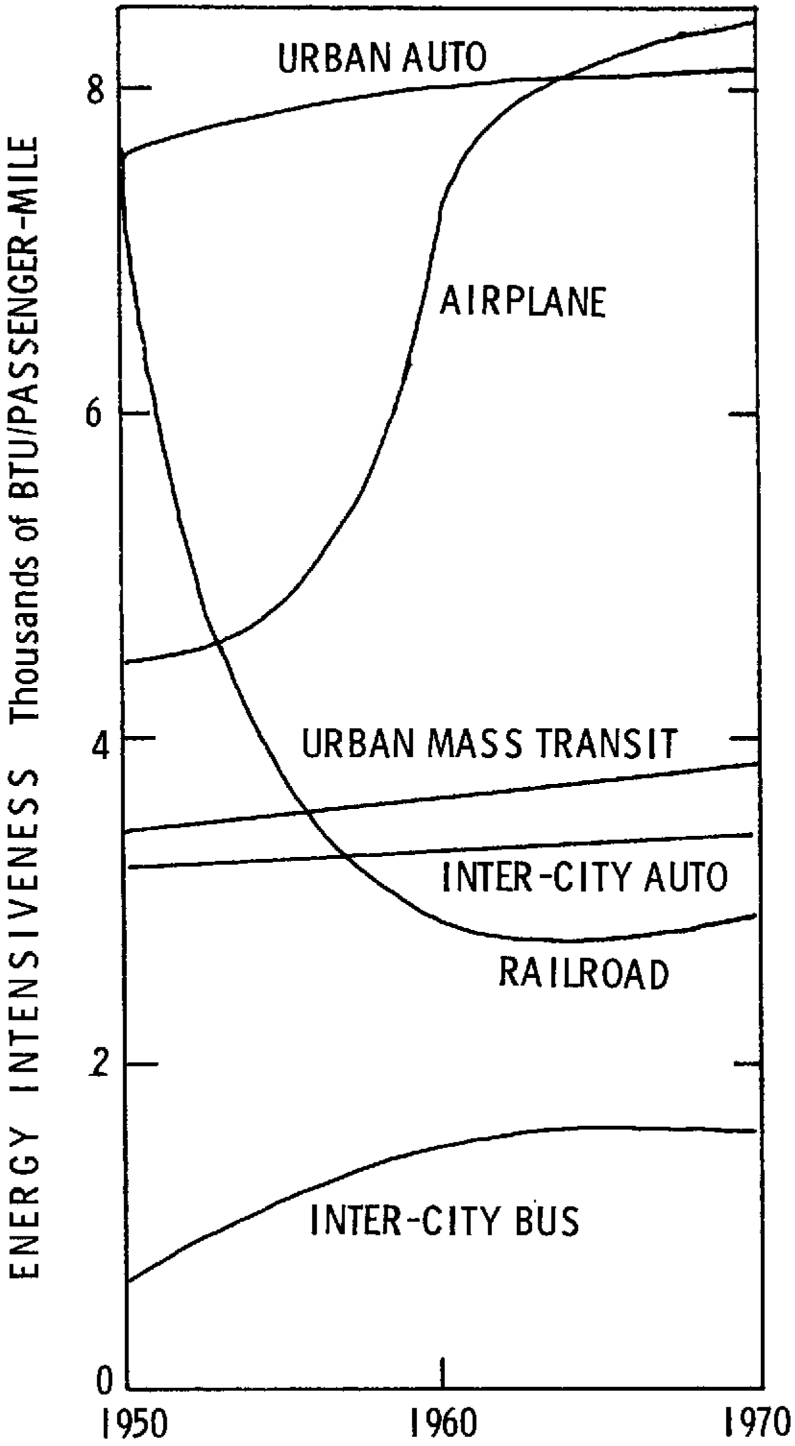

FIGURE 2.3

HISTORICAL VARIATION IN ENERGY-INTENSIVENESS OF PASSENGER MODES

Source: Hirst, E. and Moyers, J., **Potential for Energy Conservation,** 1973 discusses who travels and why, and examines some philosophical and psychological issues which relate to air travel and the energy dilemma.

II. C. Travel: The Fifth Freedom

II. C. 1. The Right To Travel

John Volpe, Secretary of Transportation, has noted that without mobility [travel], the first four freedoms (of speech, of worship, from want, from fear) cannot exist (7). While we do not postulate that freedom to travel should be added to this list, we do believe that each United States citizen has a right to travel. But that right is neither inalienable or absolute, and his abuse of it is punishable by limitation or denial.

While one may travel, he may not infringe upon the rights of others to privacy, quiet, or clean air. He has the right to travel by available mode to and from his place of residence, his job location, and to public places for cultural, familial, or recreational enjoyment. In a society so geared to movement, and so dependent upon travel as the United States, any attempt to restrict travel except to regulate its safe and orderly flow must be examined.

Should an emergency occur—requiring restriction in travel because of fuel shortage—some consideration of the appropriate philosophical principle regarding the allocation of scarce resources is in order.

A philosophical problem first posed in Aristotle's **Politics,** placed two views in juxtaposition. One he called "arithmetic (or democratic) justice," a principle which he felt was very strong in democratic societies: any resource, but particularly one which is scarce, belongs to the entire society. Since everyone in that society is equal, each is entitled to an equal share of that resource to do with as he feels best.

In opposition to this principle, Aristotle advocated "distributive (or geometric) justice." Under this principle a resource should be allocated on the basis of the extent to which it can contribute to the good of a society as a whole rather than the good of a particular individual.

A recent example may help to illustrate these principles. When the state distributes a veteran's bonus of $1,000 to every veteran, this is an example of **arithmetic justice**; the G.I. educational bill which subsidized education for different talents and interests may be considered an example of **distributive justice**. Like Aristotle, we believe scarce resources should be allocated on the basis of **distributive justice**. This argument does not imply, however, that the market mechanism is the best means of achieving distributive justice in the allocation of any resource. In fact, historical evidence indicates that when any resource becomes critically short, the market mechanism may be abandoned in favor of some other form of allocation. The market economy is often an inordinately poor way to achieve distributive justice in the allocation of almost any resource. Nevertheless, it may be the only system of allocation (in the absence of critical shortage) which American Society is willing to accept.

II. C. 2. Who Flies and For What Purpose?

Americans are people on the move. In 1900 75% of all travel was by train; by 1962 less than 3% of Americans were traveling by train. By 1970 travel by train was 1%; by air 9.7%; and, by automobile over 89%. The Bureau of Public Roads estimated the total U.S. traffic at nearly 1,000 billion vehicle miles per year, or enough to allow the nation's almost 100 million motor vehicles to make two round trips each year from New York to San Francisco. Each year Americans take a total of 257 million trips and spend two billion nights away from home (8, pp. 61-62). With the airplane becoming the number one rival to the automobile, and with the nation facing an energy shortage and a pollution crisis, we may ask "what cost freedom?" We may also ask "freedom for whom and for what?" Automobile freedom is expected, and the car has meant freedom to travel for the majority of Americans; in 1966 it was estimated that three out of four families owned their own car and by 1970, 82% of American families had a car (8, p. 61).

Figure II-4, based on Gallup Poll data, describes the percentage of persons who have ever flown in terms of their demographic characteristics (9, pp. 3, 4, 10).

Perhaps more important than an analysis of "fliers" is how many trips people take per year. A Gallup study indicated that only 23% of Americans over 18 flew in 1972. The Gallup data also showed that 17% of the fliers in 1972 took 60% of all trips. An analysis of the trip vs.


"I'LL BE RIGHT BACK, I'M GOING FOR GAS..."
GAS
MIKULKA

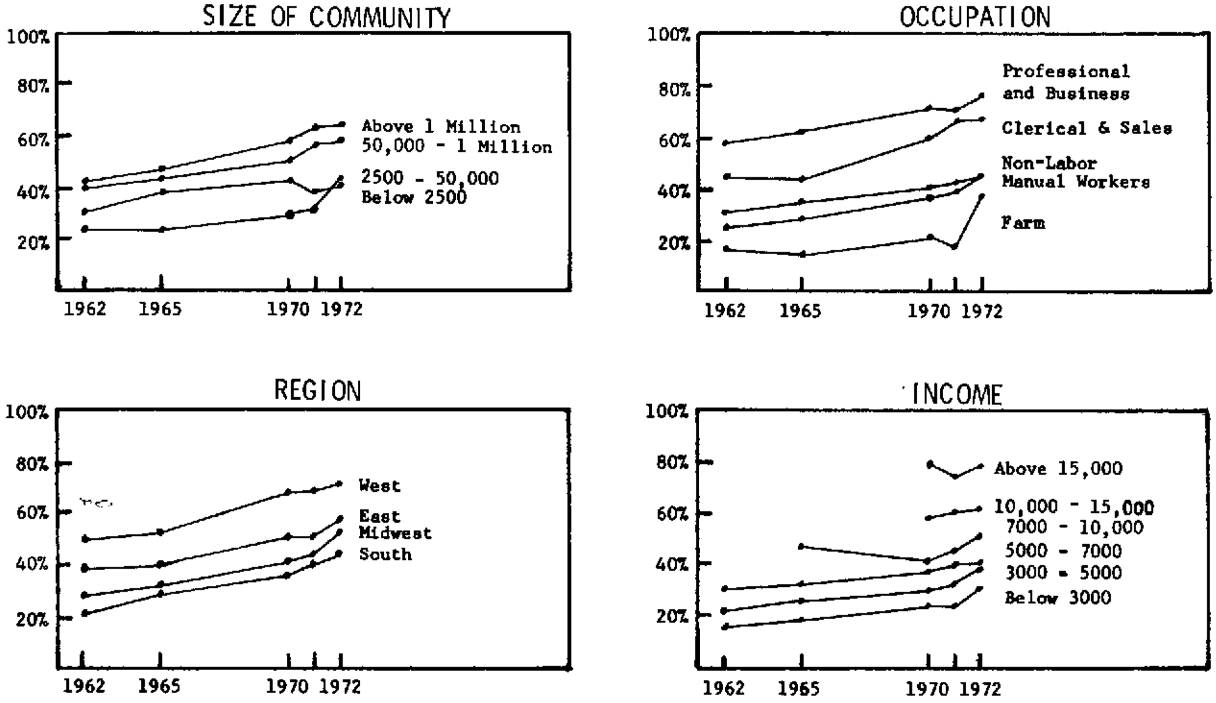

FIGURE 2.4
PERCENTAGE OF PEOPLE IN VARIOUS CATEGORIES WHO HAVE EVER FLOWN
Source: Gallup Survey, Aug. 1972

fliers data for 1972 indicated that the average flier took 5.5 trips. As might be expected, businessmen take more trips per flier than non-businessmen (9, pp. 3, 4, 10).

Knowledge of why people travel is as important as who travels. Tables II-VII and II-VIII indicate both the mode and purpose of travel.

An examination of Tables II-VII and II-VIII reveals that while air travel represents only 8% of total trips taken, it represents one-fourth of all trips taken for business and convention purposes and 36.1% of all trips taken for personal and family reasons (10).

People who have flown generally begin to perceive airplanes and airports as "good" and economically desirable. These positive attitudes are reflected in a number of survey questions which were obtained in the 1972 Department of Transportation study. This 1972 study also found that people who fly once tend to fly again, and view the airplane as a way of saving time. Approximately 50% of both business and recreational travelers interviewed, indicated that if commercial airlines were unavailable they would not have taken this trip (11, pp. 163-166).

All of these data indicate that the airplane could become a serious rival of the automobile for trips of 100-200 miles. Many Americans still use automobiles for long trips because of the Interstate system and the substantial investment they have in their automobiles, campers, and other automobile accessories. However, if car travel becomes more costly or if air travel service becomes more economical and convenient, the advantages of speed, comfort and the thrill of the ride may propel airplane travel to the foreground in American transportation.

II. C. 3. The Need for Air Travel: A Digression

There are certain psychological values which affect the "felt need" for air travel. The intention here is to provide some brief background discussion of human motivation.

A starting point for this consideration is Abraham Maslow's theory of human needs as demonstrated in his Prepotent Need Hierarchy. Maslow contended that Man is motivated by needs arranged in a hierarchical order from most basic to least basic, yet as each need emerges, it is just as strong a motivator as the need it replaces. He posited the following hierarchy:

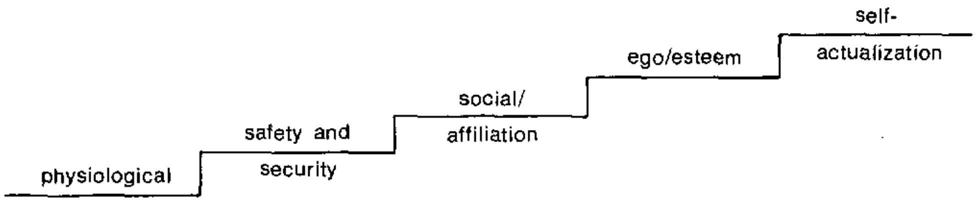

TABLE II-VII

COMPARISON OF TRAVEL BY MODES

Mode of Transportation	Percentage of Total	Person-Trips* in Millions
Commercial Air	8.0	28.8
Train	1.4	5.1
Bus	2.6	9.4
Auto	86.1	311.0
Other	1.9	6.9
	100.0	361.2

*"Person-trip" is defined by the Census Bureau as either any overnight round trip or as any round trip longer than 100 miles. On this basis the figure of 361.2 million person-trips is substantially less than the person-trips computed by DOT or Gallup.

Source: 1967 Census of Transportation, Bureau of Census.

TABLE II-VIII

COMPARISON OF TRAVEL BY AIR WITH OTHER MODES BY PURPOSE OF TRIP

Purpose	Percentage of Total		Person-Trips *In Millions* Non-Air		Person-Trips *In Millions* By Air		
	All Modes	Air Travel		%		%	
Business & Convention	16.2	51.4	43.7	(74.7)	14.8	(25.3)	(100.0)
Personal & Family	2.0	9.1	4.6	(63.9)	2.6	(36.1)	(100.0)
Entertainment & Sightseeing	22.4	13.2	77.1	(95.3)	3.8	(4.7)	(100.0)
Outdoor Recreation	17.2	2.4	61.5	(98.9)	.7	(1.1)	(100.0)
Visits to Friends & Relatives	42.2	23.9	145.5	(95.5)	6.9	(4.5)	(100.0)
	100.0	100.0	332.4	(92.0)	28.8	(8.0)	(100.0)

Source: 1967 Census of Transportation, U.S. Department of Commerce Bureau of the Census.

Before each need level is defined, one should recognize two primary tenets in Maslow's theory, namely that (1) a satisfied need no longer motivates behavior, and (2) only when a need has been at least partially satisfied can a next higher level need become salient.

Briefly described, **physiological** needs are those manifested in hunger (the need for food), thirst (the need for water), respiration (the need for air). Once physiological needs have been at least partially satisfied, **safety and security** needs emerge. This level represents the need for shelter and clothing (some form of protection from physical adversity). In humans (and perhaps in some primates) **social** needs emerge next. Simply, we need to know that there are others; there is a need for some social contact (live or media). **Ego or esteem** needs follow. This is a need to be praised, admired, wanted. One must be recognized positively by others. **Self-actualization** is the highest need level. It emerges only after all lower level needs have been at least partially satisfied. Self-actualization is truly determined by the individual. Essentially, argued Maslow, what a man can be he must be.

Classically, Maslow's Prepotent Need Hierarchy has been approached by viewing need saliency as progressing from lower to higher level needs as an individual matures. A young person beginning his career is viewed as functioning at the lower need levels. As he advances, gaining experience and wealth, he is viewed as satisfying higher level needs. Typically, under this interpretation, one self-actualizes rarely, and the persons who self-actualize are few. Representative of those who have been perceived as self-actualizing individuals would be Shakespeare and Churchill.

A second viewpoint would argue that any individual, at any time in his life, could be at any of the five need levels. Rather than progressing from a lower to a higher level as one advances through life, the second view holds that need saliency is situational and a function of the immediate need state of the individual, not some longitudinal life plan. A pilot, for example, may be fed, clothed, in the presence of others, have four stripes on his sleeve, and execute a brilliant landing under difficult conditions. He has probably self-actualized at that moment. If, however, the aircraft's landing gear collapses, his lower level needs (safety and security) would become overwhelmingly salient.

When one attempts to interpret a theory like Maslow's in a way other than in which he intended, one runs an inherent risk. Furthermore, when one attempts to apply theories of individual human motivation to the society as a whole, the risk is even greater. Nevertheless, application of Maslow's theory can be made to the American society in the form of an academic exercise that may yield fruitful insight to the problem of the apparent human need to travel.

Here we contend that the American Society is at the threshold of stage five—self-actualization. Needless to say, not all members of the society are at this level. Many are in a struggle to satisfy needs at levels one and two. Furthermore, to paraphrase Christian Bay, in **The Structure of Freedom**, a society's success should not be judged by the average level of needs satisfied but rather by the level of needs which the most deprived members of that society must struggle to satisfy.

Returning to the question of air travel, some conclusions may be drawn. If the preceding analysis is correct, a large part of the motivation for air travel is based on the salient need for self-actualization. Many who travel by air see it as part of this developmental process—it makes them less provincial and more cosmopolitan. For example, the youth who drops out of school, flies to Europe, and hitch-hikes around for six months sees this as a very meaningful and significant contribution to his development as a human being.

This viewpoint appears to be borne out by Dan A. Colussy of Pan American Airways. Colussy made the following comments:

> **There is an obvious change in life style, reflecting a trend toward greater emphasis on personal enrichment** . . . A recent Stanford Research Institute study reveals that self-expression and individualism are becoming more important value trends while status achievement and conformity are receiving less emphasis. In the 30's and 40's a trip to Europe was made for status. Today's younger generation make the trip for personal enrichment. This reduced emphasis on "materialism" is also shown in the Behavior Science Study. When asked how they would spend a windfall gift of $1,000, foreign travel was rated number 2 just behind home improvements but ahead of domestic travel or a new

automobile. New automobile placing behind travel is a significant change in the typical American's attitude (12, p. 3).

An examination of macro-economic statistics provides further confirmation. Apparently air travel will be less affected by gross changes in GNP than in the structure of GNP. There is a trend which indicates that both durable and non-durable goods will play a less significant part and both service and public goods (free adult education, clean air) will play a larger role in total GNP in the future. If this is the case, air travel will compete less in the future with the desire for refrigerators and more with the demand for education and environmental control.

Certain inferences may be drawn from these considerations if the impending fuel shortage necessitates reduced demand for air travel. First and most significant, if the general energy problem causes lower level needs to become salient, moving the public away from self-actualization, it should automatically tend to reduce demand for air travel by eliminating those who would have felt that air travel fulfilled self-actualization needs. As the general energy problem becomes acute, it will be more important for air travel to be based on "Distributive Justice" than "Arithmetic Justice."

Second, if self-actualization is a motivation for air travel, and fuel consumption is inhibiting this need, then certain less fuel-consumptive substitutes are the logical ones to offer in and art. Of course one must recognize that the key to achieving self-actualization is the concept "self." Others may not dictate how one self-actualizes.

While these observations may not lead directly to reduced demand or tell us how to reduce demand, they do provide a needed frame of reference that may alert us to potential problems in altering demand. They also indicate that reduction of air travel will not be accomplished easily unless the energy problem is of such magnitude that our society becomes motivated on a lower level of need than at present.

II. D. Economics and Regulations Affecting the Aviation Industry

II. D. 1. Government Agencies and Aviation

While the maze of governmental agencies which become involved with aviation is not nearly as extensive as those dealing with energy, it does represent a complicated mosaic. Among the agencies are the Departments of Agriculture and Interior as well as local governmental units such as county and airport authorities. We will consider only those agencies which play a major role in aviation regulation. These are the Federal Aviation Administration (FAA) a division of the Department of Transportation, and the independent regulatory agency, the Civil Aeronautics Board (CAB). There is, in addition to these two, the National Transportation Safety Board which investigates airplane accidents.

The Department of Transportation (DOT) has not been able to design a national transportation system which integrates all modes of transportation, but it does compile valuable data relating to transportation. Furthermore, it supports research and planning relating to technological innovations and environmental effects of transportation, including noise abatement and pollution control. The Transportation System Center in Cambridge, Massachusetts, managed by the DOT, is working at the frontiers of technological research and system planning in the area of transportation.

The Federal Aviation Administration

The FAA is more directly involved with the day-to-day operation of the Air Transportation System than any other Federal agency with the possible exception of the CAB. The primary concern of the FAA is with aviation safety and the technical operation of air navigation. To that end, the FAA is responsible for the control of the traffic system, the use of air space, and the integration of the national airport system. The FAA also promotes air safety by licensing and regulating aircraft and by certifying pilots and airports. The enviable safety record of American aviation stands as a monument to the effectiveness of the FAA. There were 174 air fatalities in 1972 compared to automobile fatalities of 54,200 (13, p. 40).

The Civil Aeronautics Board

A DOT-NASA Study described succinctly the function of the CAB (14, pp. 6-11):

Route Authorizations: The Board,

through the grant of certificates of public convenience and necessity, authorizes domestic carriers to perform domestic and/or foreign air service between designated points. It also issues permits to foreign carriers to promote air transportation between the United States and foreign countries and authorizes the navigation of foreign aircraft in the United States for other purposes.

Fares: The Board has authority over the *tariffs, rates and fares charged* for civil air transportation. The carriers initiate the rates and the Board oversees and approves them. The Board also authorizes and pays subsidies for service to communities where traffic does not cover the cost of service.

Inter-Carrier Relationships: The CAB passes on mergers, agreements, acquisitions of control and interlocking relationships involving air carriers. It also supervises unfair competitive practices of carriers or ticket agents.

Reports: The Board requires regular financial and operating reports to be filed by carriers. It also specifies the accounting and bookkeeping practices and procedures to be used in preparing the required information.

International: The CAB serves as an advisor to the Department of State in foreign negotiations for new or revised air routes and services.

The role of the CAB is crucial in any attempt to increase airline efficiency through such measures as reducing route competition or through merger of airlines.

One should keep in mind that the CAB, as an independent regulatory agency, is not subject to direct influence by the Executive Branch and, therefore, might be an obstacle to plans to change air transportation operations. Also, the history of independent regulatory agencies has been controversial, stretching back at least to the Brownlow Report of 1938 when they were described as the " . . . headless fourth branch of government (15)".

A number of political scientists have suggested the proposition that independent regulatory agencies appear to go through a life cycle. They come into being because of the clearly recognized need for public regulations. During infancy they are noted for their crusading and critical attitude toward the agency they are regulating. As they mature, regulatory agencies become more sympathetic to the needs of the industry than to the public at large. Frequently, regulatory agencies cease to be that except in name only. A recent article, critical of the CAB indicated that, for example, this aging process may be overtaking the CAB. " . . . 12 of the 24 CAB members who had left the board prior to 1971 took jobs as lawyers, consultants or employees of the firms they had just finished regulating (16, p. 35)."

One suggested cure for this aging process is to have the regulatory agency be given a restrictive life by its enabling legislation.

Traditionally, transportation systems planning has occurred on an **ad hoc** basis. Canals, roads, sea-going vessels, autos, and finally airplanes spurred a fragmented government response that produced the modal configuration of approach evident even in DOT. This fragmented nature of the decision-making process is one of the most serious obstacles to attaining technology's full potential in aviation.

In civil aviation this is most apparent in the cluster of problems surrounding the *nation's airport system.* This complex and interrelated system requires extensive, coordinated, and informed decision-making. Additionally, the airport planning and executing function must respond to mounting resistance to questions of siting, landsite planning, access, and finance. Environmental implications compound the diverse inputs into the decision-making process.

The ability of the Federal government to formulate a comprehensive civil aviation policy is severely limited, given the nature of the problem and the institutional structure within which it must operate.

II. D. 2. The Federal Cost of Air Transportation

One important factor for consideration is *the cost of an air transportation system and* who pays for it. This cost must be weighed against the current and future benefits of having an air transportation system. A detailed study on this point has been undertaken by the DOT office of Policy Review, but their final report is not complete at this time. The Airport and Airway Development and Revenue Acts of 1970 (P.L. 91-258), directed the DOT to conduct an aviation cost allocation study to determine (a) the total Federal cost of the Airport and Airway System; (b) the appropriate method for allocating that cost among the users; and, (c) whether any changes are needed to make the present tax structure more equitable.

Table II-IX summarizes the current Federal tax structure for aviation, and Table II-X gives the actual revenue that accrued to the Federal government during 1971 (expressed in 1970 dollars). Note that the primary sources of revenue are the domestic air passenger ticket tax ($509.6 million), the domestic air cargo waybill tax ($33.6 million), the international air passenger tax ($38.4 million), and the general aviation fuel tax (45.3 million).

The Federal cost of the air transportation system is difficult to determine. The Aviation Cost Allocation Study limited its scope to Federal programs for airports and airways funded by the (a) FAA; (b) Department of Defense; (c) Department of State; (d) NASA; and, (e) the Office of the Secretary of DOT. For various reasons, programs such as the FAA safety regulation, the CAB, National Safety Transportation Board, and several others were not included. Using these guidelines, the Federal cost of the Airport and Airway System was approximately $1.2 billion in 1971 (1, 2). If the costs of programs such as the FAA safety regulations, CAB, etc. were included, the cost would rise to about $1.5 billion (17).

Although there are many different methods for allocating cost among the users, this study concluded that air carriers are responsible for about 50% of this cost ($600

TABLE II-IX
SUMMARY DESCRIPTION OF PRESENT AVIATION USER TAX STRUCTURE

Type of Tax	Tax Base	Rate
Domestic Air Passenger Ticket Tax	Transportation Charge	8 percent
International Air Passenger Enplanement Tax	Passenger Enplanements	$3 per person
Domestic Air Cargo Waybill Tax	Transportation Charge	5 percent
Aviation Gasoline and Jet Fuel Sales Taxes (General Aviation only)	Fuel Consumption (gallons)	7c per gallon
Aircraft Registration Tax	Aircraft	$25 per aircraft
Aircraft Weight Tax	Aircraft Weight	
Non-Turbine-Powered		2c per pound
Turbine-Powered		3-1/2c per pound
Aircraft Tire and Tube Sales Taxes		
Tires	Tire Weight	5c per pound
Tubes	Tube Weight	10c per pound

Source: Airport and Airway Revenue Act of 1970 (Sections 4041, 4071, 4081, 4261, 4271, and 4491).

TABLE II-X

ESTIMATED TAX LIABILITY ACCRUING TO CIVIL AVIATION FROM USER TAXES

Fiscal Year 1971

	User Tax Revenues (millions of 1970 dollars)
	1971
Domestic Air Passenger Ticket Tax	509.6
Certified and Supplemental Carriers	494.0
Intrastate Carriers	9.4
Commuter Carriers (General Aviation)	6.1
Domestic Air Cargo Waybill Tax	33.6
Air Carriers	33.0
Commuter Carriers (General Aviation)	.6
International Air Passenger Tax	38.4
Aviation Fuel Taxes (General Aviation)	45.3
Aircraft Use Tax	20.3
Air Carrier	11.0
Registration Fee	(0.1)
Weight Tax	(10.9)
General Aviation	9.3
Registration Fee	(3.2)
Weight Tax	(6.1)
Aircraft Tire and Tube Sales Tax	3.2
Air Carrier	1.6
General Aviation	1.6
Total, All User Taxes	650.3
Air Carrier	587.4
General Aviation	62.9

Source: "Forecasts of User Tax Revenue Contributions to the Airport and Airway Trust Fund," Working Paper No. 7, Office of Policy Review, Department of Transportation, July, 1972, p. 5.

million), general aviation about 30% ($360 million), and military about 20% ($240 million). Comparing this with the tax revenue data in Table II-X (and not including military costs, which should be paid for out of general tax revenues) shows that the Airport and Aviation System was subsidized from general tax revenues at a level of $310 million. Of this total "deficit", the air carrier accounted for only $10 million, while general aviation accounted for $300 million.

As mentioned above, the analysis by the Aviation Cost Allocation Study did not include the CAB subsidy program which is of direct benefit to the air carriers, the communities they serve, and which cost $60 million in 1971. If this were included in the analysis, then air carriers would have a "deficit" of $70 million.

An additional problem is the Aviation Trust Fund. Presently the tax revenues received from aviation are placed in this fund where their use is severely restricted. For example, there appear to be substantial funds available for air traffic control hardware but severely limited funds available for controller's salaries. The history of the Highway Trust Fund should serve as warning of future potential problems.

II. D. 3. Cost Structure and Profitability: Commercial Airlines

One purpose of this discussion is to

present some characteristics and implications of cost structure in the commercial airline industry. Labor, fuel, and financing costs are analyzed. A second purpose is to present a general discussion of some causes of profit instability in the industry.

Salaries and fringe benefits are the largest component of operating costs (50%); the picture is one not only of high salaries but of salaries that have been rising at a very rapid pace. In 1972 the average annual salary of airline employees was $13,921 (18, p. 16). This compares with the average annual salary in other industries of $6,598 (19, p. 32). The industry reported that over the last three years the average salary has increased 9.3% annually. The top 600 airline pilots were paid an average of $39,700 including fringe benefits) in 1965 for an average 56 hours/month. By 1971 salary had climbed to $68,000, while hours worked had dropped to 47.5 hours. Thus the pilots were being paid much more for less work (18, p. 16; 19, p. 32).

In addition to labor costs, there is also concern about fuel costs. To get an idea of fuel cost impact, Table II-XI lists the percentage of direct operating costs attributable to fuel and oil for various types of aircraft used by truck lines in 1969 (20, pp. 1-3). Since direct costs (flight operations, maintenance, depreciation, amortization) represent approximately one-half of the total operating costs, then one can see that fuel and oil costs range from about 5% to 14% of total operating costs.

There are two reasons for future concern about fuel costs: (1) the upward trend in fuel prices, and (2) the greater fuel volume that will be required in the future. By 1975 the consumption of jet fuel is estimated to reach 17.9 billion gallons and that the price will be around $.129/gal. This will represent an expenditure on fuel of more than $2 billion, an increase by a factor of 2.54 in a period of only six years (21, pp. 54-55). As the energy dilemma deepens, the situation will worsen progressively, likely increasing the share of fuel costs in total operating expenditures. Moreover, the problem is compounded by the fact that fuel may be in short supply, regard-

TABLE II-XI

FUEL AND OIL COSTS
Domestic Trunks (12-month period ending December 31, 1971)
Passenger Configuration

Equipment Group	Percent of Direct Operating Expenses
1. Turbofan 4 engine wide bodies (B-747)	22.4%
2. Turbofan 4 engine regular bodied (B-707-100B or DC-8-61)	26.6%
3. Tubofan 3 engine regular bodied (B-727)	23.8%
4. Turbofan 2 engine (B-737 or DC-9)	21.1%
5. Turbojet 4 engine (B-707-100 or DC-8-20)	29.6%
6. Turboprop 4 engine (Electra)	8.1%

Source: (20)

less of price. For example, fuel suppliers are now bargaining for one-year contracts instead of previous arrangements which involved two or three years. Furthermore, as the Department of Defense has found out, suppliers are seeking new customers.

The commercial airline industry has been characterized by profit-instability. For example, the airlines reported net industry earnings in 1972 of $214 million. This was the best profit performance in five years and compared with the $31 million earned in 1971 and the $200 million lost in 1970 (17, p. 16). For a distribution of profits since 1958, see Figure II-5.

Some factors that may explain the profit instability are the peak problem, cross-subsidization, and inflexibility in rate adjustments. The peak problem is not restricted to airlines but is common to the entire transportation sector as well as to other industries. Stated concisely plant capacity is not determined by average demand but by peak demand. This means that many facilities go unused for a good portion of the time. In the case of airlines, peak load must be met by airplanes, runways, control towers, baggage handling, ticket counters, and personnel. One possible answer to this problem is to use fares as a leveling device; higher fares during peak periods and lower during off-peak periods. Another possible solution is more efficient scheduling.

Cross-subsidization is a term employed by the airlines to mean that a carrier is certified to provide service over certain clearly specified routes. If some routes are unprofitable, the carrier is not at liberty to abandon them. The profitable routes subsidize those which are unprofitable. The airlines would prefer to have freedom to abandon loss-incurring routes, and surrender the subsidy.

Rate adjustments are authorized too slowly. Hearings for rate changes are lengthy and by the time they are approved by the CAB,

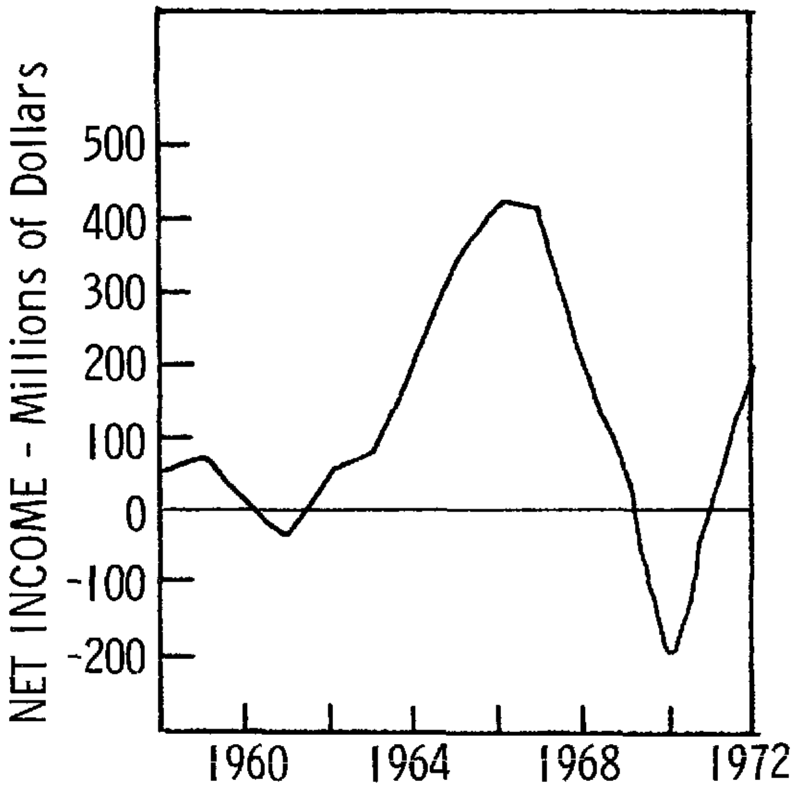

FIGURE 2.5
PROFIT INSTABILITY OF COMMERCIAL AIRLINES

Source: Air Transport Association of America, 1973 higher costs frequently outpace fare increase approval. This is particularly serious in times of runaway inflation. If fare changes could be introduced more quickly, the user would absorb the increased costs rather than the airlines.

The willingness of investors to provide equity capital to an industry with erratic earnings has been reflected in the debt/equity ratio of the airlines. In 1940, the capitalization of the airlines showed $141 million in debt (bonds, notes, etc.) and $212 million in equity. Thus the debt/equity ration was 40/60. In 1971, the situation was the opposite; the outstanding debt had become $3,885 million whereas the equity stood at $2,913 million. This implies a debt/equity ratio of 57/43 (22, p. 21-23). Airlines seem to find themselves caught in a vicious circle. Instability of earnings leads to poor investor response; this leads to deterioration in the debt/equity ratio, resulting in high interest payments which affect profitability. Thus, the circle is closed. *How airlines are going to finance the* purchase of more expensive aircraft at ever-rising interest rates is a good topic for speculation.

II. E. Summary and Conclusions

This chapter has presented considerable data regarding the air transportation system and its relation to energy consumption. Increasingly apparent is the United States' need for a unified transportation policy. Although *we may be in the process of developing* an energy policy, it concerns itself primarily with examining ways of meeting the growing demand for energy from new sources or technologies such as coal gasification. It does not focus on the consumption side of the equation.

The assumption seems to be that all demands for energy made by our society must be met. There seems to be some illogic in this assumption when one considers the fact that U.S. per capita consumption of energy is twice that of other developed market economies such as Western Europe, four times that of the socialist economies, and ten times that of the undeveloped nations. In addition to a consideration of where the energy *will come from, attention must be given to* how energy is consumed. Looking at the energy problem in this manner leads one to a consideration of transportation because transportation consumes 25% of all energy and is almost totally dependent upon petroleum, the fuel in most critical shortage.

The United States must have a transportation system that integrates water, ground, and air transportation into one network. This system would provide efficient *mass transportation in the cities, rail and* automobile transportation between cities, and air transportation where long distances and speed are essential characteristics of the service being supplied. We will not attempt to describe the components and relative role the various modes of transportation should play in such a system. Our task is to concentrate on air transportation.

Professor Richard A. Rice predicted:

> A fleet of 900 [747]—which has been forecasted—makes our future petroleum commitment look alarmingly sizable.
>
> Indeed, if all present carrier transport plans should materialize, some 88 billion additional gallons of fuel might be required per year for transportation by 1985. [This is equal to the total amount of fuel consumed by transportation in the late 1960s.] Of this increase, automobiles are estimated to need 28 billion gallons *and larger air transport craft,* 43.5 billion gallons (4, p. 2).

Given the present inefficiencies of air transportation in terms of fuel consumption, it is probably impossible and perhaps highly undesirable for air transportation to expand at the rate projected unless a new source of fuel, independent of petroleum, is developed. These inefficiencies are expected to be alleviated as advanced aircraft technology is utilized.

Knowing who travels and why is essential to the development of an air transportation policy. While at the present time air travel remains the province of the relatively well-to-do businessman, there is strong indication that future developments will see air travel become *a significant mode of travel for* **most** Americans.

An examination of the cost to the Federal government of the Air Transportation System *points out an anomaly in the commercial air* carriers, which account for 9.46 billion gallons of fuel consumption per year, operated with almost $70 million subsidy, while general aviation, which accounts for only 6.47 million gallons of fuel consumption, enjoyed a subsidy of $300 million.

Now is the time to bring the Aviation Trust Fund under control before the history of the

Highway Trust Fund is repeated. What appears to be needed is a Federal Transportation Trust Fund into which all revenues from transportation would go and out of which subsidies would be paid on a rational basis.

Related to the question of airline subsidies is the precarious profitability of the industry. Such factors as rising operating costs (including fuel and technological obsolescence) create great concern for the future profitability of the industry.

Again, the need for a comprehensive transportation plan covering all modes of transportation becomes apparent, and will become imperative if an acute energy crisis develops.

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3

ENERGY CONSERVATION and AIR TRANSPORTATION

Chapter III: Energy Conservation In Air Transportation

The complex transportation networks in the U.S. are by necessity inter-related, but are by no means integrated. Transportation exists as a system only by accident, not design, with no evidence that this mixture is the best system. However, society may not be able to afford the luxury of an unintegrated system much longer. The force driving transportation to rationality may well be energy.

The energy consumed by transportation represents about 25% of the total energy used in this country. Yet the significance of this fact is lost to the decision makers within the transportation sector because for so long the direct cost of energy has represented a relatively small portion of their total costs. One conclusion from Chapters I and II is that this cannot continue. The supply of petroleum for transportation is already becoming more expensive and the security of supply more tenuous as energy sources and competition for them undergo dramatic changes. The influence of energy will be felt particularly in air transportation, because it is currently 100% dependent upon petroleum fuels; it is a highly energy-intensive industry, and predicted future growth patterns indicate that the airlines will rival the automobile in total energy consumption.

Thus, while the previous two chapters have outlined the general energy dilemma and its potential impact on air transportation, this chapter will focus on airlines as energy consumers with the purpose of analyzing several approaches for achieving energy conservation.

The chapter is divided into two major sections: (1) air transportation demand, and (2) airline systems efficiency. Within air transportation demand, the primary factors affecting the demand for air transportation and measures for reducing this demand are developed. This section does not include material on general energy rationing which has been presented in Chapter I. The second section on airline systems efficiency deals with energy conservation via improved regulations, improved operations and improved aircraft (i.e. better hardware). Another approach for dealing with the air transportation/energy problem, fuel diversification, will be presented in Chapter IV.

III. A. Air Transportation Demand

III. A. 1. Passenger Energy Demand

Air travel represents "rapid travel" for almost all Americans. Despite airport congestion and ground traffic delays, our infatuation with speeding along at nearly 600 miles per hour in a jet is used as the standard to judge all slower forms of transportation. However, because of the potential energy problems, consideration must be given to reducing the demand for air travel.

A. Alternatives to Air Travel

(1) The No Travel Alternative: While businessmen might welcome relief from the many air trips they make, travel for the purpose of confidential negotiations and contract signings may be necessary. One alternative for business travel is the telephone. If communication networks which would allow several people to see and hear each other simultaneously were available, it could reduce business travel demands. This area has some significant potential since business travel represents about 50% of scheduled service commercial air travel.

On the other hand, while electronic communications might substitute for some travel needs, many problems with these new communication devices will have to be solved. New devices providing visual, verbal, and other sensory stimuli communication are still a long way off. We believe that better use of energy will result from the greater promotion of the telephone option and a greater effort to develop more complete communication systems.

The reasons for non-business travel exhibit great variety, and there is no doubt that no single solution will possess the flexibility to substitute significantly for this kind of travel. For example, electronically-communicated messages seem a poor substitute for outdoor recreation, sightseeing, or the personal experience of visiting distant unique places. However, nearly half of the non-business travel is taken to visit family or friends (1, p. 14). A well-developed electronic communications system might substantially reduce the need for visits, but only if the system recreated the live environment artificially. However, if the telephone is any example, new communication devices might encourage new friendships and might work to increase personal travel.

A more promising way to substitute for the desire to travel for entertainment, recreation, and education is to provide competing sources for these activities locally. Instead of flying to a distant location, individuals could be attracted to local areas. Personal enrichment that often must now be sought by travel to "centers of culture" could be found locally, and the need for cultural stimulation from afar could be more adequately fulfilled by video-tape or film media. However, there are world-class attractions that are not duplicable. The Louvre will always be in Paris; the Grand Canyon in Arizona; and the Washington Monument in the Nation's Capital. If people learn to enjoy vacations in and around their homes, then travel behavior and energy consumption will decrease—but only if the nontravel activities are less energy-intensive than travel.

(2) Alternative Modes of Travel: Effort or resistance to air travel can be broken down into such factors as the vehicle accessibility, travel mode speed, the number of stops the vehicle makes on a route, as well as cost, comfort, and safety. Often the perceived travel effort determines vehicle choice rather than actual effort. For example, a plane trip might be perceived as faster even though a train or car might get there as fast or faster when the portal-to-portal time is considered. The perceived unpleasantness of stops or on-and-off-time during travel is much greater than the effort of being in a moving vehicle.

The time getting to and from an airport and the time to deplane and get the luggage has long been a major irritant to air travelers. In selecting a flight people will not voluntarily choose a multistop flight if there is a non-stop flight available, even though it may arrive at the destination later.

No single factor will uniquely determine travel mode choice. Most people today make travel decisions based on presumptions often unrelated to fact (e.g. assuming planes are **always** the fastest mode) and hence they have no assurance that their decision is the optimum one.

One approach for dealing with travel mode choice problem is to organize a centralized travel service. A prospective traveler would submit information about where he wants to go, how crucial travel time is, and what the purpose of the trip is. In return, he would be presented with price, time and convenience alternatives. Even the energy consumption of the trip could be listed. The traveler could then make a choice which would best serve his needs.

Computer analyses of the relationship between travel alternatives and the mode chosen would make the system self-improving. The government could not only monitor travel patterns for future transportation system development but could also begin to effectively regulate travel during periods of energy of fuel shortage. (See also section III.B.2. to see how this concept could be used to improve systems efficiency.)

B. Airline Advertising

Airline advertising takes many forms, from the readily apparent use of print and broadcast media, to special classes for travel agency personnel, to night-lighting the airline insignia on the tail of an aircraft. Airline advertising has three primary target audiences: (1) commercial travelers; (2) travel agents; and, (3) leisure travelers.

The bulk of an airline's advertising is intended to attract passengers from other airlines, rather than to solicit new passengers from among those who have never flown. Because price competition is not allowed by airline regulating agencies, the airlines must rely on advertising campaigns that stress the advantages their company offers in on- and off-plane service and convenience. For example, one airline redesigned its aircraft interior and conducted an advertising campaign specifically designed to attract businessmen who travel frequently (12-14 trips annually). This particular campaign resulted in an increase in gross revenue of $110 million in a two-year period.

In contrast to the needs of business passengers for speed, comfort, and convenience, passengers traveling for leisure are primarily price oriented. Attempts are made to publicize low off-season fares, discount coupon books for use at the destination, or special vacation packages. These packages have historically involved complete tour/hotel plans. Promotion of these packages continue, and advertising of the new fly/drive plans is increasing. The fly/drive option offers the traveler more personal choice of activities and the absence of the need to always travel as a part of a larger group. Additionally, attempts have been made to attract passengers with reduced youth fares (which are being phased out as of this writing) and easily granted credit cards.

If airline advertising campaigns can create demand for travel, other advertising campaigns can modify the impact of present travel advertising. Instead of a continuous *obvious, routine surface divertible traffic will* that people go somewhere, local communities might be encouraged to advertise the recreational advantages of the home environment.

Business could be encouraged to spend more time on the phone and less time traveling to engage in face-to-face contact. Campaigns like these have already been conducted—but by the telephone company to promote their business, rather than to discourage marginal air travel. At the present time there would be minimal reduction in air travel with such a campaign.

The recommended way to reduce air travel through advertising would be to advertise how to choose between modes of travel and by extensive education about the real costs of travel. Advertising can help people realize that travel time and ticket cost are only the most obvious factors in travel decision making.

C. Airline Ticket Pricing

To the average individual the ticket price represents the primary cost of traveling. Any attempt to modify travel mode choices would surely then involve suggestions about ticket price changes because of the presumed relationship between ticket price and mode choice. The difficulty with trying to come to any conclusion about the relationship of ticket price and an individual's inclination to fly, lies in the fact that the statistical estimates of price elasticities have a wide variation in mean values. For example, the Department of Transportation made three studies which show the wide variance in estimates of the mean elasticies (2, p. A-12).

Time Period	Elasticity Coefficient
4th quarter-3rd quarter 1968	-1.43
2nd quarter-1st quarter 1967	-0.77
2nd quarter-1st quarter 1970	-0.583

Verleger (3, p. 455), in a separate study, estimated the mean price elasticity to be -0.12. Verleger based his estimate on trip distance and found that the longer the trip the more elastic is demand with respect to ticket price. This study and other work (4, p. 4) have indicated that to appreciably offset travel demand for short-haul traffic the price would have to be increased by a large margin, and by a smaller margin for long-haul traffic.

One influence tending to increase air travel will be any increase in the real amount of disposable income. An increase can occur either by total income increasing or by a shift of the priorities used to determine how the usually fixed portion of disposable income set aside for transportation is spent. In recent decades the automobile has had the primary claim on the transportation dollar, but future predictions indicate that the auto market will *become essentially saturated within the next* few decades, which leads to expectations that an increasing amount of money per capita will be used for common carrier transportation. This expectation has, in part, accounted for the dramatic rise in air transport demand predicted for the future.

D. New Fare Structures

One rational strategy for increasing the price of a ticket would be to include in the price all the economic and "social" cost of air transportation. Including all economic costs insures that no general tax revenues go towards supporting the air transportation system (See Chapter II. D.), while the social cost component includes the "costs" of such things as noise and air pollution. In addition, the new fares should be at least partially a function of energy and/or system efficiency. These additional charges could be a direct addition to the ticket price, much like the 8% passenger tax presently in use, or added indirectly to various parts of the aviation system through such means as the fuel tax or airport fees.

The price increases would tend to have two effects on demand: (1) discourage the *overall demand for transportation;* and (2) shift the demand to other modes. Shifting the same level of demand to more energy efficient modes would be a desirable effect.

On the other hand, a negative impact to be considered in such plans is how they tend to discriminate against the lower income groups. As indicated in Chapter II, air transportation is already biased in favor of business, middle and upper income level groups, and increasing the price would only exacerbate this effect since the increase would represent a smaller percentage of the wealthy person's income. If less expensive yet "good" transportation modes are available, then this ceases to be as much of a problem.

But the fact is that these less expensive modes, such as trains and buses, are not very good for medium-to-long-distance travel.

III. A. 2. Cargo Energy Demand

Between 1959 and 1969 U.S. air freight traffic increased at an annual rate of almost 15%. Most studies predict growth rates over the next several years falling in the 8-12% range. This would mean a 6-9 year doubling time and would imply that air cargo, though not now important in terms of energy, will eventually become a very significant energy consumptive sector.

Freight shipment by air is an energy intensive means of cargo transfer. An inspection of Figure III-1 (5, p. 32) shows that air cargo (excluding helicopters) on a ton-mile basis, requires from 18 to 33 times as much fuel as the same loads on a 100-car freight train. (See also Chapter II. B.).

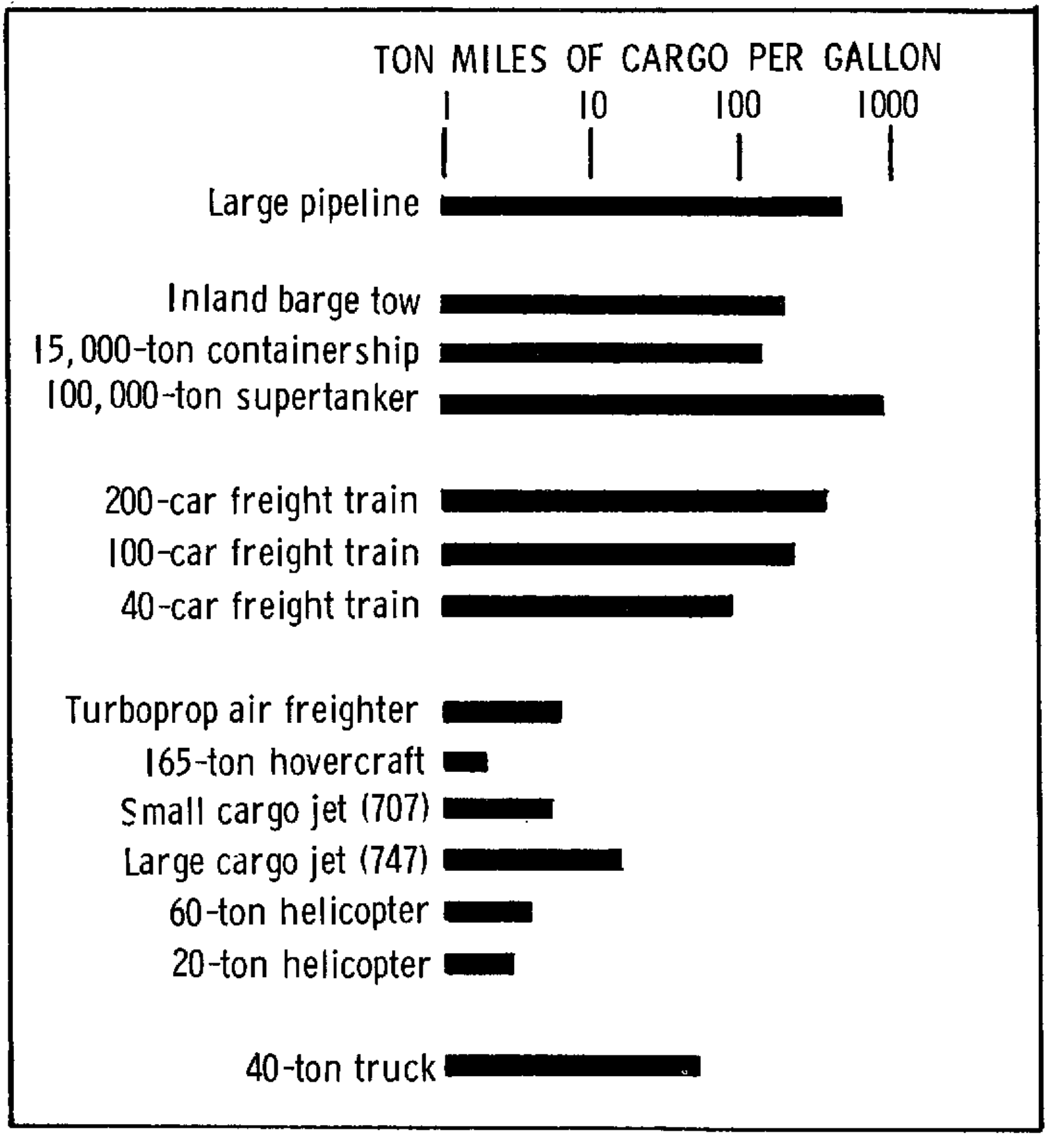

FIGURE 3.1

ENERGY-INTENSIVENESS OF FREIGHT TRANSPORT

Source: **Technology Review**; Jan. 1972

The 18/1 disadvantage is for the very efficient 747 jumbo jet. If this conservative 18/1 fuel ratio is applied to the forecasts for the U.S. air cargo market in 1980 (24.0 billion ton-miles), it indicates that 2.08 billion gallons of fuel could be conserved in the U.S. in that single year, if railroads were used instead of aircraft for cargo transportation. Since this estimate is made using the most efficient existing cargo aircraft, actual savings would be greater.

Of course, not all air freight can be switched to other modes. Three categories describe the nature of air freight traffic: emergency (unplanned); routine perishable (planned); and routine surface divertible (planned). Obviously, no energy constraints will limit genuine emergency cargo. Equally obvious, routine surface divertible traffic will increase as energy becomes more expensive.

Thus, if the predicted significant exponential growth in air freight materializes, it could further complicate the energy problem. In this case, some governmental action may be required to "discourage" certain air freight usage. On the other hand, the high energy intensiveness of air cargo relative to other modes will eventually mean that as energy cost and energy efficiency become more important factors in decision making, the energy threat that air cargo represents will become more manageable.

III. B. Airline Systems Efficiency

This section deals with the second basic approach to energy conservation, improved airline systems efficiency. The section is organized as follows: First, the factors and constraints affecting systems efficiency are discussed. These include the nature of the competition between airlines and the technological and economic aspects of aircraft energy performance. Included in this is a discussion of some potential technologies for improving future aircraft efficiency. Secondly, four examples are presented that are aimed at improving the overall efficiency of the air transportation system. The examples are meant to illustrate some of the potential and the pitfalls that exist in dealing with this complex problem.

In order to give some perspective to the prospects for improving airline system operating efficiency, an analysis of the load factor data in *Air Transport* 1973 (6, p. 24) is is presented in Figure III-2. For illustrative purposes the scales have been chosen to superimpose the three factors which determine load factor—the central measure of physical efficiency.

The three factors—revenue passenger miles, seat miles, and revenue aircraft miles—were reasonably compatible until 1966 when the load factor reached 58%. Thereafter, revenue passenger miles failed to continue its exponential growth, while revenue aircraft miles grew rapidly with the spate of additional routes approved by the CAB. Concurrently, the coming of larger aircraft caused seat miles to grow even faster. By 1969, the load factor was down to 50%.

After 1969, revenue aircraft miles leveled, but as new large jets replaced smaller craft, seat miles continued to increase. At the same time, the growth rate in revenue passenger miles slowed. Thus, the load factor slipped to 48.5% in 1971; in 1972, a sharp increase in revenue passenger miles brought the load factor back up to 53%; it appears that 1973 will show a similar load factor.

After 1969, the air carrier fleet ceased growing and remained at under 2,500 aircraft (7, p. 21). Aircraft on order (7, p. 20) seem able to offset retirements through the mid-seventies. These trends lend credibility to the FAA forecast that the fleet is expected to grow "from the current level of about 2,500 aircraft to nearly 3,600 aircraft" by 1984 (7). They also lend credibility to the FAA forecast of a load factor of 60% in 1984 (7).

The following summarize the goals for achieving energy conservation in air transportation through improved systems efficiency:

(1) The flight load factor must be increased from its present typical value of less than 50% so that fewer flights are required to move the same number of passengers.

(2) The average trip length should be increased so that airplanes spend a larger percentage of their airborne time at cruise speed where their fuel efficiency is the greatest.

(3) The type of airplane used should be matched more closely with the flight distance involved; high-speed aircraft must be reserved for long-range trips only, where the time saving compared to alternate travel modes is the greatest.

(4) Individual aircraft must be made more efficient by changes in present operating procedures, by the im-

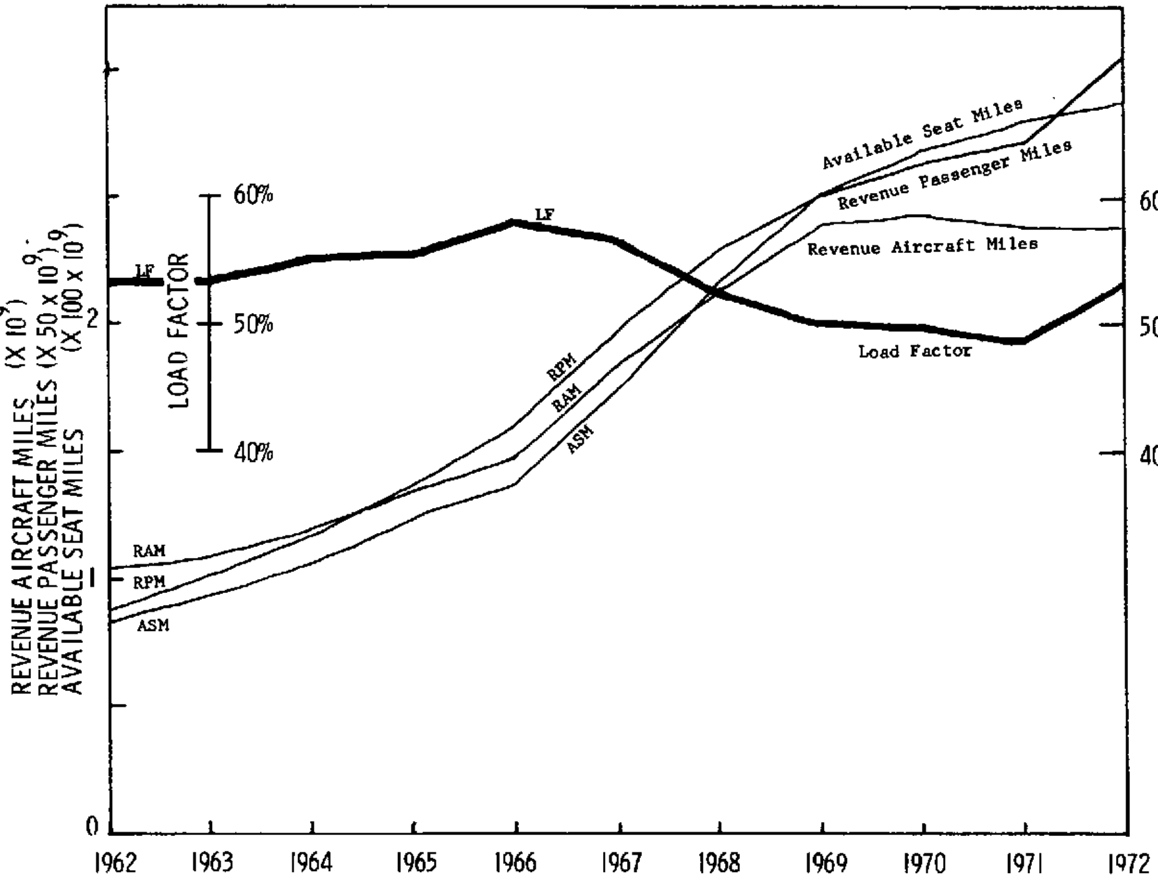

FIGURE 3.2
FACTORS INFLUENCING LOAD FACTOR
Data from Air Transport Assoc. of America, 1973

proved design of future aircraft, and further increases in aircraft capacity.

These are goals, not results realizable by governmental fiat, because energy efficiency is only one of the constraints within which modern airlines operate. It is our contention that energy efficiency is not now given the weight it should have, much less the importance the future will require.

III. B. 1. Efficiency Factors

The ability to become more energy efficient depends on the nature of the forces restricting such a trend and the changes possible. The current impact of each of these forces is discussed below along with suggested changes.

A. Competition and Regulation

The role of competition between airlines is both obvious and subtle: obvious in its effect on profit and loss, subtle in the pressures it exerts on airlines to take actions that may promote neither profit nor efficiency. No attempt to make airline systems energy efficient can succeed without an understanding of, and strategies to use, the realities of competition.

To better understand the situation, some contrasts may be pointed out between the airlines and other U.S. firms. Most companies have control over prices, freedom of entry or exit from the field, and the power to decide how much capital and labor will be used. Airlines, on the other hand, have been defined as

> a blocked-entry, price-controlled, non-price-competing cartel, or as highly competitive but regulated oligopolies with their products essentially undifferentiated, with entry of new competitors into a market made difficult because of the entrance fee in terms of government regulation and capital costs, and in

which the actions of each competitor (who supplies significant portions of the total product) can have a marked effect on the plans and actions of other competitors (8).

Thus the market in which the airlines operate is not free but oligopolistic; a given route is not serviced by many firms but by a few. One of the reasons for the regulated competition now in existence in the U.S. has been the assumption that unregulated competition would eventually lead to selective airline bankruptcies, poorer safety records, poorer service, or no service—the latter particularly on low passenger density routes. In a recent article Keeler (8) claimed that these arguments are now without foundation. In any case, it is axiomatic that profits count, that firms will pursue avenues that lead to profits and will avoid or resist those that do not. Against this background, however, is the fact that a particular airline is not free to set the price for a given route. The CAB regulates fares and an airline must charge the CAB approved fare on a given route. To some extent price rigidity can be offset by advertising in which the airlines attempt to convince the user that each offers a differentiated product.

Freedom of entry or exit exists only with the required approval of the regulatory agency, which seriously limits what the airlines can do regarding economic or energy efficiency. They may be required by law to service routes that have no justification on either economic or energy-conservation grounds.

Freedom to choose an optimal combination of factor inputs is also restricted. In contrast to the automobile or the chemical industry, airlines seem to have only minimal control over the development of relevant technology and the timing of its introduction. It is conceivable that from the efficiency point of view a slower pace of innovation and continued use of a given aircraft over a longer period of time would be better for airlines and the public, but there may be little that can be done if the pace is set by others. It should be recognized, of course, that what any particular airline company does is not entirely determined by them alone. There is at work what appears to be a "demonstration effect;" if one airline begins to use a new aircraft, everyone must use it.

Another economic factor affecting competition and systems efficiency is tax policy. Public policies with respect to air transportation should ideally be reflected in, and supported by, the taxes levied against the system. Yet the lack to date of any comprehensive air transportation (much less energy) policy has materially contributed to continued system inefficiencies because in the absence of such policies, taxes are irrationally designed.

The present air transportation tax structure includes an 8% passenger tax, part of which then goes toward maintaining the airway system. (See Chapter II. D.) But the amount of expenditure related to the support of departure, en route, and arrival traffic control is not directly coupled to the number of passengers being served; rather, it is a function of the number of planes handled and their characteristics. There is **some** relationship between passengers and FAA control expenses, but is a **variable** relationship. The cost of airborne control of a Boeing 747 is constant for a given flight regardless of whether there are 100 or 300 people on board. Conversely, the total cost to the FAA is less if 300 people are on a single 747 rather than on four 737's, since one plane uses the airway system rather than four.

Tax assessments that do not pay for service received can tend to institutionalize inefficiency. From a taxation viewpoint, an airline now has no reason to increase its efficiency by raising its average load factor or lowering its flight frequency. An integral part of a national transportation policy will be taxation designed to promote efficiency by coupling taxes to costs rather than arbitrarily to passengers.

The energy efficiency of an airline will depend to a great extent on the competition it is allowed or forced to meet, constrained by the economic factors just discussed. There has long been an assumption that increased airline competition between two major cities will provide the customer with a broader choice of flight frequencies, better service from each airline, and possibly lower fares. At the same time the airline is expected to benefit from economies of scale arising through lower unit costs or new technology, from larger passenger markets. Fares that are higher for the airline and lower for the passenger obviously cannot occur simultaneously on any single route however traditional the assumptions or powerful the regulating agency!

Keeler has suggested that both the public sector and the airlines would benefit if the airlines were not regulated (8). His data show that a CAB-unregulated, intra-state airline (e.g., Pacific Southwest Airlines in California) operate with lower fares and better profits than comparable CAB-regulated airlines. His thesis is that the latter airlines have chosen to compete primarily through increased flight frequency which has resulted in excess capacity, lower load factors and hence the existence of fare levels higher than would be necessary without the excess capacity. His calculations indicated that in 1972 regulated fares were 45% higher than unregulated fares on short-haul routes, 84% higher for long-haul segments.

Though the recent paper by Hubbard started from the same base as Keeler in recognizing the problems attendant to excess capacity, Hubbard proceeded to the conclusion that limitation of competition is the surest way to best resource allocation (9). He showed that excess capacity has been a self-perpetuating tendency of airline life. All other things being equal one could expect an airline's percentage of a market to equal its percentage of flights in that market, yet historically an S-curve relationship has been found (Figure III-4).

Of course, all other things are **not** equal, and market share depends on a complex of factors—convenience, food, baggage handling, etc. Even so, the airline that thinks it has done well in these areas relative to its competitors might use this curve as the impetus toward adding more flights and hence more capacity because they believe each additional percent increase of flight share will be rewarded by an even larger increase in market share.

Both Keller and Hubbard supported the contention that present airline practices are energy inefficient due to the interrelated pressures of competition and regulation. A suggested alternative way of operating would be to limit individual routes by regulation to an optimum number of airlines, then allow these airlines to operate in free competition. Equity, could be maintained by balancing an airlines removal from one route with removal of some of its competitors from a similar market.

B. Aircraft Energy Performance

Features of aircraft use which promote energy inefficiency are the relatively low load

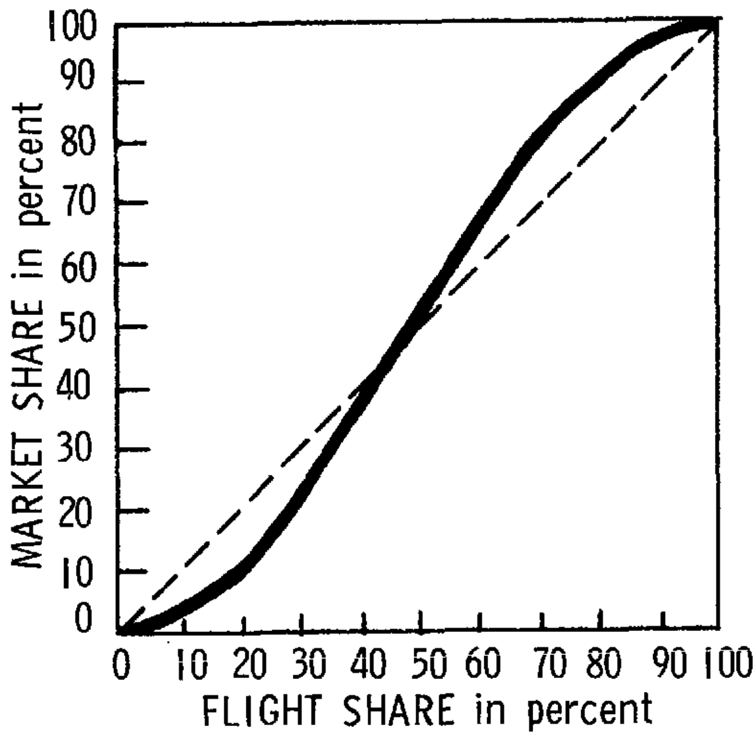

FIGURE 3.3
AIRLINE MARKET SHARE AS A FUNCTION OF FLIGHT SHARE
Source: Hubbard, H. MIT/NASA Workshop

A SOLUTION?

factor in the average flight, the short average stage length in comparison to the design range and, in general, the apparent mismatch between aircraft capability and transportation mission from an energy perspective.

There are several means available to improve aircraft energy performance. They involve either modifications to current operating practice or the use of new technology. Changes in aircraft utilization patterns, fuel conservation, and advanced technology are discussed below.

(1) Aircraft Utilization: To better understand airline energy expenditures domestic trunk jet aircraft performance for 1971 is reviewed in Table III-I. The data is illustrative of the types of aircraft in use. The data is based on the block-to-block period, which extends from the time the engine is started until the time it is shut down.

These data reveal several features of the way aircraft are used as opposed to their optimum capabilities. Designed cruise speeds are of the order of 600 mph but congestion and long climb and descent times result in considerable lowering of this value. The difference between block-to-block speed and airborne speed for these cases is typically 10-20%. The maximum ranges vary from roughly 2,000 miles for the 737 and 727 to over 5,000 miles for the 707 and 747 while average use involves much shorter distances.

The load factors are typically of the order of 50%, except for the 747, which manages a respectable value of fuel consumption in passenger miles per gallon despite a low load factor, only because its seat capacity is so large. At 39% loading the average number of 747 passengers is over twice the value for any of the smaller Boeing craft. This capacity mitigates the much higher absolute value of fuel consumption for the 747.

The total fuel consumption as a function of flight length for each of the four aircraft is compared in Figure III-4. If one looks at a mission such as transporting 100 people a distance of, say 1,000 miles, from the point of view of fuel conservation, the superiority of the 737 is clear. However, this analysis, which emphasizes equal loading for all aircraft, is not the usual approach.

In Figure III-5 fuel consumption is plotted against the product of flight length and average number of passengers for each of the four planes. The distinction between the 747, 707, and 727 is less obvious, although the 737 still emerges as the most fuel-efficient.

Total emphasis on fuel savings is not possible for airlines whose primary interest is in profits. Table III-II summarizes direct operating costs for the aircraft under consideration.

Because of the higher per seat contributions to costs from maintenance and depreciation, the fuel-efficient 737 has the highest costs per seat mile, although not per airborne hour. However, the relatively small cost percentage presently accounted for by fuel becomes more significant when expected rises in fuel costs per gallon occur. Both these factors lead to a strengthening of the importance of fuel conservation in determining the utilization of aircraft.

Local service aircraft performance for 1971 is illustrated in Table III-III. These data are also based on block-to-block times. Both the Boeing 727 and 737 are used to a significant extent in local service. The flight fuel efficiency (miles per gallon) of the Boeing aircraft is markedly lower than the last four

TABLE III-I
JET AIRCRAFT PERFORMANCE, 1971
(Domestic Trunk Service)

Type	Avg. Speed Block-to-Block	Fuel Consumption (gal/hr)	(mi/gal)	(RPM/gal)	Loading (pass.)	(%)	Stage Length (mi/flight)
B-747	463	3367	0.137	17.7	129	39.2	1986
B-707-100B	427	1657	0.258	14.7	57	47.8	1097
B-727-200	364	1395	0.261	15.8	52	48.8	518
B-737-200	306	901	0.340	17.6	52	56.1	298

Source: CAB (10)

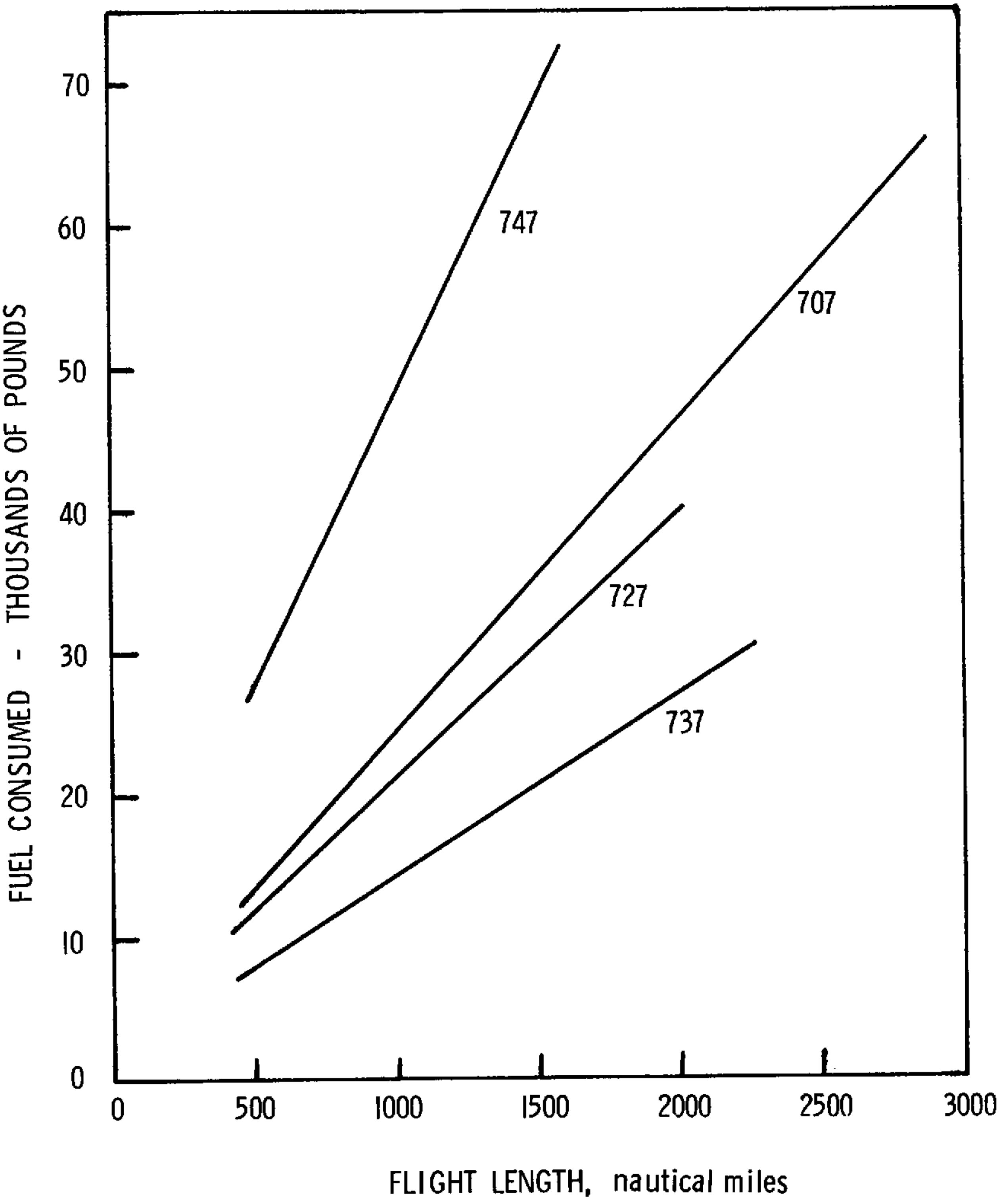

FIGURE 3.4

FUEL CONSUMPTION vs. FLIGHT LENGTH IN NAUTICAL MILES FOR VARIOUS BOEING AIRCRAFT

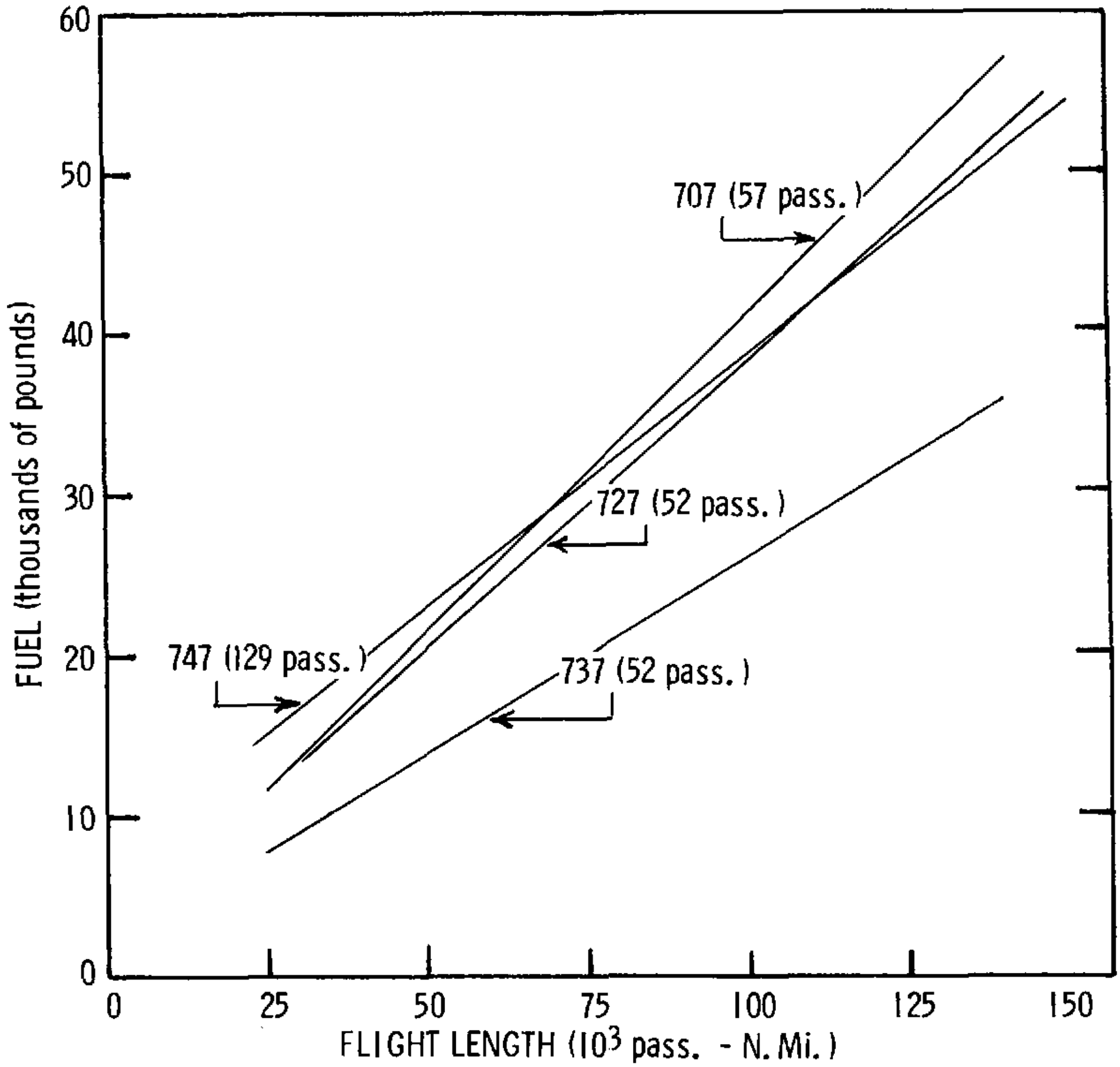

FIGURE 3.5
FUEL CONSUMPTION vs. FLIGHT LENGTH in PASSENGER-MILES FOR VARIOUS BOEING AIRCRAFT

TABLE III-II

JET AIRCRAFT COSTS, 1971
(Domestic Trunk Service)

Type	Fuel Cost/Total (%)	$/hr	c/RPM	c/seat-mile
B-747	22.4	1891	2.898	1.135
B-707-200B	26.9	798	2.947	1.409
B-727-200	24.6	790	3.031	1.480
B-737-200	20.1	691	3.551	1.993

SOURCE: CAB (10).

models which are slower airplanes specifically designed for short-haul traffic. In terms of revenue passenger miles per gallon, the distinction is less clear.

The direct operating costs for these local-service aircraft are summarized in Table III-IV. Here the advantage of the larger numbers of passenger capacity in the 727 and the 737 is clear. The cost per airborne hour is much less for the last four models. The comparison which favors, for example, the YS-11 relative to the 737 would be one in which, for example, one wanted to fly 35 people a distance of 250 miles. For the YS-11 this would require approximately 450 gallons of fuel while for the 737 we need nearly 750 gallons. All other factors in the makeup of an air transport system have been ignored in citing such an example. The point is, however, that to the extent that fuel availability and cost is likely to become increasingly important in the future these sorts of calculations will become more significant to the airline companies.

Comparisons of aircraft fuel efficiencies can also be made by calculating how much energy is needed to carry one passenger one mile. The units for these factors are BTU/seat-mile. The use of BTU's in place of gallons or pounds of fuel burned facilitates a comparison between aircraft using different fuels, e.g. liquid hydrogen and JP.

The efficiencies displayed in Figure III-6 are for aircraft currently in service and some proposed future aircraft. For each airplane, calculations were made assuming maximum possible load of passengers and maximum range. The value for an automobile is given to provide perspective. The auto efficiency was calculated assuming 13.6 miles per gallon and five passengers which are optimistic relative to actual 1973 experience.

It is immediately apparent from Figure III-6 that for planes flying today, the extremes range from the very efficient 747 to the very inefficient Concorde—the latter being nearly six times as fuel consumptive. The proposed

TABLE III-III

AIRCRAFT PERFORMANCE, 1971 (LOCAL SERVICE)

Type	Avg. Speed Block-to-Block	Fuel Consumption (gal/hr)	(mi/gal)	(RPM/gal)	Loading (pass.)	(%)	Stage Length (mi/flight)
B-727-200	350	1434	0.244	14.0	57	41.4	416
B-737-200	302	902	0.335	15.4	46	49.1	215
CV-580	195	351	0.556	12.6	23	45.7	119
FH-227	166	273	0.608	13.4	22	48.9	100
YS-11	167	300	0.557	14.9	27	44.7	110

Source: CAB (10)

TABLE III-IV

AIRCRAFT COSTS, 1971 (LOCAL SERVICE)

Type	Fuel Cost/Total (%)	$/hr	c/RPM	c/seat-mile
B-727-200	23.4	936	3.953	1.637
B-737-200	21.8	611	3.691	1.811
CV-580	14.8	390	7.256	3.317
FH-277	13.1	356	8.064	3.940
YS-11	14.2	336	6.262	2.797

Source: CAB (10)

efficiencies for the other SST's are better since they would be second generation aircraft. However, it should be pointed out that these maximum efficiency calculations based on seat-miles are biased in favor of the 747 because of its large capacity compared to the other aircraft.

The proposed hydrogen-fueled aircraft appear to compare more favorably with existing passenger aircraft than with cargo aircraft. These aircraft have been compared on a maximum efficiency basis and therefore, actual operating efficiencies previously seen show considerably larger variation and may not follow the same relative trend indicated in these graphs.

(2) Fuel Conservation Techniques: Various potential fuel saving procedures have been suggested, from changes in individual aircraft operational procedures to changes in equipment used over certain routes.

United Airlines has lowered the speed of some of its flights from Mach .82 to Mach .80, a decrease in speed of about 15 miles per hour. This translates to about one additional minute per hour of flight time and a savings of around 170 gallons of JP-4 on a Chicago-Los Angeles flight. Such conservation is equivalent to 2.5% of the fuel burned. Since it is a change in cruise mode operation only, no similar saving is possible in climb or descent. Lowering the speed any further becomes counterproductive as the aircraft altitude must be changed in such a way that fuel consumption climbs again. Use of more efficient optimum computer-determined flight profiles which enable aircraft to get to the efficient cruse mode in less time than is the present standard is another way to get immediate fuel savings.

The suggestion that various fuel conservative taxiing procedures be used has also been investigated. One measure was to reduce the number of engines used throughout the taxiing maneuvers. However, it was determined that this would not save significant amounts of fuel and would introduce noise and blast problems because those engines that were used would have to be operated at close to maximum thrust. This would significantly increase the noise level at the airports, which would conflict with governmental noise regulations.

Towing aircraft between the terminal and runway would save jet fuel; but, the major airlines feel that this method is too slow and thus would add to the already increasing airport congestion problem. This line of reasoning is reinforced by CAB statistics. The 747 (our most efficient airplane) spends about 10% of its departure to arrival time taxiing.

Suggestions of greater use of flight simulators to reduce the number of training flights and elimination of premature engine start-ups prior to departure are estimated to result in minimal fuel savings.

Even though each of these suggestions represents by itself only an incremental fuel savings, they should not be ignored. We recommend that the airlines and the CAB jointly develop a program of fuel conservation.

(3) Advanced Transport Technology: The application of "advanced transport technology" (ATT) to subsonic conventional take-off and land (CTOL) transport aircraft, can have a significant impact on fuel consumption.

Advanced transport technology, refers to: (1) composite materials and advanced structures, (2) "supercritical" aerodynamics, (3) active flight controls, (4) engines and airframes designed for reduction in noise and exhaust emissions, and (5) improved avionics. NASA has been doing research in these areas for a number of years. Much additional R & D is required to bring these technologies to a state where they could be put on an airplane. Additional development by the manufacturers would then be required before the first plane could be brought into service.

Table III-V summarized the particular design characteristics of the five aircraft evaluated in a study by United Airlines for NASA. Although the notation used will refer to speed and noise, comparisons cannot be made solely on these factors since the aircraft involve different designs by different manufacturers. Also, note that what is referred to as Conventional M.82 is a conventional airframe with an advanced engine to reduce noise, the cruise speed of which is Mach .82. All aircraft were designed for a range of 3,000 nautical miles, 195 passenger payload(normal) and had one tail engine and two wing engines.

In order to obtain estimates of fuel consumption, United took fuel consumption per departure and per flown hour, and then simulated how the aircraft would be used over their routes, which are representative of the United States domestic airline system. The results are presented in Table III-VI, in terms of BTU per available seat-mile. For a comparison, figures for B-747s and B-707-100Bs calculated from acutal CAB operating statistics during 1971 are also included (10).

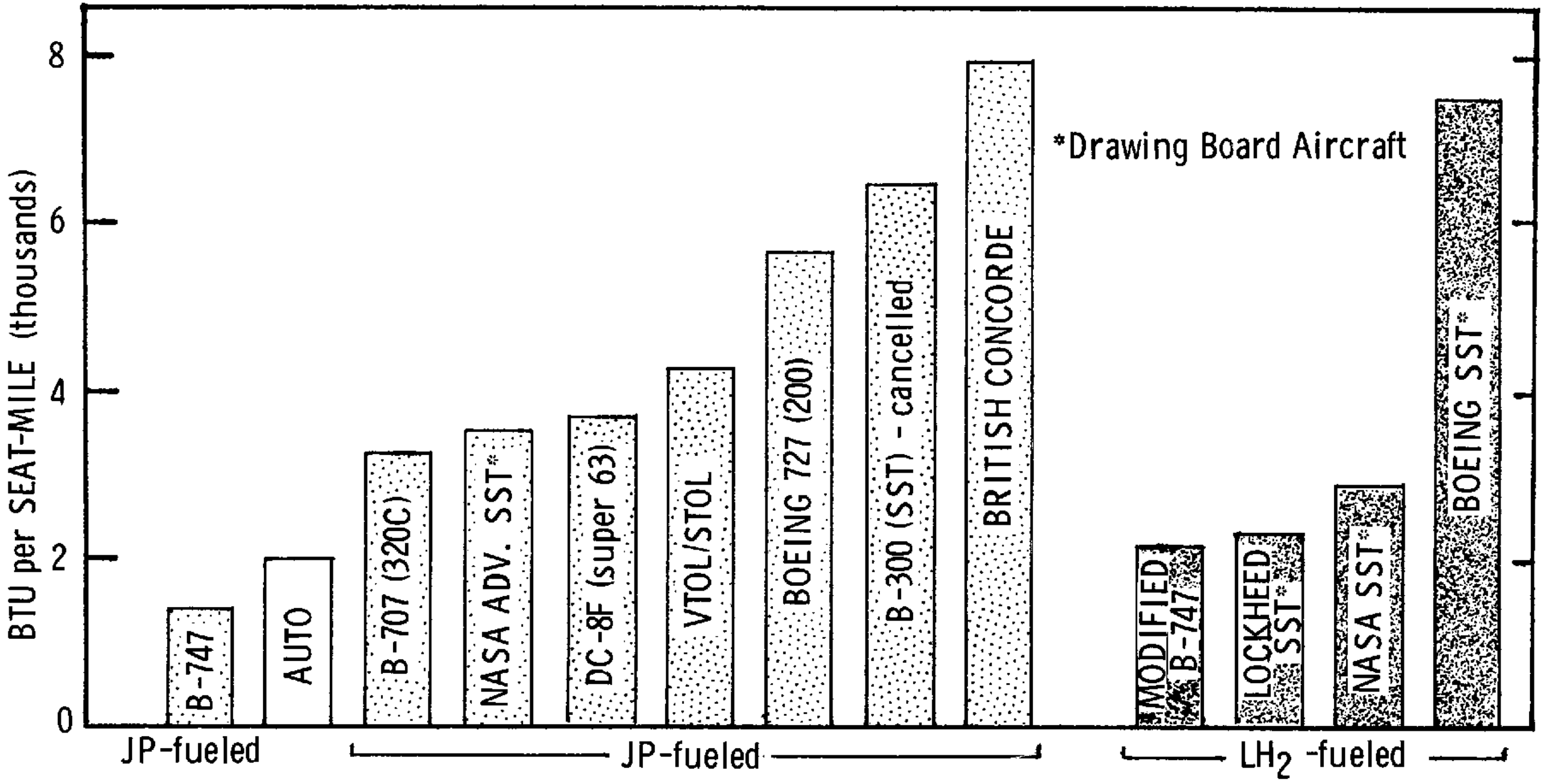

FIGURE 3.6
MAXIMUM EFFICIENCY COMPARISON OF PASSENGER AIRCRAFT

TABLE III-V
STUDY AIRCRAFT CHARACTERISTICS

	AIRCRAFT TYPE				
	Conv. M.82	ATT M.90	ATT M.95	ATT M.98	ATT M.84
DESIGNER	Gen. Dyn.	Boeing	Boeing	Gen. Dyn.	Boeing
Supercritical Wing	No.	Yes	Yes	Yes	Yes
Composite Materials	No	Metal Bond/ Composite Mix	Metal Bond/ Composite Mix	All Composite	Metal Bond/ Composite Mix
Area Rule Fuselage	No	No	Yes	Yes	Yes
FAR 36 Noise 1 Level	-10&PNdB	-15&PNdB	-15&PNdB	-10&PNdB	-15&PNdB
MTOGW[2]					
-kg	138260	137760	145150	124210	134580
-(lb)	(304800)	(303700)	(320000)	(273840)	(296700)
Engine Thrust					
-kn	119.0	134.3	150.3	177.8	132.1
-(lb)	(26760)	(30200)	(33800)	(26480)	(29700)
Active Controls	No	Partial	Partial	Partial	Partial

1 Far 36-10 EPNdb means that the Effective Perceived Noise (EPN) level is 10EPNdb below the standard specified by Federal Air Regulation 36.
2 MOTGW is maximum take-off gross weight.

Source: United Airlines

TABLE III-VI
FUEL CONSUMPTION

	Pass.	Noise Level (FAR)	Fuel Consumption* (BTU/avail. seat mile (Stat.))
M.82 Conv.	195	-10EPNdb	2,845
M.98 ATT	195	-10	2,216
M.84 ATT	195	-15	2,037
M.90 ATT	195	-15	2,253
M.95 ATT	195	-15	2,544
B-747	385	-1	2,876
B-707-100B	120	+10	4,218

*Based on 130,000 BTU per gallon.

Source: CAB (10)

The move from a M.82 Conv. aircraft (-10 EPNdb) to a M.84 ATT aircraft (-15 EPNdb) represents a 28.4% fuel savings, and the move to a M.98 ATT (-10 EPNdb) represents a 22.1% fuel savings. One conclusion to be drawn here is that the application of these advanced technologies can allow for significant fuel savings. However, it is equally important to realize that, if these technologies are applied primarily to the lower speed aircraft (M.84) greater fuel savings and significant noise reductions can be obtained simultaneously. In general, if the noise levels were raised, say to current Federal Air Regulations (FAR) 36 levels, then even greater fuel efficiencies could be realized. The significance of this is that the country can have greater fuel efficiency if it is willing to accept current technology noise levels.

United calculated operating costs as shown in Table III-VII. The savings with new aircraft are primarily because they assumed (1) an increase in purchase cost (which increases the depreciation portion of operating cost), (2) an inability to use the productivity of increased speed effectively on their route system, (3) a 15% increase in maintenance cost per hour flown, and (4) the M.84 ATT met lower noise levels than the conventional aircraft (M.82). The assumed purchase prices ranged from 9% higher (.84 ATT) to 25% higher (.98 ATT). If the purchase price were to remain constant then their sensitivity analysis shows that the ATT aircraft would have significant economic advantages.

Overall, United Airlines concluded that any applications of advanced technology should be used at lower speed range (M.84) to reduce operating costs, and should not be used to increase speed to M.98 range. One criticism of their economic analysis is that they did not study a full technology aircraft at M.84 meeting the FAR 36-10 EPNdb noise levels to use as a comparison against technology all which meet FAR 36-10. Also, United did not do any sensitivity analysis on fuel costs. In any case, the advantages in terms of environmental impact and energy consumption are very significant and NASA should be funded for meaningful work in these areas.

III. B. 2. Improving Systems Efficiency

Four examples of measures for attempting to improve the energy efficiency of the airline system are: (1) capacity reduction

TABLE III-VII
OPERATING COST COMPARISONS

Operating Cost
(Cent/avail. seat mile (naut.))

	CONV M.82	ATT M.84	ATT M.98
Direct Operating Cost	1.316	1.311	1.289
Fuel	.303	.217	.236
Flight Crew	.286	.286	.270
Maintenance	.385	.435	.376
Hull Ins.	.013	.014	.015
Depreciation	.329	.359	.392
Indirect	1.226	1.219	1.168
Total	2.542	2.530	2.457
% Savings from M.82 Case	—	.4%	3.34%

Source: United Airlines

agreements, (2) changes in local service airline operations, (3) an integrated air-ground transportation system, and (4) a centralized travel agency.

A. Airline Capacity Reduction Agreements

Capacity reduction by limiting flight frequency on certain routes through agreements between airlines is a method of reducing fuel consumption presently in use. The airlines feel that by reducing the number of scheduled flights on given routes the load factor would increase and fuel would be saved, not to mention the added benefits of reduction in noise, pollution and airport congestion. Such reasoning has certain appeal and, therefore, ought to be examined.

In August, 1971, the CAB authorized American, TWA and United to enter into an agreement to reduce capacity in the following markets:

New York/Newark—Los Angeles
New York/Newark—San Francisco
Chicago—San Francisco
Washington/Baltimore—Los Angeles (12, p. 1)

The initial agreement lasted from October 3, 1971 to September 16, 1972; it was subsequently extended through April 28, 1973. Since this time the airlines have held authorized discussions on this matter and have petitioned the CAB for authorization to continue the agreement for another two years. They estimate fuel savings of some 300 million gallons over the 2-year period. On the surface the argument is convincing; however, the Department of Transportation has registered serious reservations about the merit of capacity reduction agreements (12).

One of their objections is the question of fares. If the fares remain at the level prevailing before the capacity reduction agreement the airlines may get a large and unjustified windfall profit. Their return on investment could rise to about 40% on those routes instead of the 12% authorized for the entire system. Even the latter rate might be unwarranted because under the agreement the market risk would be reduced.

Secondly, DOT believes the environmental benefits are questionable. If the airlines convert nonstop flights to one-stop flights and/or if they divert aircraft to markets not covered by the agreement, the fuel burned would still create environmental problems, yet not subtracted from the fuel ostensibly saved. According to DOT, this has already occurred (12, Exhibit B).

Another disadvantage in DOT's view is the danger that the agreement—or this type of agreement—might become permanent. It could limit competition (the prime mover of the free market system), and therefore the need to keep costs under control. Non-agreement carriers, moreover, may be subject to unfair competition.

DOT claimed the method used to estimate the fuel savings is open to question. The airlines used as the base period the situation prior to the 1971 agreement when the carriers were operating with load factors of only about 38%. If the savings are recomputed using a more representative base period with higher load factors, the savings amount to less than 19 million gallons.

The course of action recommended by DOT is market oriented, based on their assumption that airlines operate with excess capacity. (See, for example, Chapter III. B. 1.). DOT's recommended solution is lower fares. When supply outruns demand, to clear the market you lower the price. This type of action, moreover, could apply to all carriers; it would then affect all markets rather than a few and the resulting fuel savings would be much greater. Of course, lower fares would require action of the CAB. DOT has estimated (12, p. 44-45) that a fare reduction of 27.9 percent would lower capacity by 16.7 percent, increase the load factor to 62.5 percent, and simultaneously increase traffic 19.5 percent. All this can be achieved without capacity reduction agreements, though in essence the same purpose would be served.

The CAB granted a 6-month extension of the original capacity agreement effective September 15, 1973 and simultaneously instituted an investigation of the entire matter. Other carriers have petitioned the CAB for authorization to enter discussions leading to similar agreements or for authorization to put into effect such agreements. Given the import of the issues at stake, a definitive investigation of the facts seems the appropriate course to follow. It is clear that capacity reduction could promote significant fuel savings, but the question remains as to what the best method is for achieving these goals.

B. Local Service Air Transportation

The "local service" airlines are a class of air carrier begun in 1944 as an experiment designed to provide air service to smaller, more isolated communities. These local service carriers received government subsidies so that cities could be served from which too few passengers originated to allow economic unsubsidized service.

In 1972, this class of air carriers consisted of Air West, Allegheny, Frontier, Mohawk, North Central, Ozark, Piedmont, Southern, and Texas International. The local service airlines in 1969 flew 227 million aircraft miles (6, p. 25) 6,312 million passenger miles (6, p. 25), consumed 540 million gallons of fuel (13), and drew a government subsidy of $40.5 million (14).

Several studies have analyzed the history of this program and have concluded with strong critiques of the CAB's regulatory decisions. (See, for example, 14, 15, 16, 17, 18.) The authors generally felt that CAB subsidy payments (which have amounted to approximately one billion dollars over the life of the program) and CAB route policies have encouraged the development of nine weak trunkline carriers. They argue that the original goal of providing service to the smaller, more isolated communities has been neglected, and that the same level of service to these communities could be provided by "air taxi" type carriers at little or no cost to the taxpayer. Our primary interest pertains to the side effect of improved fuel consumption efficiency.

As reported by Eads, the Systems Analysis and Research Corporation performed a study in 1964 for the FAA in which they projected local service traffic growth through 1975 and simulated operations at these levels to determine the aircraft size which maximized or minimized losses on the low density routes (14, p. 187; 15, p. 12). Using this study as a basis, Eads conservatively estimates that in 1969 41 million miles were flown by aircraft that were too large (CV-580s and FH-227s primarily). He argues that these air miles could have been flown with smaller aircraft, such as Nord 262s or DHC-6s (Twin Otters). Table III—VIII below summarizes some actual operating data for the four aircraft during 1969 (13).

Using an average fuel efficiency for the CV-580s and FH-227s of 1.75 gal./mile, we can calculate the amount of fuel that would have been saved if the 41 million miles had been flown with N-262s or DHC-6s. These calculations are summarized in Table III-IX.

For the local service airlines as a whole, changing operations over 18% of the routes (41 million miles compared to a total of 227 million miles) would result in a fuel savings of 36.1 million gallons or 48.9 million gallons depending upon whether N-262s or DHC-6s are used.

These data illustrate the importance of the general factors affecting system efficiency. Significant improvements in energy

TABLE III-VIII

1969 Operating Data for Certain Local Service Aircraft

Aircraft	Actual Aircraft Miles	Avg. Stage Length	Fuel Efficiency	Avail. Seat/Aircraft
CV-580	56.8 million	118 miles	1.79 gal./mile	50.7
FH-227	21.8 million	109 miles	1.71 gal./mile	44.6
N-262	2.2 million	96 miles	.87 gal./mile	22.1
DHC-6	0.8 million	81 miles	.56 gal./mile	14.2

Source: CAB (13).

TABLE III-IX

Potential Fuel Savings Based on 41 Million Aircraft Miles

Aircraft	Total Fuel Usage (gal).	Savings
CV-580/FH-227	71.75	—
N-262	35.62	36.1
DHC-6	22.90	48.9

utilization can occur if the importance of energy is recognized. Regulations and operations must be changed to allow energy factors to be reflected in the decision making.

C. Integrated Air-Ground Hub System

Another method suggested for achieving better systems efficiency is to establish an integrated air-ground network centered about major trading and traffic hubs. (The hubs may contain several airports; for example, New York consists of JFK, La Guardia, and Newark airports.) Approximately 85% of the passengers enplaned in the continental U.S. are enplaned at the 66 major air hubs shown in Figure III-8, which also coincide with the major trading centers. This suggests that the present air traffic hubs would be appropriate centers for an air-ground transportation network.

Under the network plan ground transportation would serve the short-haul area surrounding the major hub; not only to the downtown area of the hub, but also to the airport. This would eliminate some short-haul air traffic, with the side benefits of reduced airport congestion and fuel economy.

The medium and long-haul traffic would continue much as they do now but with more emphasis on optimally designed planes for the load and range as discussed in the previous section.

It is strongly suggested that the regulatory agencies investigate the present network to check for routing and scheduling optimally and to determine the routes which could be most effectively served by ground transportation.

D. Central Travel Agency

Another option for promoting energy efficiency in the airline system would be the establishment of a centralized travel agency. Such an agency would provide a service not now available anywhere—a way to enable both passengers and airlines to make choices between alternatives based on a rational weighted set of ordered priorities.

For example, a prospective traveler would provide the agency with his trip constraints—where he wanted to go, when, personal priorities, etc. The agency would respond with listing of all possible alternatives available for that trip. Included would be information on modes, schedules, costs, and even energy consumption. His decision could then be made based on these facts. No claim is made that such a service would always give him an optimized single best way to travel. It would be an improvement over present practice if it did nothing more than minimize the uncertainities of travel decision making. Such an agency would be the interface between the traveling public and the transportation companies. From an industry viewpoint, the centralized agency concept would provide a base from which service could be scheduled for maximum efficiency—e.g. minimize energy expenditures and maximize load factors. This centralized approach would also allow the government access to detailed data on travel **needs** to permit better transportation systems planning.

From the public viewpoint, such a system would insure that as energy becomes even more precious it is being expended in a manner consistent with common goals—minimum consumption, maximum efficiency, and a true reflection of total societal cost in energy cost.

III. C. Conclusion

The substance of this chapter lies in the recognition that the role of energy in air transportation decision making has usually been a minimal one. Even where it has been a direct concern, it was usually a concern for fuel consumption as a dollar cost—not in the more general sense of concern for energy in all of its ramifications. No airline by itself can take a "different" (i.e., energy rational) course of action because to do so would mean either no easily perceived incremental benefit to itself or (so they believe) a diminished position relative to other airlines. Custom, competition, and regulation perpetuate these attitudes. Together, they result in an unconscious policy which contributes to an energy problem, in both relative and absolute terms.

This chapter has illustrated the kind of changes that can lead to better efficiency. The modifications that were analyzed included such diverse items as allowing people to choose their travel rationally, using advanced transport technology in future aircraft, modifying the CAB subsidy program, flying at lower speeds, reducing the demand for business travel by improving electronic communications systems, and allowing capacity limit agreements among commercial airlines. Overall, the analysis shows that there **is** some significant potential for reducing energy con-

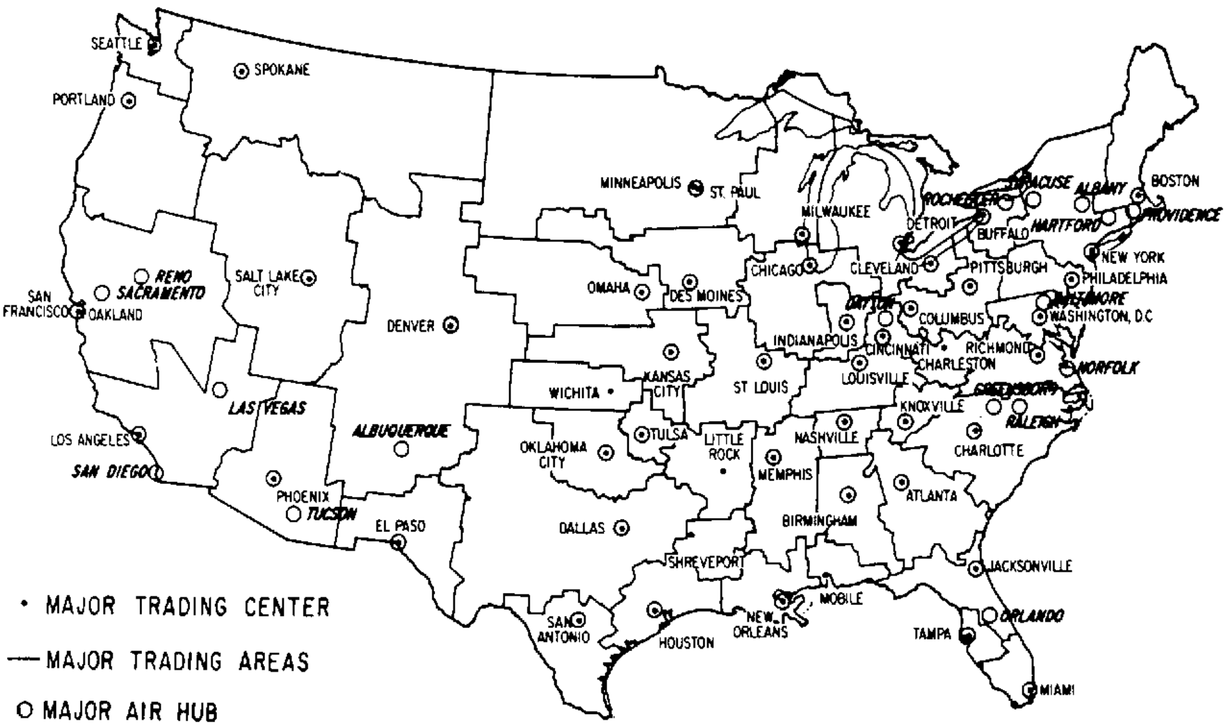

FIGURE 3.7
MAJOR AIR HUBS IN THE U.S.
Source: Webb, H. M., "Study of Low-Density Air Transportation Concepts," 1972

sumption in the air transportation sector; but to do so will require cooperation among the government, the airline industry, and the user. The government will need to develop a national transportation policy, from which air transportation can be put into proper perspective. Also, the Congress and the appropriate federal agencies need to re-think their current economic regulatory policies and taxation policies, so as to encourage economic and energy efficiency. The airline industry in addition to aiding and cooperating with government efforts, needs to reflect energy concerns in their decision making. Indeed, this will be forced to some extent as energy becomes more expensive. And finally, transportation users need to reflect energy concerns in their decisions about why, where, and how to travel, and to tolerate the inconveniences which will occur as the airlines make the transition to improved systems efficiency.

Another approach to alleviating the energy problem in air transportation is to develop alternative fuels, so as to decrease the total dependence upon petroleum. One attractive alternative fuel is hydrogen, and the feasibility of this approach is the topic of the following chapter.

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4

AN INITIAL STEP – A DEMONSTRATION PROJECT

CHAPTER IV
AN INITIAL STEP—
A DEMONSTRATION PROJECT

In order to initiate the transition into a clean and diverse energy environment independent of fossil-based fuels, the rapid development of a subsonic, hydrogen-fueled aircraft is recommended. Such a project would accelerate the achievement of energy self-sufficiency for the United States by providing technology not only for the aircraft industry, but also for other energy consuming sectors.

IV. A. Introduction

The energy problem has been documented exhaustively by many panels, studies, hearings, and technical symposia. The intent here is to review briefly its essential factors in order to substantiate the need for demonstrating the use of alternative fuels, and specifically, the use of hydrogen for aircraft.

Current energy needs are served primarily by direct use of fossil fuels. Although the U.S. still has considerable resources, production and new discovery rates of crude oil and natural gas have fallen behind demand. In the case of natural gas, some use curtailment is already in effect. Coal, on the other hand, is comparatively abundant, but nevertheless, is also a finite resource.

The increasing demand for energy, coupled with justifiable restrictions imposed by environmental and importation regulations can only reduce our supply of fossil fuels. In the not too distant future, the majority of our energy will have to come from solar, nuclear, and possibly, geothermal sources. The conversion of energy from these sources to electricity is already well established, but only on a modest scale. These same sources must eventually supply our transportation needs, which are now almost totally dependent on petroleum. Electricity is used for some ground transportation but at present is not very promising.

Clearly, there is a strong need for a "clean burning," abundant, easily transportable fuel which can be generated from nuclear, solar, and geothermal primary energy sources. Several fuels have been proposed, and are discussed in detail in Section B of this chapter. Of these, hydrogen appears to be the best candidate since it is almost ideally suited for an aircraft fuel and can be easily adapted for many other applications. Also, hydrogen is an excellent energy storage medium which could be produced by the utility industry during off-peak hours.

The most obvious attribute of hydrogen is its high heat of combustion. Additionally, it is relatively non-polluting when burned in air, non-toxic, adaptable to nearly all conventional fuel uses, and an abundant element available from water. Hydrogen does suffer some disadvantages; it is not very dense, and for uses requiring volume restrictions it will require cryogenic storage. Problems in hydrogen safety and containment are certainly not completely resolved, but technology has successfully resolved those difficulties for the space program and clearly offers encouragement that those difficulties can be resolved on a larger scale for general use in the economy.

Since hydrogen is a component of other fuels, and is very versatile in its usage, it must necessarily be considered a strong candidate for use as the future fuel. In addition, it is very abundant and is regenerated in the form of water vapor in the combustion process. For these reasons hydrogen has been chosen as the fuel for this demonstration project.

As described in detail in Section C of this chapter, the proposed demonstration project involves the development of a subsonic, hydrogen-fueled aircraft complemented by a complete fuel delivery and storage system.

The airline industry was chosen to initiate the use of the new fuel for several reasons. The industry is familiar with handling large quantities of fuels and has personnel trained in rigid safety procedures. Also, the airline industry is an advanced technology user group which can adapt more readily to a new fuel system. At first we suggest that only two or three airports be involved so that widespread distribution of hydrogen will not be required. This still permits crucial handling, storage, and transferring problems to be experienced.

Considerable hydrogen research has already been conducted by airframe and jet engine producers, giving them sufficient background to proceed with the project. Currently air travel is one of the major modes of intercity transportation and could equal the automobile in energy consumption by the year 2020. Consequently, the anticipated petroleum shortage should privide some impetus for the aircraft industry to develop alternate fuels.

We are not certain when the general use of hydrogen will begin. The economics of production and handling hydrogen versus the economics of reduced fossil fuel supplies and pollution controls will be the decisive factor. Inevitably, hydrogen will be a part of our energy economy and now is the time to take the initial step in preparation for its use.

The demonstration project will determine whether the difficulties described above can be resolved. If current technology is not adequate, the project will aid the search for the proper technology. Also, the project will enable the public to observe the use of hydrogen and notice that with proper care, it is a safe fuel. In this manner public acceptance of hydrogen as a fuel for airplanes, home heating, cooking, water heaters, and many other uses can be encouraged.

There is a need to stress that although the demonstration project involves the use of hydrogen as an aviation fuel, the project will serve as this nation's first major step in becoming fuel import independent in addition to developing technology which will accelerate the achievement of a clean, non-fossil based energy system.

IV. B. The Selection of a Suitable Alternative Fuel

IV. B. 1 Possible Fuel Candidates

Several synthetic fuels have been proposed as replacements for JP-4 as an aircraft fuel. These are listed in Table IV-I and compared to JP-4 and gasoline. Of the possible synthetic fuels, hydrogen appears best, especially with respect to decreasing overall aircraft weight, or increasing the ratio of payload to overall gross weight. This is due to the high heat of combustion of hydrogen, 51,600 BTU/lb., or almost three times that of JP-4. Using hydrogen not only reduces the fuel weight that must be carried, but also reduces the aircraft structural weight required to carry that fuel.

Hydrogen also has the advantage of being essentially non-polluting, versatile, adaptable to nearly all conventional fuel uses, and non-toxic. Perhaps of greater importance for long-range planning, however, is the abundance of hydrogen. The oceans provide a plentiful supply of water from which hydrogen may be generated through electrolysis. This of course requires the utilization of some primary energy source, such as nuclear or solar energy.

Whether on a grand scale or simply as an aircraft fuel, the use of hydrogen has some disadvantages. For use in transportation, cryogenic storage will be required to reduce the volume. Even as a liquid, the density of hydrogen is only 4.4 lbs. per cubic foot, less than one-tenth the density of JP-4. Therefore, even though hydrogen has almost three times the BTU content (per pound) of JP-4, an equivalent quantity of energy requires about four times as much volume.

Safety is another area where hydrogen has some drawbacks. It is easily ignited in air and its effects on storage containers is still under investigation. The wide flammability limits of hydrogen (shown in Table IV-I) make it dangerous in terms of accidental leakage and ignition, but this is put in perspective by comparing the flammability limits in air (4.0 - 75% H_2 by volume) with those of acetylene in air (2.3 - 80% C_2H_4 by volume). This is of some interest since acetylene is common in every workshop where welding is done. Certainly leakage and mishandling of equipment occurs, but the resulting mishaps have not resulted in an uproar of national disapproval or abolishment of oxy-acetylene welding. In some respects, liquid hydrogen (LH_2) is safer than other less volatile liquid fuels, because it diffuses upward rapidly, reducing the danger of secondary explosions or fires, and it burns quickly and with much less radiation of heat than a gasoline fire. However, its high diffusivity and low ignition energy result in a tendency to leak and ignite more readily than other fuels.

Cost is an additional disadvantage of LH_2 as an aircraft fuel; however, two offsetting factors are at work. Large scale production of hydrogen would reduct its cost, making it more competitive with JP fuels (1). Second, the continued increase of JP fuel price as petroleum becomes more difficult to obtain will make hydrogen more competitive.

Of the other possible alternate fuels listed in Table IV-I, methane and propane are produced from fossil fuel and off no incentive for changing from JP-4. What is needed is a long-term fuel which will not be depleted and which can be obtained from a variety of energy sources. Aside from hydrogen, the only listed candidates which fulfill these requirements are methanol and ammonia, both of which require hydrogen as a raw material in their manufacture.

TABLE IV-I

CHARACTERISTICS OF SYNTHETIC FUELS AND COMPARISONS WITH JP-4 AND GASOLINE

Fuel (Formula)	Heat of Combustion* (BTU/lb)	Heat of Combustion* (BTU/gal.)**	Density** (lb./ft.³)	Boiling Point (°F)	Ignition Temperature (°F)	Ease of Storage (1-easiest)	Toxicity (1-least toxic)	Flammability Limits In Air (% by volume)
Hydrogen H_2	51,600	30,400	4.4	-423	1,085	8	1	4.0 - 75.0
Ammonia NH_3	8,000	45,600	42.6	-28	—	4	6	15.0 - 28.0
Hydrazine N_2H_4	7,170	60,500	63.1	236	166++	3	7	4.7 - 100.0
Methanol CH_3OH	8,580	56,700	49.4	149	800	2	5	6.0 - 36.5
Ethanol C_2H_5OH	11,530	76,000	49.3	173	700	1	4	3.5 - 19.0
Methane CH_4	21,500	74,500	25.9	-259	1,200	6	2	5.0 - 15.0
Propane C_3H_8	19,900	97,000	36.5	-44	—	5	3	2.1 - 9.5
Acetylene C_2H_2	20,734	—	—	-119	635	7	—	2.3 - 80.0
Gasoline	19,100	112,000	43.8	257	—	(1)	(4)	1.1 - 7.0
JP-4	18,600	121,000	48.7	210	480	(1)	(4)	0.8 - 5.6

*Lower heating values
**Liquid
++ Hydrate

Source: Summer Design Team Data

Methanol would be available in a hydrogen economy by using known technology to react hydrogen with carbon dioxide. The latter could be obtained from limestone or from the atmosphere. Methanol is fairly easy to store but it is toxic, has a low heat of combustion (per pound), and its combustion products cause greater pollution than hydrogen.

Ammonia could be produced by reacting hydrogen with atmospheric nitrogen using known technology. However, ammonia is toxic, its storage requires refrigeration, it has a low heat of combustion, and severe pollution problems can be expected in the form of oxides of nitrogen (NO_X) since nitrogen exists in a combined form in the fuel.

Ethanol may be manufactured independently of hydrogen and independently of fossil fuel resources by the utilization of solar energy. Photosynthesis could convert the solar energy into cereal grains which could undergo fermentation to produce ethanol. Future generations, however, will find difficulty justifying the use of food crops for this purpose.

Hydrogen is an excellent alternate fuel which could be produced in large quantity, is environmentally acceptable, is versatile, and can be produced from a variety of primary energy sources. Although problems in safety and containment of hydrogen are not completely resolved, technology has successfully dealt with these difficulties for the space program and clearly offers encouragement that these difficulties can be eliminated (or reduced to a minimum) on a larger scale for general use in the economy.

IV. B. 2. An Analysis of Liquid Hydrogen As An Aircraft Fuel

The intent of this section is to present the results of an investigation of the technology involved in the transition of aircraft for LH_2 fuel and to analyze the advantages and disadvantages of such a transition. The investigation was conducted on the assumption that LH_2 could be economically produced, transported, and stored at or near airfields. This section has four main divisions: (1) transition of the propulsion and fuel supply system; (2) ecological effects of the combustion of LH_2 in aircraft engines; (3) aircraft tankage problems with liquid hydrogen; and (4) safety precautions.

A. Transition of the Propulsion and Fuel Supply Systems

To the airplane designer the most favorable characteristic of LH_2 is its high energy content per pound, since weight reduction of an aircraft is highly desirable. The most unfavorable characteristics of LH_2 are its low boiling point and low density. The boiling point of JP-4 is practically the same as for water, whereas LH_2 has the second lowest boiling temperature known (-423°F). This is undoubtedly the cause of the majority of the problems, both present and future, which are associated with the use of LH_2 as an aircraft fuel. For instance, the aircraft designer is unable to capitalize completely on the savings in fuel weight of an LH_2-fueled aircraft because of the increased weight required by cryogenic storage tanks.

The actual operation of jet engines on LH_2 has already been accomplished. As early as 1957, a group at the NASA-Lewis Research Center made three successful flights in a modified B-57 Canberra which used LH_2 as a fuel (2). The airplane took off and climbed to cruise altitude (50,000 ft.), where the engine was shifted from JP fuel to hydrogen and then back to JP after the hydrogen supply was exhausted. Both transient and steady-state operations were highly satisfactory. Furthermore, satisfactory combustion was attained in very short combustors, which would allow for the possibility of relatively short engines compared with present JP-4-fueled engines, and consequently, reduced engine weight and space requirements. No cryogenic pumping problems were encountered in this initial system, since the LH_2 was forced into the engine by a pressurized helium tank carried on the aircraft.

Concurrent with the NASA-Lewis effort, Pratt and Whitney Aircraft conducted research in the area of LH_2-fueled turbine engines (3). This effort was directed at engines that would operate entirely on LH_2 and initially involved a modified J57 engine. The investigation included development of an LH_2 regeneratively cooled and fueled afterburner. This engine was static-tested but never flown.

More recently, under a NASA sponsored activity, the General Electric Company launched a study concentrating on the development of a delivery and control system for cryogenic fuels (4). An additional preliminary fuel system study and design was performed in 1971 in connection with a potential LH_2-fueled turbofan for booster and orbiter propulsion of the NASA Space Shuttle vehicles. This effort was conducted for both liquid hydrogen and liquid methane fuels and involved general tests only. The significant problem areas to be overcome by designers of LH_2 fuel control systems for large sized turbojets or turbofans were summarized as follows:

(1) fuel pumping arrangements for high flow, high turn down requirements;
(2) design of oil-to-fuel heat exchangers which avoid oil freezing;
(3) design of air-to-fuel heat exchanger cores with adequate fire safety to permit integration within the engine structure; and,
(4) effects of two-phase flow in fuel manifolds and injectors where liquid metering is used.

B. Ecological Effects of the Combustion of LH_2 in Aircraft Engines

The current major environmental problems associated with aircraft power plants are noise and air pollution. There is speculation that a liquid hydrogen-fueled aircraft will produce less noise than an equivalent JP-4 fueled aircraft. However, the technology of noise abatement appears to be making significant progress. Noise pollution is believed to be solvable regardless of the type of fuel.

Hydrogen fuel may be able to contribute favorably toward reducing air pollution. Table IV-II lists 1972 and 1975 auto emission standards for comparison with typical JP-4-fueled supersonic and subsonic aircraft emissions. Although present total aircraft emissions are much lower than automotive emissions, in the future they may become of more importance, especially in the case of NOx.

The major concern for NO_x emission in the upper atmosphere is that NO_x reacts with, and depletes, ozone. The importance of this reaction is that the ozone content in the stratosphere is the earth's natural shield from biologically harmful ultraviolet radiation. The lower limit of the stratosphere over the U.S. is found at altitudes ranging from about 30,000 feet to 55,000 feet depending on the season. Some present flights are exhausting NO_x into this region. Concentration variations of 5% are known to be tolerable without harmful effects; in fact, the atmospheric nuclear test program of the mid-fifties to early sixties caused an ozone reduction of approximately that magnitude. From 1963 to 1970 a natural increase occurred, indicating the return to some natural equilibrium concentration.

Liquid hydrogen has several advantages over fossil fuels in regard to pollutant emissions. Use of hydrogen as a fuel would eliminate the exhaust of unburned hydrocarbons and carbon monoxide. For any air breathing aircraft, however, NO_x will still be a matter of concern regardless of the type of fuel. However, the properties of hydrogen allow a greater flexibility to reduce this pollutant than does conventional JP-4 fuel.

The two principal methods for reducing NO_x emissions are lowering the flame temperature and reducing the reaction-zone dwell time. The reaction-zone dwell time is the time that gaseous combustion products

TABLE IV-II

EMISSION DATA - AIRCRAFT*

Engine	Mach No.	Alt. (Ft.)	CO (gm/kg)	THC (gm/kg)	NO_x (gm/kg)
GE-J93	.8	20,000	6	.07	5
GE-J93	1.4	35,000	8	.16	5
GE-J85	1.6	55,000	90	.5	3.7
"Typical Subsonic Gas Turbine"	(At 100%) (Power)		≈5	≈1	≈10

AUTO EMISSION CONTROL STANDARDS

Year	CO (gm/kg)	THC (gm/kg)	NO_x
1972	224	3.4	6
1975	27	2.6	.5

*Source: (10)

*Emission Index given in terms of grams of pollutant per kilogram of fuel. Simulated flight conditions, not actual in-flight data.

CO: carbon monoxide
THC: unburned hydrocarbon
NOx: oxides of nitrogen

remain at temperatures high enough to allow the formation of NO_X. Hydrogen has a burning velocity approximately eight times that of JP-4 fuel, thus allowing the design of shorter engines with considerably less reaction-zone dwell time than a comparable JP-4 engine. Conversion of existing aircraft engines to hydrogen would offer the flexibility of being able to vary fuel/air ratios over a wide range to reduce NO_X emissions. Naturally engine performance and fuel economy would be considerations as well as the reduction of NO_X.

The full advantage of hydrogen as a fuel would be realized with the design of new engines. Smaller, lighter engines could be designed utilizing the cryogenic properties of hydrogen for cooling purposes. Grobman indicated that the elimination of local hot spots of combustion by premixing the air and fuel would significantly reduce NO_X emissions even if overall design operating temperatures were higher than comparable JP-4 engines (5, p. 22). Ferri presented a curve illustrating the NO_X pollution index (grams of NO_X produced/kilogram of fuel burned) for hydrocarbons and LH_2 bs. the maximum temperature reached in the combustion engine (6, p. 193). As one might expect, there was no significant difference between the two fuels. The curve simply verified that the NO formation varies exponentially with flame temperature. A better comparison is made by plotting the pollution index in terms of gm NO_X/BTU, as shown in Figure IV-1. This curve indicates that on any given flight requiring a certain number of BTU's (total energy) the total NO_X emissions will be reduced with hydrogen as a fuel. Increased engine efficiency with hydrogen could further reduce NO_X emissions.

The one possible environmental disadvantage of hydrogen as an aircraft fuel is the combustion product water. There is a water-ozone reaction which may result in a net decrease in ozone, and as previously mentioned, this could be of major consequence for stratospheric flying. The Department of Transportation's Climatic Impact Assessment Program currently under way should resolve the ozone question, including the significance of the water reaction. As a result of water exhaust, there is a possibility that airport fogging could result in cold climates.

In summary, liquid hydrogen as a non-polluting fuel for aircraft (and eventually ground transportation) has the advantages of:

(1) elimination of CO, CO_2, and unburned hydrocarbons from exhaust emissions;
(2) reductions in nitrogen oxides; and,
(3) if hydrogen can be produced from "clean" sources of energy such as nuclear or solar, the pollution from obtaining, transporting, and conversion of fossil fuels could be considerably reduced.

C. Aircraft Tankage Problems with Liquid Hydrogen

Due to its very low boiling temperature, liquid hydrogen must be stored in properly insulated tanks to prevent losses. Accordingly, the problems associated with prolonged ground storage of liquid hydrogen have been studied in depth, particularly by NASA, and are generally understood. Unfortunately, however, the technique commonly used to design a ground storage system produce a structure that is far too heavy to be considered for aircraft use. As a result of the increase in required fuel volume and the necessity of good thermal insulation, the empty weight of LH_2 aircraft fuel tanks will be significantly greater than equivalent JP-4 fuel tanks. However, for a specific payload-range designation, the overall structural weight of the LH_2 airframe will be less than that of the JP-4 airframe. This is attributable to the lower fuel weight of the LH_2 airplane, thus requiring less wing area, smaller control surfaces, and lighter landing gear structures. Many other critical aspects of aircraft design such as highly reliable structural integrity and precise thermal control systems present new and very important problems to be overcome in using liquid hydrogen. As a result of the inherent danger of the wide flammability range of hydrogen in air, the space between the fuel tank and outer skin of the airplane would likely contain an inert purge gas, such as nitrogen or helium.

The two main classes of materials to be considered in designing liquid hydrogen fuel tanks are the structural and insulating materials. Factors such as relative expansion rates of insulating materials and the fuel tank, and the cryogenic effect of embrittlement, will need careful analysis.

Embrittlement of metals upon contact with gaseous hydrogen is an old, frequently encountered and often misunderstood phenomenon. It is a form of delayed fracture which can occur minutes or days after the ap-

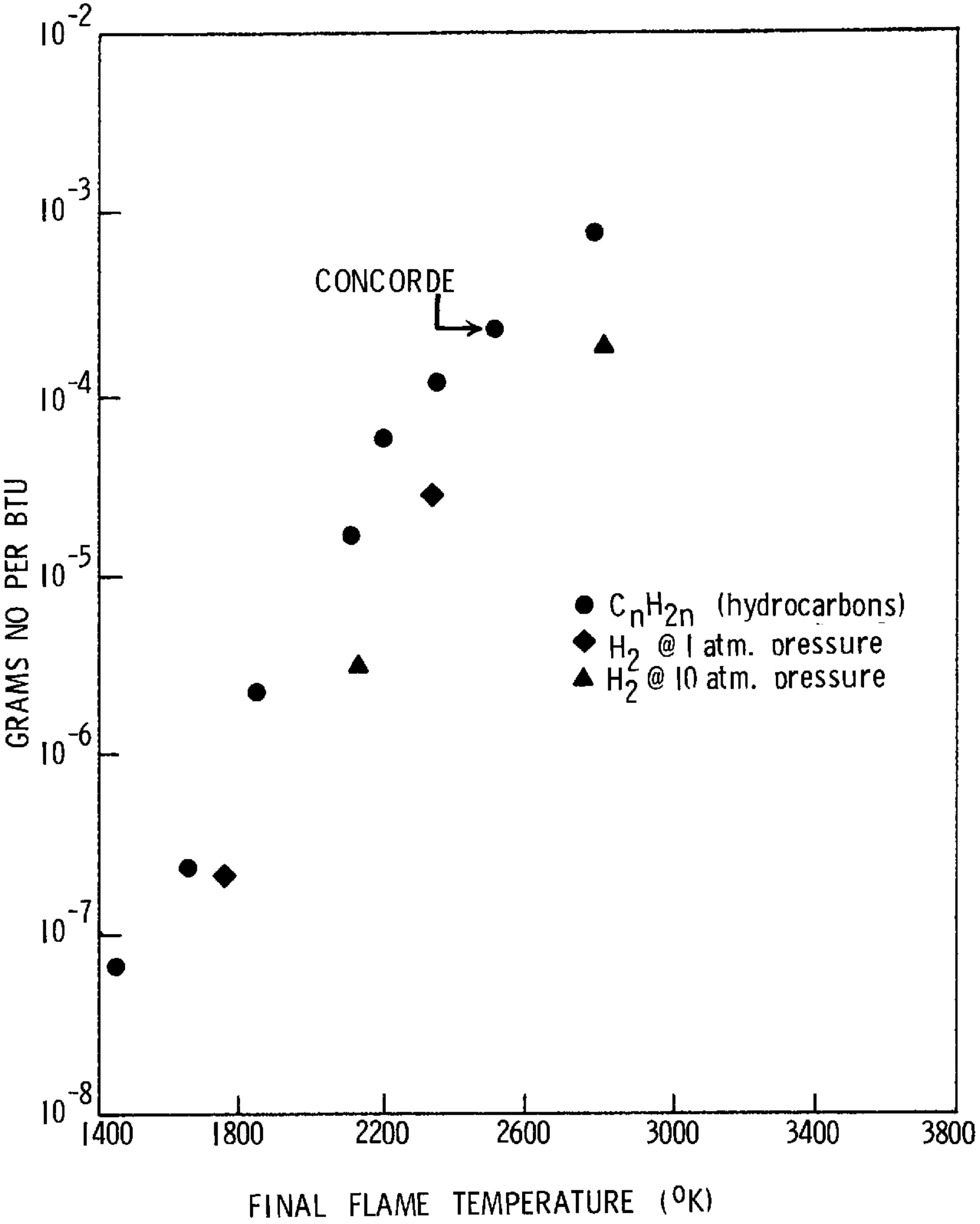


FIGURE 4.1
COMPARISON OF NITRIC OXIDE EMISSIONS FROM HYDROCARBON AND HYDROGEN FUELS vs. FINAL FLAME TEMPERATURE

Source: Ferri, A., New York University

plication of a load. High strength steels are particularly susceptible to this type of failure, as are titanium, zirconium, and their alloys. The effect is due basically to the presence of excess absorbed hydrogen, which collects in pores or inclusions and builds up high internal pressures eventually leading to failure of the material. Hydrogen can be removed from a metal by vacuum baking at 350°C, but it is better to prevent initial pick-up whenever possible. The hydrogen embrittlement phenomenon is confined to the gaseous phase only, and no insurmountable storage problems have been experienced in the liquid phase. An extensive investigation at NASA-Ames on the effects of gaseous hydrogen on structural alloys has resulted in an analytical technique which can be used to predict the service life of components operating in a hydrogen environment. This technique is based on fracture mechanics and permits life prediction over a wide range of hydrogen pressures, temperatures and stress levels (7, p. 277).

Nearly all conventional fabrication techniques have been used in the cryogenic field. Conventional arc-welding, heliarc-welding, silver soldering and soft soldering have all been used with success; however, the quality of a solder joint is usually more sensitive to the solder composition than would be true for room temperature application (8, p. 60).

Present technology can minimize many of the problems associated with liquid hydrogen storage in aircraft tanks; however, extensive research is required in order to use materials reliably in a gaseous hydrogen environment above about .O°F at both low and high pressures. Life prediction techniques must be verified and applied to assure conservative design approaches for structural components that must operate for long periods of time in a hydrogen environment. To insure reliable service of hydrogen-fueled aircraft, a large amount of additional research is required to simulate the actual service conditions that the aircraft will experience.

D. Safety Precautions

Although the layman may consider LH_2 a dangerous fuel, this general impression may be attributed to the often viewed fire-belching of liquid hydrogen-fueled rockets, and reminders of the Hindenburg disaster. Hydrogen can be dangerous, but so are natural gas and gasoline which are ever present in our day-to-day life. The intent of this section is to examine the prospects of handling hydrogen as a fuel for aircraft and to consider the attendant problems of safety.

Table IV-III

COMBUSTION PROPERTIES OF HYDROGEN

Conditions Affecting Ignition Characteristics

—contents of gas mixture
—temperatures
—pressure
—geometry of surrounding walls
—ignition energy

Ignition Sources

—hot solid body
—flames or hot gases
—explosive charge
—sparks

Flammability Limits
(in air saturated with water vapor at ambient temperature and pressure)

$4 \leq \%\ H_2$ by volume ≤ 74

Ignition Energy

—about 1/10 that required to enflame most hydrocarbons
—auto-ignition temperature about 1075°F.

Source: (9, p. 7-9)

Aside from the difficulties in handling cryogenics, the liquid form is not dangerous unless splashed on exposed skin or brought into contact with air. The unconfined evaporation from liquid to gaseous form provides a mechanism for hydrogen to mix with atmospheric oxygen, causing fire or explosion to exist. Furthermore, the presence of hydrogen is not detectable to unaided human senses. Adding an odorizing agent to hydrogen has been proposed so that its presence can be detected. Such agents are presently added to natural gas. In addition, a coloring agent could be included so that potentially dangerous accumulations of hydrogen in overhead voids or ceilings could be detected visibly.

In either the gaseous or liquid form, hydrogen can escape from systems which appear to be perfectly sealed for other fluids. The very low density of the gas means that if leaks do occur, the gas rises and if confined will accumulate in overhead voids. This property is to be contrasted with gasoline vapors which accumulate in low places.

Inevitably during handling, storage, or operation of hydrogen systems at some time leakage will occur and the possibility for fires will exist. This has been part of our experience with natural gas, gasoline, and JP-4, regardless of how rigidly safety standards and operating procedures are established and enforced. The information in Table IV-III helps to assess the hazards associated with leakage of hydrogen.

Comparing the lower flammability limit (LFL) of hydrogen with that of propane, methane, and gasoline (Table IV-I) one sees that propane and gasoline are capable of ignition at lower volume percentages than is hydrogen. The LFL of methane is only slightly above that of hydrogen; yet these fuels are part of everyday experience for many Americans and with proper care are safely used.

The low density of hydrogen actually provides some inherent safety factors. Whenever a leak occurs the gas rises and rapidly diffuses into the surrounding medium. If the leakage gas is confined by overhead structure, it may accumulate to flammable concentrations. However, since we always know where to look (in the absence of convection currents) for possible accumulations, leak detector placement is simplified venting provisions are also simplified. Several methods for detecting small amounts of hydrogen have been proposed and in some cases employed (see Table IV-IV). Some of these methods could be used to warn the crew of accumulation of leaking hydrogen. Methods such as bubble testing and listening devices would not be applicable on board aircraft.

IV. C. The Proposal

IV. C. 1. The Aircraft Selection

Discussions with several major aircraft and engine corporations have indicated that the best method of developing a liquid

TABLE IV-IV

SENSITIVITY LIMITS OF LH_2 DETECTORS

PRINCIPLE	MINIMUM DETECTION LIMITS IN AIR			
	Atm-cc/sec	% H_2	% LFL	Ign Hazard
Catalytic Surfaces	8.0	0.02	0.5	Yes*
Bubble Testing	1 X 20^{-4}	NA	NA	NO
Sonic	1 X 10^{-2}	NA	NA	No
Thermal Conductivity	1 X 10^{-3}	5 x 10^{-4}	0.01	Yes*
Gas Density	1 X 10^{-2}	5 X 10^{-3}	0.1	No
Hydrogen Tapes	o.25	1.5	35	Yes
Scott Draeger Tubes	NA	0.5	13	No Info
Electrochemical	NA	0.05	1.2	No

* Can use flame arrestors
Quenching material available

Source: (9, p. 22)

hydrogen aircraft for **demonstration** purposes would be to convert an existing plane rather than design and build a totally new aircraft. The factors that led to this conclusion were (1) cost; (2) time required for the project to be initiated and completed; and (3) technical considerations of the project.

Although no estimates for the development costs of a totally new, subsonic, hydrogen-fueled airframe have been made by the aircraft industry, estimates for development of a new hydrogen jet engine may be of the order of $700 to $800 million. Past experience shows that the airframe cost would be even greater than the engine cost. On the other hand we estimate the conversion of an existing jet engine to liquid hydrogen to be the cost of the existing engine plus 10%. The cost of a typical jet engine for a wide-bodied airplane is about $900,000; therefore, the conversion cost would be approximately $1 million per engine we estimate. The airframe conversion has been estimated at $6 million.

Both the engine manufacturers and the airframe industry estimate that an existing airplane could be converted to a hydrogen-burning craft within two years. To develop a new plane would probably require almost a decade.

In addition to low development costs and the short time needed to convert an existing craft to liquid hydrogen, the technology developed during the project would significantly help in the later design of a plane designed specifically for hydrogen. Although the conversion would not take full advantage of the excellent properties of hydrogen as a jet fuel, the problems encountered and solved in the conversion would help expedite any future design of a hydrogen-fueled craft.

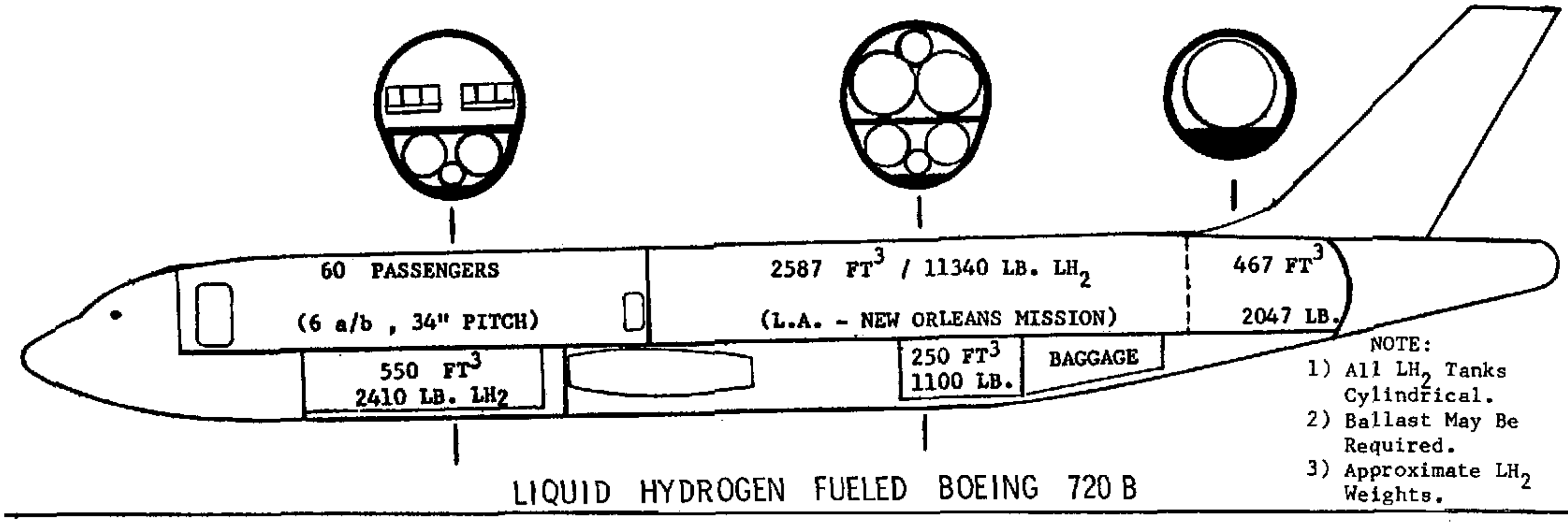
Several factors were instrumental in the selection of the airplane to be converted: a useful mission should be flown by the aircraft and it should be capable of carrying at least 30,000 pounds of cargo or 50 passengers.

Three different airplanes have already been examined by the aircraft industry for potential conversion to hydrogen. However, these are only preliminary choices and certainly other options should be investigated before the final selection is made.

A Boeing 720 passenger aircraft was considered as one possibility, with the fuel tanks and passenger compartment as shown in Figure IV-2. The design concept in this case would be to replace portions of the passenger and cargo carrying volume with hydrogen fuel tanks. Depending on the length of the mission, the modified aircraft would be able to carry between 33 and 80 passengers as compared to the normal 149 passenger capability. In this type of modification scheme, there would be no external changes necessary in the airframe. As shown in the schematic of the plane, separate cylindrical pressure vessels would be used for fuel since they are easy to install and would be less expensive than integral tanks. The obvious disadvantage of such tanks is the poor utilization of available volume.

Another preliminary design possibility would be the modification of a Boeing 747, as shown in Figure IV-3. This concept would involve a slight change in aircraft shape to allow the inclusion of a large integral hydrogen fuel tank in the upper lobe. Obviously, the airframe modification for the large integral fuel tank allows the characteristics of the liquid hydrogen-fueled plane to be comparable to the JP-4 version. The cost involved for such airframe modifications would be considerably greater than installing separate tanks, and consequently, the modified 747 may not be as suitable as the 720 for a demonstration plane.

The third aircraft considered was a Lockheed C-141 cargo plane. This plane was considered because it is large enough to carry sufficient hydrogen for long duration flights and has a large cargo bay which may be used for instrumentation during test flights. The design configuration in this case includes wing tanks rather than integral tanks, as shown in Figure IV-4. This arrangement as shown is intended to illustrate the relative size of the tanks only. Further aerodynamic and structural investigations would of course be required to determine the final configuration. Other possible tank locations would be above the wing at the location of the center of mass of the present JP fuel tankage, above the fuselage, or below the wing on either side of the fuselage. The tanks as shown are 66 ft. long, 9.5 ft. in diameter, and are capable of carrying a total of 26,500 pounds of liquid hydrogen. The modified airplane would be capable of carrying a 30,000 lb. payload with a range of 2,500 nautical miles. The wing mounted tanks eliminate the need for a complex purge and vent system that would be required for an integral tank arrangement. This configuration is also more representative of a system which could be used to convert existing transport aircraft to hydrogen when



MISSIONS:	HYDROGEN FUELED			JP4 FUELED
	L. A. — NEW ORLEANS	L. A. — OKLAHOMA CITY	EDWARDS — POPE	3400 NAUT. MILES
T. O. GROSS WEIGHT (lbs)	147,000	149,500	143,485	234,340
MISSION FUEL WEIGHT (lbs)	11,750	8,900	14,750	108,064
LANDING WEIGHT (lbs)	135,250	140,700	128,765	175,000
PAYLOAD (Pass. @ 205 lb)	60/12,300	80/16,400	33/6,765	149/30,545
RESERVE FUEL (lbs)	5,150	5,200	5,000	
OEW (lbs)	118,080	119,000	117,000	120,000

FIGURE 4.2
MISSION SPECIFICATIONS
Source: Boeing Company, Seattle, Washington

the unavailability and/or the high cost of JP fuel makes the change economically attractive. The given ranges closely correspond to the proposed routes as discussed in the next section of this chapter. Figure IV-5 is a photograph of a presently operating C-141. To insure continuation of the project should a major failure occur during the test and evaluation period, conversion is recommended for two aircraft. There is usually a high level of skepticism concerning any new technology. A non-hydrogen related malfunction (landing gear, control surfaces, etc.) could terminate the project causing undeserved criticism of hydrogen and delaying its widespread acceptance for years.

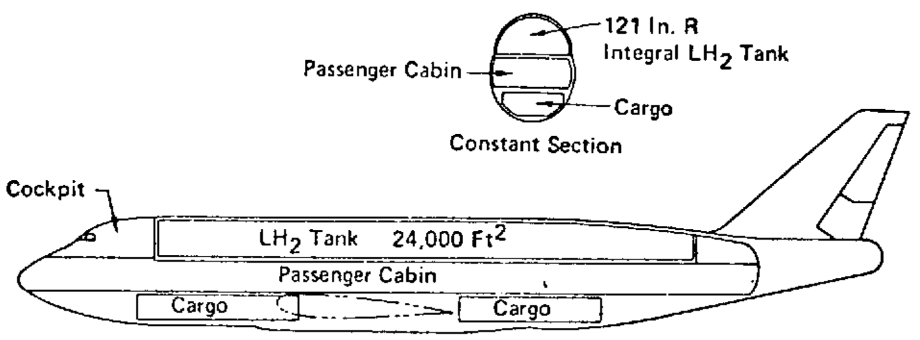


FIGURE 4.3
B747 - LH_2 INBOARD PROFILE

COMPARISON OF 747 CHARACTERISTICS

	747-LH_2	747-200B
Fuel Type	Liquid H_2	JP-4
Max T.O. Weight	590,000 lb	775,000 lb
Passenger Capacity	369	385
Lounge Passengers	0	16
Mission Performance: (Full Passenger Payload)		
Range (M=.86)	5,100 N Mi	4,950 N Mi
T.O. Weight	574,000 lb	775,000 lb
Fuel Burned	90,500 lb	268,000 lb
T.O. Field Length	5,150 ft	10,200 ft
Initial Cruise Altitude	36,000 ft	31,000 ft

Source Brown, R. B., The Boeing Company, Seattle, Washington

IV. C. 2. The Proposed Routes

An initial demonstration project of a liquid hydrogen-fueled aircraft involves the same problems affecting flights of any large aircraft, with the added complexities associated with hydrogen fuel. Liquid hydrogen must be available at the two or three airports involved in the project, but special flights to airports not routinely involved in the demonstration could occur for special tests and public exposure.

The primary requirement affecting the choice of airport location was convenient access to existing liquid hydrogen plants. The three largest liquid hydrogen plants in operation today are located in Ontario, California (near Los Angeles); Long Beach, California; and, New Orleans, Louisiana. All three plants have an installed capacity of 30 tons/day, but only the Linde plant at Ontario is operating close to this limit. The Air Products plants at Long Beach and New Orleans are currently operating at about 50% capacity. The airport locations investigated were in the vicinity of these three plants.

In choosing a particular airport within the aforementioned regions one must first decide whether the carrier will be commercial (civilian) or military. A commercial aircraft would be capable of larger public exposure than would a military aircraft. However, FAA certification regulations would be involved if a commercial air carrier were chosen. FAA officials have indicated that even an experimental certification would be a long time coming. The operation of the military demonstration aircraft between Air Force bases would enable the FAA to observe the craft in operation and to formulate appropriate regulations for hydrogen-fueled airplanes.

The largest fleet of wide-bodied military aircraft is flown by the Air Force Military Airlift Command (MAC). A triangular route is proposed between Norton AFB in San Bernadino, California; Tinker AFB near Oklahoma City; and, England AFB in Alexandria, Louisiana to introduce liquid hydrogen as an aircraft fuel (See Figure IV-6).

Norton AFB is about 15 miles east of the Linde plant in Ontario; the current flight frequency between Norton AFB and Tinker AFB is about 3 flights per week. These missions involve cargo being shipped from Tinker to overseas bases. Consequently, this would require a transfer at Norton from LH_2 aircraft to a JP-fueled aircraft instead of the present procedure of through-plane service which means an added cost to the Air Force. The distance from Norton to Tinker is 1150 miles, requiring about seven tons of LH^2 per flight for the converted C-141 aircraft. The Linde plant at Ontario could easily handle this increase in production and the LH^2 could be trucked the 15 miles to Norton without any anticipated problems.

Tinker AFB, about 8 miles southeast of Oklahoma City, is roughly 575 miles from the Air Products plant in New Orleans. This is near the limit of LH_2 trucking experience, although, Tinker AFB is not proposed as a primary refueling airfield, but only as an enroute touchdown in order to pick up cargo.

The other primary refueling airfield would be England AFB which is about 1500 miles from Norton AFB and about 400 miles from Tinker AFB. The England airfield is about 175 miles from the Air Products plant in New Orleans. No charge for the services at the three airfields mentioned above is anticipated outside of the expense for constructing LH_2 storage facilities which are discussed in the following chapter.

An alternative route from Norton AFB to Pope AFB, North Carolina, was also considered. The current flight frequency is twice weekly in support of airborne training at Fort Bragg. However, due to the large transportation distance (750 miles) involved, Tinker AFB seemed to be the more likely candidate.

IV. C. 3. Fuel Delivery and Storage

The logistics of supplying liquid hydrogen over long distances have been established to a certain extent by the NASA space program. During the course of the Apollo program alone, NASA-owned tanker trailers logged over two million miles with only one significant highway incident. The majority of the LH_2 shipped to the Kennedy Spaceflight Center was from New Orleans, La., a distance of approximately 700 miles. These trailers were of two sizes; 13,000 gallons (7,600 lbs.), and 16,000 gallons (9,300 lbs.). The average boil-off experienced by these trailers was 0.25% per day. The 1970 price of the 7,600 lb. trailer was $145,000.

The supply of LH_2 to Norton AFB from the Linde plant in Ontario presents no major problems. One design possibility for the C-141 conversion would be to have removable interchangeable fuel tanks. The interchangeable tanks could be loaded at the Linde plant and

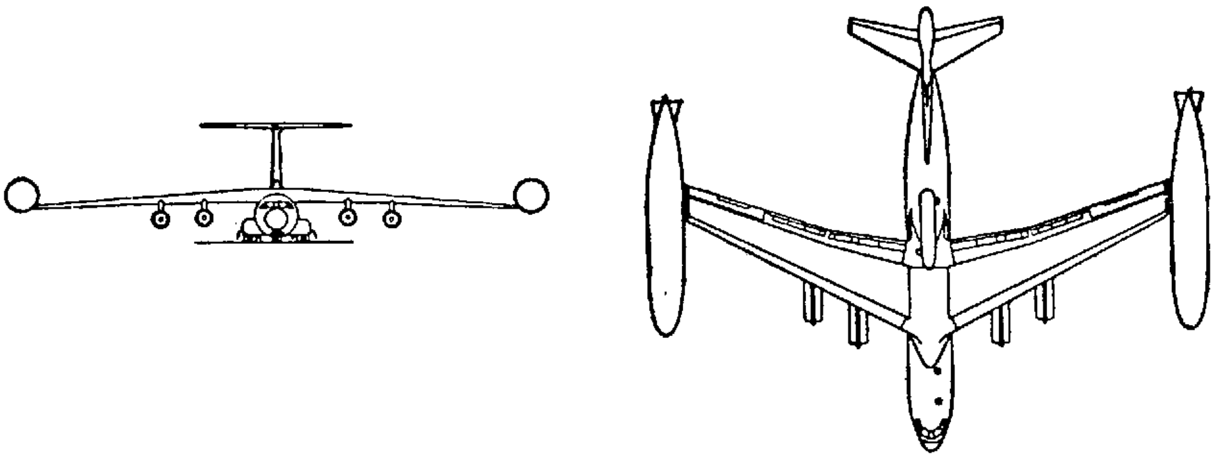


FIGURE 4.4
RANGE/FUEL CONSUMPTION OF LH_2 - FUELED C-141

✱ Drag Increase of External Tanks Included.

✱ OEW Increased by H_2 Tanks and Installation Weight

RANGE - NM:	1000	1500	2000	2500
ZFW (LBS)	172,500 ←			→
FUEL WTS:				
Reserves	2,750	2,960	3,190	3,440
Descent, LDG. & Taxi	1,100	1,100	1,100	1,100
Cruise	6,510	10,200	14,400	19,050
Taxi, T.O. & Climb	2,650	2,740	2,810	2,910
TOTAL FUEL	13,000	17,000	21,500	26,500
TOGW	185,500	189,500	194,000	199,000 (MAX)

Source: Lockheed-California Company, Burbank, California

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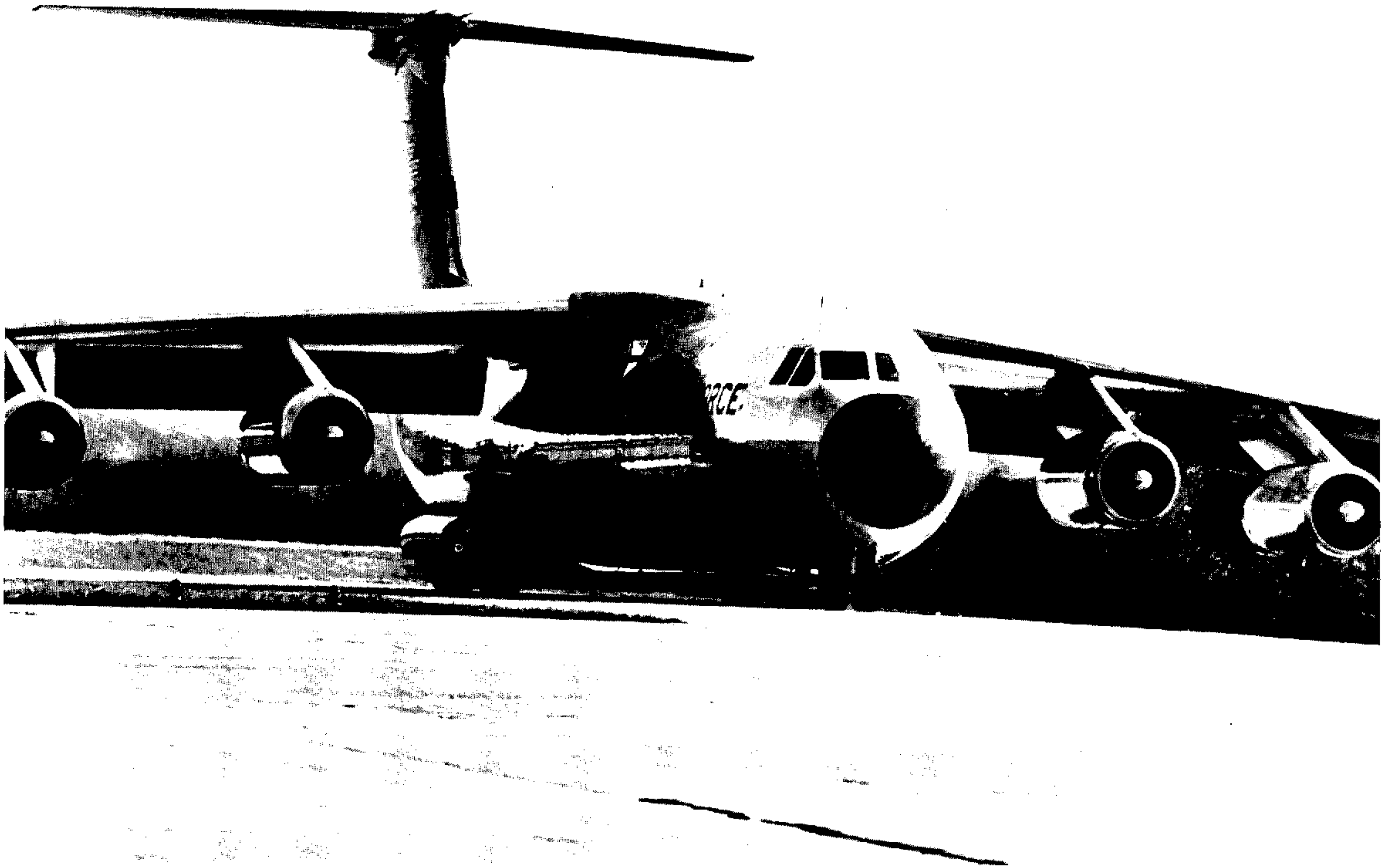

FIGURE 4.5
LOCKHEED C-141 TRANSPORT

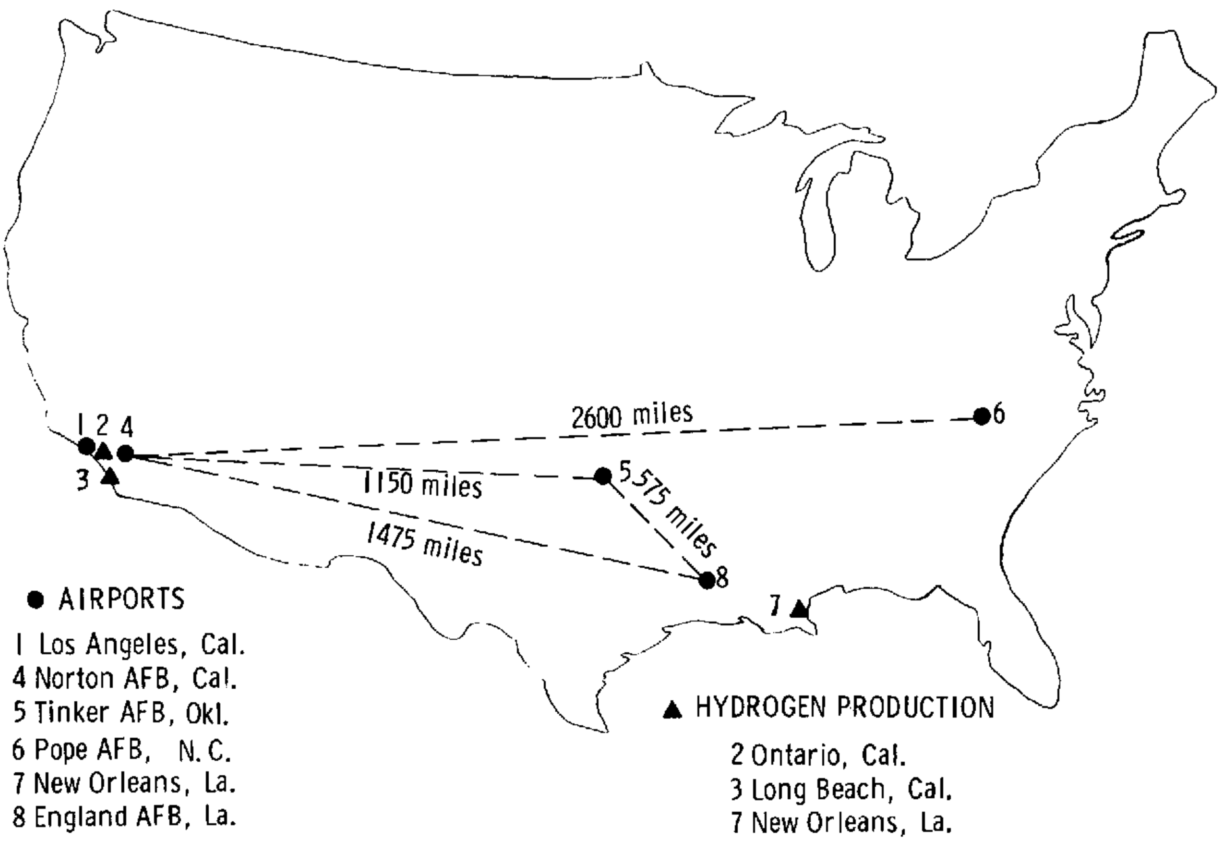

FIGURE 4.6
LOCATION OF AIRPORTS AND SUPPLIERS OF LIQUID HYDROGEN

trucked to Norton AFB, replacing the empty tanks from the previous mission. The weekly requirement of fuel at Norton would be about 45,000 lbs. of LH_2 (three flights per week at 15,000 lbs. per flight). Two of the smaller truck-trailers would be sufficient per flight and fixed storage at the airfield would be unnecessary. If the LH^2 supplier were the Air Product plant in Long Beach, the logistics would be basically the same except that the fuel must be transported 65 miles.

The situation at the Tinker and England airfields is somewhat different due to the greater transportation distances involved. Although liquid hydrogen could be trucked from the Air Products plant in New Orleans to Tinker AFB, railroad cars may be a better alternative. Each of these rail cars may be purchased with capacities of 8.35 tons and 11.8 tons for $185,000 and $250,000 respectively. The boil-off rate for these vehicles is comparable to the truck-trailers and the estimated freight costs are about $3,000 per car per round trip. Since Tinker AFB will be a secondary refueling airfield, there would be no need for a permanent LH_2 storage tank. A small amount of fuel could be stored at the airfield in either the truck-trailers or the railroad tank cars.

Supplying LH_2 to England AFB could be accomplished by either truck-trailer or railroad tank car. However, some storage facilities probably would be necessary. The smallest LH_2 storage tank currently available is 500,000 gallons or about 300,000 lbs. If the design storage pressure is 60 psia this tank would cost about $600,000.

The possibilities of pipeline transmission of liquid hydrogen to Norton AFB and gaseous hydrogen to England AFB were also investigated. Although the experience gained from either technique would be invaluable for later applications in the hydrogen economy both systems were found to be extremely costly, and consequently were passed over. There are hydrogen pipelines currently in service; one Texas line is over 12 miles long.

The present proposal is that the two airplanes fly regularly for a two-year period in order to establish reliability and other basic criteria for FAA certification. This would require about 500,000 pounds of LH^2 per month for a total of 12 million pounds, half of which would be purchased in California, the other half in New Orleans. At the current rate for these quantities (70c/lb.) this would amount to $8.4 million for the two-year period.

Another alternative would be to purchase the hydrogen at a delivered price. This could run as high as $1/lb. for a total of $12 million, which is only slightly higher than the F.O.B. price of LH_2 plus the purchase of the transportation and storage equipment.

The lead time for the procurement of the first truck-trailers and the railroad tank cars is 18 months, with a two-week delivery per unit thereafter. The LH_2 storage tank could be built and tested in less than two years.

IV. C. 4. Summary of the Proposal

In summary, the proposal is that two airplanes be modified and used to demonstrate the feasibility of using liquid hydrogen as a future aircraft fuel. These planes would fly a regularly scheduled triangular route from Alexandria, Louisiana to Oklahoma City, Oklahoma to San Bernadino, California carrying military cargo and personnel. An LH_2 supply and/or storage system would be provided for each airfield.

The project would take a total of five years; the first three for construction and testing of the various components, the last two for evaluation. Based on a rough estimate, the total expense for fuel and equipment would probably be in the neighborhood of $32 million. A summary of the economic aspects of the project is given in Table IV-V. These costs neglect possible reductions in aircraft productivity due to the conversion to hydrogen fuel.

Figure IV-7 suggests the potential impact that the demonstration project could have on the overall energy situation. In this concept of a "hydrogen economy," all energy consuming sectors could utilize hydrogen which would be generated through electrolysis by solar, nuclear and geothermal primary energy sources. This type of future energy picture is a very real possibility, although not feasible until fossil fuels become unreasonably priced or unavailable. The importance of the demonstration project is highlighted by the technological feedback to other energy users.

Table IV-V

Cost Breakdown for the LH_2 Fueled Aircraft Demonstration Project

	$ (in millions)
I. Aircraft	
8 modified jet engines @ $1 million each	8.0
2 modified airframes @ $6 million each	12.0
II. Fuel Supply and Storage	
1/2 million lbs. LH_2 per month @ $.70/lb. (3-year supply)	8.4
Rail freight @ $65/ton (Tinker & England AFB)	1.0
4 - 7,600 lb. trailer-trucks @ $150,000 each (Norton AFB)	0.6
4 - 11.8 ton railroad tank cars @ $250,000 each	1.0
500,000 gallon LH_2 storage tank (England AFB)	0.6
TOTAL	**31.6**

The demonstration project would help facilitate a smooth transition from petroleum fuels to alternates as fossil fuels are depleted.

IV. D. Liquid Hydrogen for Large-Scale Air Transportation

Initially, the proposed demonstration will require two aircraft and use hydrogen generated from existing plants. For large-scale use, Johnson analyzed the problem of supplying 2,500 tons of hydrogen per day, enough to supply the fuel capacity for 60 jumbo jets (1).

Johnson considered two domestic sources of hydrogen: (1) coal gasification, and (2) water electrolysis by nuclear-generated electricity, although electricity from other primary energy sources could be used. Table IV-VI summarizes the costs of providing 2,500 tons/day, including suitable transportation and storage tanks. The analysis

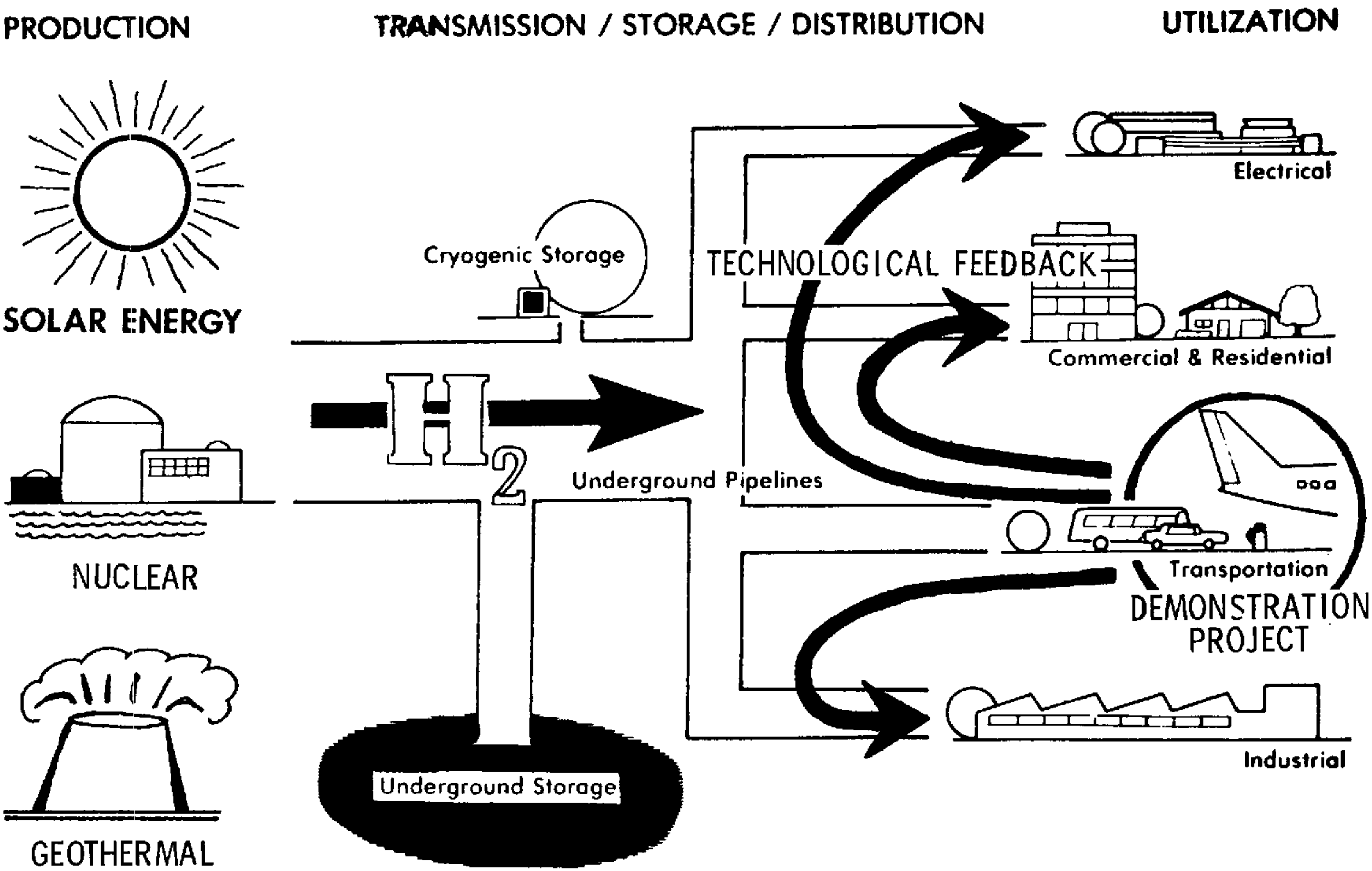

FIGURE 4.7
THE HYDROGEN ECONOMY

TABLE IV-VI

INVESTMENT FOR 2,500 TON/DAY LIQUID HYDROGEN SUPPLY SYSTEM

		Investment Million Dollars
Coal Conversion Process		
Coal Requirements	31,000 Tons/Day, (12,000 BTU/lb.), 31,000 MM BTU/hr.	
Coal Conversion Plant	4 - 400 million CFD H_2 Gas Generators eff. - .58	$ 500
Pipeline—H_2 Gas	1 - 300 Mile, 36" Dia., 900 psi	147
Compressor Stations	2 - 12,000 HP ea. Gas Drive	3
Refrigeration/Air Compression	10 - 125,000 KW - Steam Drive eff. - .65	250
Oxygen Generators	10 - 1,200 T/D Cold Boxes	50
H_2 Liquefiers	10 - 250 T/D Cold Boxes	100
LH_2 Storage Tanks	10 - 12,500,000 Gallon Flat Bottom Tanks	63
Distribution Area	5 - Filling Stations per tank	5
	TOTAL INVESTMENT	**$ 1,118**
Nuplex - Electrolysis Process		
Nuclear Energy Requirements	6,200 Megawatts, 64,000 MM BTU/hr.	
Nuclear Plants	6 - 1,033 MW Reactors - eff. - 33	$ 2,188
Desalination Plants	6 - 1 Million Gallon/Day Units	5
Electrolysis Units	6 - 175 MM CFD H_2 - 820,000 KW ea. train, 1 atm pressure	220
Refrigeration Compressors	10 - 125,000 KW - Electric Drive	125
H_2 Liquefiers	10 - 250 T/D Cold Boxes	100
Barges - H_2 Liquid	8 - 1,100,000 Gallon Barges, 1 day turnaround	20
LH_2 Storage Tanks	10 - 12,500,000 Gallon Flat Bottom Tanks	63
Distribution Area - Docks		15
	TOTAL INVESTMENT	**$ 2,736**

Source: [1]

was based on present technology and included enough hydrogen storage capacity for 15 days (1). The immediate implementation and development of hydrogen production for aircraft and other uses can proceed logically and without interruption from coal to nuclear, and eventually, to solar energy.

Johnson concluded:

(1) Liquid hydrogen can be produced by

conversion of our domestic coal reserves in an environmentally compatible manner for approximately $2.50/MM BTU.

(2) Conversion of our domestic coal reserves to hydrogen aviation fuel could provide significant near-term relief in meeting our growing energy requirements.

(3) Liquid hydrogen aviation fuel offers the best strategy to counter overpricing and overdependence on imported fuels while gaining aircraft exports through continuing technical dominance.

(4) There is no technical or economic prohibition that should impede early development of liquid hydrogen-fueled air transportation.

(5) Thorough system planning is required to permit early economic introduction of liquid hydrogen fuel (1, p. 12).

IV. E. Summary—The Goals of the Demonstration Project

The subsonic hydrogen-fueled aircraft demonstration project would serve as this country's initial step toward the development of a non-fossil fuel economy. Hydrogen appears to be an excellent candidate as the secondary energy source to replace the present fossil fuels, and the sooner research is conducted to evaluate the potential of hydrogen as a fuel, the better the position the United States will be in concerning the nation's overall energy situation. The continuing depletion of fossil fuels will make them more difficult and more costly to obtain, as witnessed by localized gasoline shortages during the summer of 1973 and predicted home fuel oil shortages for the following winter. To predict the exact time at which the country will no longer be able to obtain ample supplies of petroleum is difficult, if not impossible. The immediate initiation of the hydrogen-fueled aircraft demonstration project if successful and followed by a large-scale effort to expand and develop primary energy sources, which do not depend on a dwindling fossil-fuel supply, could substantially accelerate the transition to a "clean fuel era."

The major goals of the demonstration project are summarized below:

(1) It will allow liquid hydrogen to be handled as an aircraft fuel in an operational manner. Also, the practicability of aircraft tank insulation and pressurization systems could be evaluated from the points of view of inspection, maintenance, durability, and performance.

(2) The project will prove the operational advantages of hydrogen in a subsonic airplane (i.e., performance, reduced pollution, and maintenance).

(3) It will show that existing subsonic aircraft can be successfully converted from JP to hydrogen fuel.

(4) A degree of confidence will be established in the minds of the public that hydrogen can be safely used in aircraft.

(5) Should the demonstration project prove highly successful as anticipated, the experience and technology gained will contribute significantly to the design of the next generation of liquid hydrogen-fueled aircraft. Also, some of the innovations and design concepts might be directly applicable to other industries, particularly the other modes of transport such as automobiles and trains. Additionally, there are bound to be technological spin-offs immediately useful to the society as a whole.

(6) The demonstration project would be an important step in diversifying the country's energy supplies. With increasing dependence on imported oil, an immediate effort should be made to be more nearly energy self sufficient. In addition to the balance of payments problem, continued petroleum imports could eventually affect national security. The nation should develop the technology and capability to make a transition to hydrogen as a fuel. Initially, our coal reserves could be used to produce hydrogen, and ultimately clean energy sources, preferably solar and possibly nuclear, would be used.

(7) From an environmental standpoint, hydrogen is excellent. The initiation of this demonstration project could accelerate the realization of a clean environment plus continued technological and the resulting economic growth.

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CONCLUSIONS and RECOMMENDATIONS 5

Three major areas were considered in this study: (A) an analysis of the total energy situation; (B) the effect of the energy problem on air transportation; and (C) a demonstration project for the use of hydrogen as an aircraft fuel.

This chapter will review the major problems encountered for each topic and present conclusions and recommendations concerning their solution.

V.A. The Total Energy Situation

V.A.1 Energy Demand

Americans are energy gluttons; they comprise 6% of the world's population and consume one-third of its energy resources. Demand forecasters predict an ever increasing rate of energy consumption by the United States to a point where, with a 4.0% annual growth rate, energy consumption would more than triple by the year 2000. Related forecasts predict that the demand for transportation fuel will rise at equivalent rates. If this rapid consumption of energy continues without a successful transition to alternate energy sources America will have to face the possibility of further degradation of the environment, waste of natural resources through overdevelopment, and the economic, political, and social consequences of overdependence on foreign sources of fossil fuels. Such overdependence may mean that both national security and the quality of life in America will be jeopardized. Therefore, sensible energy planning must be started now, with the understanding that during the period of transition to alternate energy sources, the equilibrium between energy supply and energy demand may be maintained only by effective energy conservation and regulation. Failure to conserve energy may result in unnecessary human suffering.

V.A.2 Energy Supply

A very large percentage of the energy used in the United States today is derived from a finite supply of fossil fuels, particularly coal and petroleum. Because these supplies are being exhausted rapidly, alternate energy forms must supplement, and eventually replace, fossil-based energy. Greater Federal funding will be required for energy research. In the past almost all energy research funding has been channeled into nuclear energy; now substantial expansion of solar and geothermal energy research is required.

Additional problems arise because all the predicted alternate energy forms at some time require the production of electricity, which is difficult to store and, presently, is not economical to transmit over long distances due to energy losses. Fortunately, hydrogen gas can be produced from water by electrolysis. Hydrogen appears to be a desirable secondary energy source into which primary energy forms can be converted, and it has many of the advantages of petroleum fuels. In addition, hydrogen is clean burning and abundant, and hydrogen technology is now at a state of development where, in some applications, hydrogen can be substituted for petroleum in a short period of time. The development of a hydrogen-energy economy seems both feasible and predictable. Hydrogen could be used as a substitute for natural gas, gasoline and jet aviation fuel. It can also be used as an energy storage medium when produced from off-peak electrical power, and can be transmitted through pipelines over long distances at low cost. Unfortunately, the hydrogen economy is not near at hand; the hydrogen production capacity of the U.S. is low, and it is presently too expensive to compete with fossil-derived fuels.

Interim Research

Because the alternate energy forms will be implemented in the future at different, unknown points in time, it is wise to broaden the use of available fossil fuels as an interim energy resource. There are substantial remaining resources of coal in the United States, at least 200 years at today's consumption rates. Refinement of existing coal liquefaction and gasification processes would help to provide additional synthetic gas and gasoline supplies. Shale oil development should be researched to enable economic chemical processing and to resolve environmental difficulties.

V.A.3 National Energy Policy Recommendation

The United States does not have a national energy policy. In a highly technological and therefore energy dependent society, it is imperative that decisive action be taken to implement such a policy. Therefore, the design team strongly recommends that a comprehensive national energy policy be developed now and be administered by a central agency such as the recently proposed National Energy Commission. The policy should address itself initially to a Government sponsored reassessment of available U.S. fossil fuel reserves and to the diversification of research funding for the development of new sources of energy.

Specific recommendations for such a policy include:

1. A comprehensive research effort into sources of coal, nuclear, geothermal, and solar energy should be organized. Funds should not go almost exclusively to nuclear research but should be expanded into a broader research effort.

2. A program for development of multiproduct coal conversion plants must be intensified to serve the nation's energy needs for the immediate future. Along with this development, research funds should be allocated for improved mining techniques and land reclamation methods. Shale oil development should be studied.

3. The development of solar energy should be given a high priority with emphasis on wind and solar thermal conversion methods initially and ocean thermal gradients and photovoltaic generation for the long term.

4. An extensive research effort should be made to develop a means of deriving hydrogen economically from water.

5. Energy regulation on the basis of BTU consumption should be considered. Rationing of gasoline alone would not solve the problem because petroleum is so entwined with other sources of energy for home, transportation and industrial purposes. A total BTU method of regulation would also be more effective in dealing with problems of pollution and human needs than fiat rationing or taxation of petroleum products.

6. Energy allocation priorities should be established for energy-limited and transition periods to minimize technological problems and human suffering.

7. An adjunct energy conservation plan should be established to coordinate conservation efforts and, more importantly, to establish an energy conservation consciousness in the people of the United States.

8. The Federal Government should establish an energy data bank to provide information necessary for rational policy decisions. A portion of this bank should be devoted to research data on hydrogen.

9. Regional energy centers should be established so that long range planning to develop regional resources could be coordinated efficiently.

10. The Federal Government should undertake an extensive research program to resolve the present impasse between preservation and restoration of the environment and the nation's real energy demands.

Once the guidelines for a National Energy Policy have been established, it will be possible to begin developing a National Transportation Policy which is energy conservation oriented.

V.B. Energy and Air Transportation

The consumption of energy for the transportation of goods and people has averaged, and is expected to continue to average, about 25% of the total annual U.S. energy consumption. Since transportation relies almost exclusively upon petroleum for energy, and since shortages and/or cost increases in the supply of refined petroleum products are a current and future fact of life, there is a need to restructure the decision-making process in the transportation sector of the economy. Historically, energy consumption has been controlled through the market place and this control has been insignificant due to the low cost and relative abundance of fuels. With increasing demand for decreasing supplies of fuels, these costs will probably rise sharply, giving impetus to the development and implementation of energy conservation methods.

V.B.1 Air Transportation Problems

Air transportation is certain to be impacted by the energy problem because: (1) it is 100% petroleum dependent, (2) it is energy-intensive in comparison to other intercity transportation modes, and (3) it has a predicted growth rate much greater than that of any other transportation mode. In addition, airlines suffer from economic problems caused by governmental policies, labor costs, regulation, competition, and capital investment requirements. These factors have caused air travel to be relatively expensive and, consequently, to serve the travel needs of business, middle and upper income groups primarily. Air transportation is also plagued by problems of air congestion, excessive noise, and land use requirements, and ground congestion. Taxation policies also constitute a severe problem, because they do not make users (specifically general aviation users) pay for services rendered. The deficit must be recovered from general tax revenue. To compound this problem, the taxes that are collected are put into the Aviation Trust Fund and withdrawals from it are only authorized for a limited number of uses.

Energy and Air Transportation

The role of energy in air transportation decision making has usually been minimal. Even where energy has been a direct concern, it was usually a concern for fuel availability consumption as a dollar cost—not in the more general sense of concern for energy conservation.

V.B.2 Improved Air Transportation Efficiency

The kind of changes that can lead to better efficiency include such diverse items as allowing people to choose their travel rationally, using advanced transport technology in future aircraft, modifying the CAB subsidy program, flying at lower speeds, making users pay for all costs, reducing the demand for business travel by improving electronic communications systems, and allowing capacity limit agreements among commercial airlines. Analysis shows that there is significant potential for reducing energy consumption in the air transportation sector; but to do so will require cooperative action by the Government, the airline industry, and the users. The Government will need to develop a national transportation policy, in terms of which air transportation can be put in proper perspective. Also, the Congress and the appropriate federal agencies need to alter current regulatory and taxation policies, to strongly promote both energy and economic efficiency. The airline industry needs to be decisively energy conscious. (This consciousness may be forced to some extent as energy becomes more expensive.) Finally, users of all transportation modes need to reflect energy concerns in their decisions about why, where, and how to travel, and they need to tolerate the inconveniences which will occur as the airlines and other modes make the transition to improved systems efficiency.

V.B.3 Air Transportation Policy Recommendation

In summary, energy conservation and greater social benefits can all be affected through the institution of a national transportation policy, the air transportation part of which should include the following recommendations:

1. Government sponsored research should continue toward the development of energy-efficient subsonic aircraft for a wide range of uses, with a reduction in noise and air pollution characteristics.
2. The CAB subsidy program should be modified to force efficiency in air service to small communities.
3. The Federal Government should revise the air transportation tax structure so that general tax revenues are not used to support air travel, and so that the payment of air transportation taxes encourages energy efficiency.
4. To achieve economic and energy efficiency, the CAB should revise its regulatory policies so that the airlines will minimize the duplication of flights and better match aircraft to their intended mission.
5. Airlines should encourage economy and charter flights which will fill airplanes to capacity.
6. Airlines should provide stand-by economy ticketing for the poor and elderly.
7. User tax revenues should be placed in a general Transportation Fund; all allocations from this fund should be based on a National Transportation Plan.

V.B.4 Alternate Fuel

Another approach to alleviating the fossil-fuel energy problem in air transportation is to develop alternate non-fossil aviation fuels. As mentioned previously, one attractive alternate fuel is hydrogen, and the feasibility of this approach is the topic of the following section.

V.C. The Liquid Hydrogen Airplane Demonstration Project

The final focus of this study concerns itself with a demonstration project which might have a major impact on the nation's future energy posture. While the project is limited, it will demonstrate the feasibility of hydrogen as an alternate fuel.

V.C.1 Substantiation of Project

The design team has shown in the body of the report that the airplane has become the chief alternative to the automobile in intercity travel, as well as the principal mode of public transportation for intercity travel. As existing transportation modes depend almost solely on petroleum-based fuels it becomes increasingly important to find an alternate fuel. Hydrogen appears to be the best fuel for the project because it can be derived most readily from predicted future primary energy sources, it is abundant in water and practically non-depletable, and has the additional advantage of being an environmentally desirable fuel with water being its principal combustion product. Further, its low density and high heat of combustion make it a particularly attractive fuel for aircraft.

The technology for storing and transferring liquid hydrogen has been developed to a large extent by NASA, although the two technological problems remaining to be completely reconciled are: (1) the relatively large volume of storage tanks necessary to hold a unit weight of hydrogen and (2) its potential "corrosive" properties, particularly as a high purity, high pressure gas.

The technological competence of the airline industry would make it the logical choice for an impact demonstration. More importantly, hydrogen can be used by energy consumers other than the transportation sector, and the experience and tachnology gained in the demonstration project can be fed back to the appropriate industry and for general consumer benefit.

V.C.2 Project Recommendation

Greater fuel diversification has been indicated as a national need. To facilitate the transition to the widespread use of hydrogen the study team recommends that the Federal Government fund a demonstration project of a liquid hydrogen fueled aircraft. The logical government agency to direct the project would be NASA. The liquid hydrogen fueled aircraft, carrying cargo and/or passengers, would fly to several airports throughout the nation in order to demonstrate the practicality of hydrogen as an energy source. It is recommended that the demonstration project aircraft be a converted C-141 jet airplane. It is recommended that military airports be used while FAA certification regulations for hydrogen-fueled aircraft are being formulated.

V.C.3 Project Cost and Duration

The demonstration project should be started immediately. The duration of the project would be five years, with the estimated cost of the project being thirty-two million dollars.

V.D. Summary

In summary, the design team recommends a comprehensive National Energy Policy which will extend and expand research into energy sources such as coal, shale oil, nuclear fission and fusion, geothermal, and solar. In addition, such a policy should encourage regulation of fossil fuel consumption until adequate alternate energy supplies are developed which will meet strict environmental protection standards.

Within the framework of a National Energy Policy, a National Transportation Policy should be developed which not only would conserve fossil fuels but be consistent with the national goal of serving the human and environmental needs of the nation. Finally, an extensive research program should be initiated to prepare for a hydrogen economy, and a liquid hydrogen fueled airplane demonstration project be initiated immediately.

APPENDICES

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APPENDIX A
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NASA-ASEE ENGINEERING SYSTEMS DESIGN PROGRAM

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APPENDIX B

GUEST LECTURERS

Date	Speaker/Affiliation/Topic
June 11	Dr. Wayne D. Erickson Technical Advisor for Systems Design Team, NASA-Langley "An Overview of the Energy Crisis"
June 12	Mr. Mike Ellis Associate Chief, Hypersonic Vehicles Research Group, NASA-Langley "The Oil Crisis and Aviation Planning"
June 13	Dr. Dwight Baumann College of Engineering, Carnegie-Mellon University "Methodologies for Multidiciplinary Cooperation"
June 14	Mr. Robert Jones Head, Aerodynamics and Heat Transfer Section, NASA-Langley "Liquid Hydrogen as a Fuel for Aircraft"
June 15	Dr. George Szego Intertechnology Corporation "Energy Conservation"
June 19	Dr. Joseph Pettit Georgia Institute of Technology "Trends in Engineering Education"
June 22	Mr. Paul Johnson Director, Energy Trends in Aircraft Fuels Study, OAST "Overview and Direction from the OAST Study on Future Aircraft Fuels"
June 26	Mr. Dal V. Maddalon Aeronautical Systems Office, NASA-Langley "Problems in Civil Aviation with Attention to the Fuel Problem"
July 9	Mr. Derek Gregory Assistant Director, Engineering Research, Institute of Gas Technology "Forecasts of Oil and Gas Supply/Demand
July 11	Dr. Harold Podall U.S. Office of Coal Research, Department of Interior "Current Coal Research"
	Mr. George M. Bennsky Deputy Director of Office of Fuels and Energy, U.S. State Department "International Aspects of the Energy Problem"
July 12	Dr. Joseph Coates Physical Sciences Administrator, National Science Foundation "The Role of NSF in the Energy Problem"
	Dr. William E. Heronemus Department of Civil Engineering, University of Massachusetts "Alternate Energy Sources"
July 13	Mr. Gil Keyes Professional Staff Member, Committee on Aeronautics and Space Sciences of the U.S. Senate "Policy Planning in Civil Aviation: Civil Aeronautics Board"
	Dr. Barry Hyman Resident Fellow, Senate Commerce Committee "Modes of Transportation and Energy Conservation"
	Mr. Ed Morrison Legislative Assistant for Congressman Vanik of Ohio "Civil Aeronautics Board, Subsidies and Feeder Air Carriers"
July 16	Dr. Jack Byrd West Virginia University "Development of an Interactive Simulation Model to Obtain Energy Decision Maker Profiles"
July 17	Mr. Cornelius Driver ASO-ADV Supersonic Technology Office, NASA-Langley "Hydrogen for Aircraft"

July 18	Mr. James Ridgeway Author of *The Last Play* "Impact of the Energy Crisis"
July 26	Mr. John Lichtblau Executive Director, Petroleum Industry Research Foundation, Inc. "Economic and Political Aspects of the Oil Shortage"
August 3	Mr. Richard E. Kuhn Assistant Chief, Low-Speed Aircraft Division, NASA-Langley "The Future of VTOL and STOL as Alternative Transportation Modes
August 7	Dr. Peter E. Glaser Vice President, Arthur D. Little, Inc., Cambridge, Massachusetts "Conversion of Solar Energy in Space to Produce Power on Earth"

APPENDIX C
ACKNOWLEDGEMENTS

Appreciation is expressed to the following persons and organizations for providing material, information and assistance: These individuals are not responsible for any inconsistencies that might be in this report.

Name	Organization
Anton, Paul	College of Business, Ohio University, Athens, Ohio
Anschutz, Richard	Pratt and Whitney Aircraft, West Palm Beach, Florida
Baker, Robert E.	School of Journalism, Ohio University, Athens, Ohio
Beebe, James	Braden Industries, Inc., Broken Arrow, Oklahoma
Betancourt, J.	Combustion Engineering, Co., Windsor, Connecticut
Bower, George	The Boeing Company, Seattle, Washington
Brewer, G. Daniel	Lockheed Aircraft Corp., Burbank, California
Brown, Robert B.	The Boeing Company, Seattle, Washington
Cox, Fletcher	National Business Aircraft Association, Washington, D.C.
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Winns, Peyton	Office of the Assistant Secretary for Policy and International Affairs, Department of Transportation, Washington, D.C.
Witcofski, Robert D.	Hypersonic Vehicles Division, Advanced Aircraft Section, NASA-Langley Research Center, Hampton, Virginia

APPENDIX D
CONVERSION FACTORS

ENERGY

1 kilowatt-hour - 3415 BTU (1 BTU - 2.928×10^{-4} kw-hr)

1 horsepower - hour - 2545 BTU (1 BTU - 3.9×10^{-4} hp-hr)

1 BTU - 1056 joule (1 Joule - 9.47×10^{-4} BTU)

POWER

1 horsepower - 42.4 BTU per min. (1 BTU/min - 0.0236 hp)

1 kilowatt - 1.341 horsepower (1 hp - 0.7457 kw)

MASS AND VOLUME

1 barrel - 42.0 gallons
(1 gal. - 0.0238 barrel)
1 barrel - 5.6146 cubic feet (1 cu. ft. - 0.178 barrel)
  1 ton (short or net) - 2000 pounds
  1 ton (long) - 2240 pounds
  1 ton (metric) - 2205 pounds
1 ton (metric) - 7.454 barrels (36° A.P.I.)
1 barrel - 296 pounds (36° A.P.I.)
1 kilogram - 2.2046 pounds
(1 lb. - 0.0454 kg.)

The chemical energy stored in:

1 gallon of gasoline - 136,000 BTU
1 barrel of crude oil - 5.8×10^{6} BTU

1 ton bituminous coal - 25×10^{6} BTU

1 ton TNT - 4.0×10^{6} BTU
1000 SCF natural gas - 1.013×10^{6} BTU

1000 SCF hydrogen gas - 0.325×10^{6} BTU

Earth's daily receipt of solar energy - 14,100 quadrillion BTU

1 quad BTU - enough energy to keep the autos in the U.S. going for little over one month.

PROPERTIES AND PRODUCTION COSTS OF FUELS

Fuel	Freezing Point (°F)	Boiling Point (°F)	Density (lb/ft³)	(upper) Heat of Combustion (BTU/lb)		PRODUCTION COST (FCST Summary—Sept. 1972) Process	Fuel Cost (¢/10⁶ BTU)
				(BTU/lb)	(BTU/ft³)		
Hydrogen	-435	-423	4.4 (liquid at - 425°F) 0.0051 (gas at 77°F)	61,000	268,000 (liquid) 311 (gas)	Ntl Gas at 40¢/10³ CF Coal at $7/ton Lignite at $2/ton Electrolysis at 8 mils/ kwtt Advanced Tech at 8 mils Off Peak Power at 2.5 mils (Liquefaction	97 132 78 368 233 155 ~150)
Gasoline	-70	258	44 (at 77°F)	20,500	900,000	Petroleum Crude	105
JP4	-290	-250	49 (at 77°F)	18,600	911,000	Petroleum Crude Shale Oil Coal	80-100 ~150 ~150
Methane	-296	-258	26 (at -258°F)	24,000	622,000	Well-head gas LNG, Imported Coal (Liquefaction	15-40 80-100 80-100 ~ 50)
Methanol	-144	148	49 (at 77°F)	10,000	490,000	Ntl Gas at 40¢/10³ CF Coal at $7/ton Lignite at $2/ton H_2 via Electrolysis at 8 mils and CO_2 from air	158 148 ~125 ~550
Ammonia	-108	-28	51 (at -130°F)	9,700	493,000	Ntl Gas at 40¢/10³ CF H_2 via Electrolysis at 8 mils	157 517
Coal	-6330	7500	120 (at 77°F)	14,600	1,750,000		

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APPENDIX F

SURVEY DATA ON PREDICTING FUTURE DEVELOPMENT IN ENERGY AND TRANSPORTATION

A series of questionnaires were completed by members of the NASA-ASEE Design Fellows regarding possible future developments in energy and transportation. The initial survey asked the respondents to make "open-ended" replies to the following questions:

(1) What do you foresee as significant events affecting the energy supply? Between now and 1985?, 2025?

(2) What do you foresee as significant events affecting transportation? Between now and 1985?, 2025?

(3) What do you foresee as significant events affecting non-transportation use of energy? Between now and 1985?, 2025?

(4) What do you foresee as significant political, economic, social or psychological events which will affect energy or transportation? Between now and 1985?, 2025?

Based on initial essay responses, a series of 112 questions were generated. Participants were asked to rate events in terms of certainty during the second round of the survey. The questions covered topics such as energy supply, demand for energy, the oil shortage, future urban and inter-city travel, and political, ecological and social problems related to energy.

From the number of responses to the 112 questions, a third interation was developed based on those questions which while appearing to be significant had not developed any consensus among the respondents.

Following the third interation the results were analyzed. Throughout the process some questions were discarded because they appeared to be poorly worded and other questions were added where it was thought they could clarify responses or could evoke responses to issues that appeared to be significant as our summer project developed.

The results of our analysis are presented below in three parts.

Part A lists those questions in which the events seemed to have "high probability of occurrence."

Part B lists those questions in which the events seemed to have "low probability of occurrence."

Part C provides a narrative summary of the most interesting predictions of the group.

Part A: High Probability Events

If 67% or more of the NASA-ASEE design fellows reported that an event was either "virtually certain" or "probable," the event is referred to as a "high probability event." The "high probability" events are listed below:

(1) In 1985 and 2025 at least 20% of the U.S. energy supply will be derived from coal (includes synthetic natural gas).

(2) In 2025 at least 20% of the U.S. energy supply will be derived from nuclear fission.

(3) In 1985 at least 20% of the U.S. petroleum will be supplied from foreign oil fields.

(4) In 2025 at least 20% of the U.S. petroleum will be supplied from new drilling off the U.S. shore line.

(5) In 1985 at least 20% of the passenger miles for trips of less than 3 miles will be made using petroleum-powered automobiles.

(6) In 2025 at least 20% of the passenger miles for trips of less than 3 miles will be made using mass transit systems (buses, trains, subways).

(7) In 1985 and 2025 at least 20% of the passenger miles for trips of from 3 to 50 miles will be made using petroleum-powered automobiles.

(8) In 2025 at least 20% of the passenger miles for trips of from 3 to 50 miles will be made using mass transit systems (buses, commuter trains).

(9) In 1985 at least 20% of the passenger miles for trips of from 50 to 500 miles will be made using petroleum-powered automobiles.

(10) In 2025 at least 20% of the passenger miles for trips of from 50 to 500 miles will be made using high-speed trains.

(11) In 2025 at least 20% of the passenger miles for trips of from 50 to 500 miles will be made using commerical, subsonic aircraft.

(12) In 1985 and 2025, 20% of the passenger miles for trips of over 500 miles will be made using subsonic aircraft.

(13) In 1985, 20% of the passenger miles for trips of over 500 miles will be made using petroleum-powered automobiles.

(14) By 2025, there will be an occurrence of a major "NASA-type" national program to develop new energy resources.

(15) In 2025 at least 20% of U.S. energy will be transmitted and stored as hydrogen.

(16) By 2025 technological solutions will be found to solve major pollution problems connected with fossil fuels.

Part B: Low Probability Events

If 67% or more of the NASA-ASEE Design Fellows reported that an event was either "possible" or "almost impossible," the event is referred to as a "low probability" event. The "low probability" events are listed below:

(1) In 2025 at least 20% of the U.S. energy supply will be derived from natural gas.

(2) In 1985 at least 20% of the U.S. energy supply will be derived from nuclear fission.

(3) In 1985 and 2025 at least 20% of the U.S. energy supply will be derived from nuclear fusion.

(4) In 1985 at least 20% of the U.S. energy supply will be derived from solar energy.

(5) In 1985 and 2025 at least 20% of the U.S. energy supply will be derived from geothermal energy.

(6) In 1985 and 2025 at least 20% of U.S. petroleum will be supplied from new drilling in the continental U.S.

(7) In 1985 at least 20% of U.S. petroleum will be supplied from oil shale and tar sands.

(8) In 1985 at least 20% of U.S. petroleum will be supplied from coal.

(9) In 2025 at least 20% of U.S. petroleum will be supplied from Alaska via pipeline.

(10) In 1985 at least 20% of the U.S. energy will be transmitted and stored as hydrogen.

(11) In 1985 at least 20% of the passenger miles for trips of less than 3 miles will be made using personal vehicles powered by electricity.

(12) In 1985 and 2025 at least 20% of the passenger miles for trips of less than 3 miles will be made using moving sidewalks.

(13) In 1985 and 2025 at least 20% of the passenger miles for trips of less than 3 miles will be made using human power (walking, bicycles).

(14) In 1985 and 2025 at least 20% of the passenger miles for trips of from 3 to 50 miles will be made using personal vehicles powered by electricity.

(15) In 1985 and 2025 at least 20% of the passenger miles for trips of from 3 to 50 miles will be made using helicopter-like vehicles (VTOL).

(16) In 1985 and 2025 at least 20% of the passenger miles for trips of from 3 to 50 miles will be made using dual mode conveyers.

(17) In 1985 at least 20% of the passenger miles for trips of from 3 to 50 miles will be made using mass transit systems (buses, commuter trains.)

(18) In 1985 and 2025 at least 20% of the passenger miles for trips of from 50 to 500 miles will be made using personal vehicles powered by electricity.

(19) In 1985 at least 20% of the passenger miles for trips of from 50 to 500 miles will be made by high-speed trains.

(20) In 1985 and 2025 at least 20% of the passenger miles for trips of from 50 to 500 miles will be made using personal airplanes.

(21) In 1985 and 2025, 20% of the passenger miles for trips of over 500 miles will be made using supersonic aircraft.

(22) In 1985 and 2025, 20% of the passenger miles for trips of over 500 miles will be made using hypersonic aircraft.

(23) In 1985, 20% of the passenger miles for trips of over 500 miles will be made using high-speed trains.

(24) In 2025, 20% of the passenger miles for trips over 500 miles will be made using petroleum-powered automobiles.

(25) If the real price of petroleum used for transportation doubles in 1985 it would result in a reduction in auto use of 20%.

(26) If the real price of petroleum used for transportation doubles in 1985 it would result in a reduction in air travel of 20%.

(27) If the real price of petroleum used for transportation doubles in 1985 there would be an increase of 20% in the use of human power (walking, bicycles).

(28) In 1985 and 2025 the Federal government will intervene through the relaxation of anti-trust laws to permit mergers and limitations of competition in energy industries.

(29) In 1985 the Federal government will nationalize the energy industries.

(30) Federal government subsidies to consumers will encourage use of energy-efficient modes of travel by 1985 and by 2025.

(31) Federal government intervention will ban automobiles in major cities by 1985.

(32) Environmental standards will be lowered to permit exploitation of U.S. energy resources by 2025.

(33) Public concern for the preservation of the environment and support for the efforts of environmental groups will be inflexible by 2025.

(34) A major reactor accident will result in at least 1000 deaths by 1985.

(35) There will be a cut-off in the supply of oil from the Middle East.

(36) There will be a cartelization of the marketing of strategic minerals controlled by underdeveloped nations by 1985.

(37) There will be an abandonment of inner cities by 1985 and by 2025.

(38) There will be a general deterioration in standard of living for majority of U.S. citizens by 1985.

(39) The energy crisis will be resolved through the application of laws and government regulation by 1985 and 2025.

(40) By 1985 and 2025 improved communications (picture-phone for example) will provide a substitute for travel so that there will be a 20% reduction in travel demand.

(41) By 1985 a major technological breakthrough will occur so that the energy problem will be solved.

Part C. Summary and Conclusions of Survey

1. Energy Sources

An analysis of the group's responses in the area of energy indicate a belief on the part of the participants that at least 20% of the U.S. energy in 1985 will be supplied by the following source: coal (including natural gas). By 1985, 20% of the U.S. energy **cannot** be supplied by nuclear fission or any of the other "new" energy sources such as solar, geothermal, etc. The group does believe that by 2025 nuclear fission will supply at least 20% of the energy in the U.S. However, the group indicates that natural gas will no longer supply 20% of the energy, nor will either nuclear fusion nor solar energy nor geothermal provide as much as 20% of the energy by 2025.

2. Fuel Source

It is predicted that 20% of U.S. petroleum by 1985 will be supplied from foreign sources and that by 2025—at least 20% of the petroleum will be supplied by new offshore drillings. However, the group believes that new drilling in the continental U.S. cannot supply 20% of the petroleum in either 1985 or 2025. Furthermore, the group does not see oil shale and tar sands or coal as a source of petroleum by 1985. There is agreement that by 2025 the Alaska oil will no longer provide 20% of the petroleum.

One further note on fuel—while there was agreement that hydrogen would not be an alternate fuel source by 1985, there was concensus however that by 2025 at least 20% of the U.S. energy will be transmitted and stored by hydrogen.

3. Transportation

Regarding air travel, the group sees that by 1985 the airplane will provide 20% of the passenger miles for trips over 500 miles and by 2025 20% of the passenger miles for trips over 50 miles. However, this will be done by subsonic aircraft; the group was in agreement that neither supersonic or hypersonic aircraft would supply as much as 20% of the passenger miles for trips over 500 miles. There was also concensus that the more exotic forms of transportation (such as moving sidewalks and "dual mode" transportation) will **not** become significant forms of transportation by the year 2025.

There seems to be a concensus that in the near future (1985) the various modes of transportation will not be drastically changed; very substantial changes however, are predicted by 2025. The group sees a significant increase in the use of mass transit for trips of less than 50 miles and a large increase in the use of high speed travel for distances between 50 to 500 miles. The group does nevertheless see the automobile as still providing about 20% of the travel of less than 50 miles.

4. Other Predictions

The group did believe that by 2025 there would be a crash program to develop new energy sources and that technology will solve major pollution problems connected with fossil fuels.

There does seem to be a concensus that the government will not take drastic action such as barring the automobile from major cities or nationalize the energy industry by 1985, although there was no concensus by 2025 that they would either occur or not occur.

The group seems rather optimistic in that they do not foresee a cut-off of Middle East oil supplies nor will they see an abandonment of the inner city by either 1985 or 2025.

However, the group sees the energy crisis as potentially very alarming in spite of the fact that there is concensus that there **will not** be a general deterioration of the standard of living for the majority of U.S. citizens by 1985; there is no concensus concerning the U.S. living standard for the year 2025.

Furthermore, there is a remarkable concensus that for the foreseeable future (up to 2025) the energy crisis will not be resolved through the application of laws and governmental regulations.

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APPENDIX G

ORGANIZATION OF STUDY TEAM

A. Preliminary Study

In order to attain the goals of the project within an eleven-week time frame, the design study was organized into various phases. Participants were divided initially into the following two basic groups for preliminary study.

Group A (Demand)	**Group B (Supply)**
A. H. Jacobs, Chairman	W. A. Barkley, Chairman
M. Avila	B.S. Cooper
M.D. Devine	C.R. Dyer
J.J. Evangelista	R.A. Fiedler
C.A. McCoy	M.L. Hailey
T.G. McRae	C. Kuo
A.J. Patton	R.S. Pappa
M.Z. Sincoff	D.T. Pederson
J.M. Veigel	L.K. Rothberg
P.C. Wolff	W.K. Talley

B. Group Assignments for In-Depth Study

Following two weeks of preliminary investigation, the design team was reorganized into six task groups to study the following specific areas:

Task Group I—Consumption Facts/Forecasts (Demand)

A.H. Jacobs, Chairman
M. Avila
M.D. Devine
J.J. Evangelista
M.L. Hailey
C.A. McCoy
T.G. McRae
A.J. Patton
M.Z. Sincoff
J.M. Veigel
P.C. Wolff

Task Group II—Known Energy Resources (Supply)

B.S. Cooper, Chairman
W.A. Barkley
C.R. Dyer
R.A. Fiedler
M.L. Hailey
C. Kuo
R.S. Pappa
D.T. Pederson
L.K. Rothberg
W.K. Talley

Task Group III—Alternate Energy Sources

J.M. Veigel, Chairman
B.S. Cooper
C. R. Dyer
J.J. Evangelista
C. Kuo
D. T. Pederson
M. Z. Sincoff

Task Group IV—Socio-Politico-Economic Obstacles To Alternative Energy Sources

M.Z. Sincoff, Chairman
M. Avila
W.A. Barkley
M.D. Devine
R.A. Fiedler
C.A. McCoy
A.J. Patton
L.K. Rothberg
W.K. Talley
J.M. Veigel
P.C. Wolff

Task Group V—Human Needs

P.C. Wolff, Chairman
W. A. Barkley
C. R. Dyer
A. H. Jacobs
M. Z. Sincoff

Task Group VI—Aircraft/Hydrogen Fuel Transition

T.G. McRae, Chairman
R.A. Fiedler
R.S. Pappa
A.J. Patton

As the project evolved, it became apparent that additional areas needed to be investigated and, as a result, the following new groups were added:

Task Group VII—Reduced Demand

M.D. Devine, Chairman
B.S. Cooper
C.R. Dyer
M.L. Hailey
C.A. McCoy
M.Z. Sincoff
P.C. Wolff

Task Group VIII—Fuel Diversification

R.A. Fiedler, Chairman
W.A. Barkley
C.R. Dyer
J.J. Evangelista
A.J. Patton
D.T. Pederson

Task Group IX—Improved Airplane Fuel Efficiency

T.G. McRae, Chairman
M.D. Devine
A.H. Jacobs

Task Group X—Improved Airline Systems Efficiency

M.L. Hailey, Chairman
B.S. Cooper
J.J. Evangelista
A.H. Jacobs
C.A. McCoy
M.Z. Sincoff
J.M. Veigel
P.C. Wolff

Task Group XI—Demonstration Project

A.J. Patton, Chairman
M. Avila
W.A. Barkley
J.J. Evangelista
R.A. Fiedler
T.G. McRae
R.S. Pappa
W.K. Talley
J.M. Veigel

C. Chapter Coordinators

As the efforts of the Task Groups neared fruition, their results were systematically incorporated into the major sections of this report. The following chapter coordinators were responsible for the organization of this material:

Special Recommendations..........................J.J. Evangelista
I. The Energy Situation....................................A.H. Jacobs
II. The Air Transportation/Energy System.....C.A. McCoy
III. Energy Conservation and Air Transportation ....J.M. Veigel
IV. An Initial Step—
A Demonstration Project ............................A.J. Patton
V. Conclusions and Recommendations .......W.A. Barkley
Appendices ....W.K. Talley

D. Standing Committees

During the last four weeks of the project, the following standing committees were established:

Editorial Committee

C. R. Dyer, Editor-in-Chief
M. Z. Sincoff
P. D. Cribbins

Illustration Committee

D. T. Pederson
R. S. Pappa

Oral Presentation Committee

M. Z. Sincoff, Chairman
W. A. Barkley
B. S. Cooper
M. D. Devine
M. L. Hailey
R. S. Pappa
A. J. Patton
D. T. Pederson
W. K. Talley

APPENDIX H
SOME DIGRESSIONS

I

THERE ONCE WAS A GROUP NAMED OPEC,
WHICH HELD MOST OF THE CARDS IN THE DECK,
THEY RAISED PRICES AT WILL
(AND THEY'RE DOING SO STILL)
WHILE THE REST OF US PICK UP THE CHECK

II

A STEWARDESS FROM BOSTON, MASS.
(A CONSERVATIVE, FORESIGHTED LASS)
INCREASED HER LOAD-FACTOR
THE C.A.B. BACKED HER
SHE GOES FARTHER NOW—USING LESS GAS.

III

THE INGENIOUS SHAH OF IRAN
SELLS CRUDE OIL AS FAST AS HE CAN
HE BUYS GUNS AND TANKS
FROM HIS GOOD FRIENDS THE YANKS
AND SWAPS SPARE PARTS WITH MOSHE DAYAN

APPENDIX I
ADDITIONAL RECOMMENDATIONS

Two categories of recommendations were generated during the study: those which are supported by textual material and those which due to lack of time are not supported by textual material. Furthermore, each of the two categories had recommendations which were not supported by a majority of the group membership. Nevertheless, it is felt that these ideas are significant and merit further study.

1. Following are those recommendations which appear in the text but do not have the support of the majority of the study group:
   - Energy should be regulated using a BTU credit card system, as part of a national energy conservation program.
   - Fossil fuels should be reserved for chemical uses.
   - The Government should sponsor an advertising campaign to reduce air travel.
   - A national travel service should be established to supply travelers with information concerning transportation modes, travel times, energy use and cost.
2. The following recommendations are not supported by text material but have the support of the majority of the group and it is recommended that these topics be investigated:
   - Labeling of energy requirements for all new appliances should be required.
   - Utility rates should be restructured to encourage energy conservation.
   - Priorities for the allocation of energy should be established for energy-limited periods, and rationing imposed where necessary.
   - Federal support for research and development of nuclear energy should be scaled down.
   - Development of rail travel should be supported.
   - NASA should take the initiative to establish a clearinghouse for the exchange of information on hydrogen research.
   - Increased revenue to support alternate fuel research should be supplied by an additional tax on gasoline.
   - NASA should develop an accurate low-cost fuel consumption meter for automobiles.
3. Recommendations which are not supported by text material and did not receive the support of the majority of the group but may be feasible ideas are listed below:
   - Travel by government employees should be limited.
   - A national speed limit should be established to conserve fuel.
   - The nation should begin a program of modest stockpiling (30 days supply) and reserve capacity of fossil fuels.

APPENDIX J
ECONOMIC ASPECTS OF HYDROGEN PRODUCTION

by M. Avila

As is commonly known, the production of hydrogen is not new. Hydrogen was already being produced by the turn of the century. Marchetti notes that as early as 1927, engines had been adapted to burn hydrogen.[1] Until the 1950's, however, it played an inconspicuous role, except for the 1930's when it came into momentary preeminence. In 1956 the space program started a new phase, more specifically, the production of liquid hydrogen. Since then it has been used to power the Centaur SII and SIV space vehicles and is being used in the Apollo/Saturn V program. The technology of hydrogen production as well as its economic viability have been well established. In what follows, certain economic aspects of hydrogen production are considered within the context of the fossil-fuel shortage.

On purely theoretical grounds, one can expect that the production of hydrogen would exhibit the characteristics of other industrial products, i.e., decreasing average cost with respect both to time and increases in volume. In practice this has been the case. Data for the last few years show that the price decreased as capacity expanded.

A word of caution may be inserted at this point. There is no organized exchange market for hydrogen, therefore, discrepancies of fact originate from different sources. Quoted prices are not spot prices; more often than not they are based on contractual arrangements. With this in mind, it still appears that the price-time relationship of liquid hydrogen production has shown the trend given by the following table.

TABLE J-I
INSTALLED CAPACITY AND PRICES OF LIQUID HYDROGEN
1952-1971

Year	Capacity (tons/day)	Price ($/lb.)
1952	—	18.00
1954	—	10.00
1956	—	5.00
1958	—	1.75
1959	—	1.25
1960	7	.60
1962	37	.42
1963	73	.34
1964	127	.28
1965	157	.20
1966	162	—
1970	150	—
1971	—	.17
1973	103[a]	—

[a] As of July.

Data sources: John E. Johnson, *Economics of Large Scale Liquid Hydrogen Production,* Paper presented at Cryogenic Engineering Conference University of Colorado, June, 1966; 1973 data from Linde, Air Products and Chemicals, Inc., and NASA.

The figures clearly show the tendency for price to decline with time. In a period of approximately twenty years, the price has gone down from $18 a pound in 1952 to approximately $0.165 a pound in 1971. The information is plotted in Figure J-1.

As far as capacity is concerned, a distinction may be made between total hydrogen production and production of liquid hydrogen. The production of hydrogen as a distinct chemical product is old. Furthermore, it is

[1]C. Marchetti, "Hydrogen and Energy," **Chemical Economy and Engineering Review,** January, 1973, p. 13.

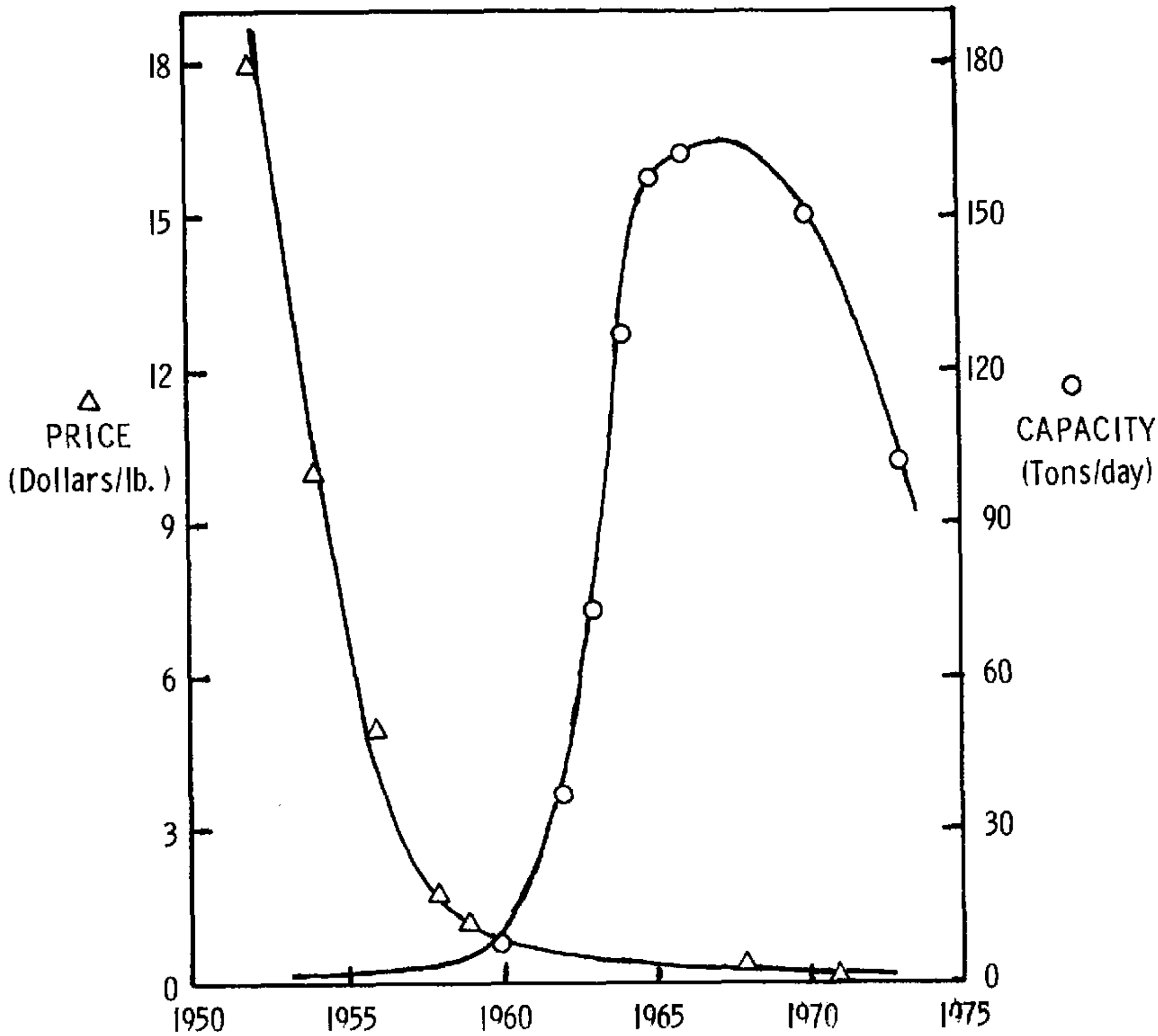

FIGURE J-1
LIQUID HYDROGN PRODUCTION: PRICE AND CAPACITY
1950-1973
Data from Johnson, J. E., "Economics of Large Scale LH[2] Production"; Linde; Air Products; Airco; and NASA

relatively large. Gregory reports the 1960 total production of hydrogen as 3.8 billion pounds, a figure that had already climbed to 12 billion pounds in 1968.[2] It is also noted that most hydrogen is produced in the catalytic steam reforming of hydrocarbons and that more than 95 percent of the total production is used on site to manufacture ammonia, methanol, and other refined petroleum fuels and chemicals. The other 5 percent is sold as an industrial gas. By comparison, the capacity figures for liquid hydrogen shown in Table J-1 are quite small. If the 7 tons/day figure for 1960 is converted to an annual figure and taken as a percentage of the total mentioned above, the resulting figure is only 0.13 percent. On a worldwide basis the production of liquid hydrogen in 1968 amounted to between 200 and 400 tons/day, most of it being used as rocket fuel. Of course one could consider liquid-hydrogen production as an industry separate from the production of

[2]D. P. Gregory, D. Y. C. Ng, G.M. Long, **Electrolytic Hydrogen As A Fuel (Chicago: Institute of Gas Technology, January, 1971), p. 8. Some of the price-capacity data quoted in what follows were obtained from Mr. R. D. Witcofski, NASA, LRC. See also his "Hydrogen Fueled Hypersonic Transports," Paper presented at the American Chemical Society Symposium on Non-Fossil Chemical Fuels, Boston, April 1972 and "potentials" and Problems of Hydrogen Fueled Supersonic and Hypersonic Aircraft," paper presented at the Seventh Intersociety Energy Conversion Engineering Conference, San Diego, September 1972.**

hydrogen in general. In this case one would date its origin in the late fifties, with two companies dominating the field (Union Carbide and Air Products),[3] even though prior to this time the Air Force operated some rather small plants.[4] Until 1966 the demand for hydrogen did go up. Since then the largest and most efficient installation (Union Carbide's plant in Sacramento with a capacity of 60 tons/day) has gone out of operation due to lack of demand, thus reflecting instability in the industry.

To better understand the price changes shown by Table I, the discussion is shifted from the aggregate level to the level of the firm. Figure J-2 portrays a 1971 volume-price relationship for a 30-ton capacity plant.

The price (f.o.b. plant) for this particular supplier ranges from a high of).69/lb. if the monthly volume to be supplied is 250,000 lb., to a low of $.165 if the volume is 1.8 million lb. That this should be the case is of course explained by economies of scale. In 1971, NASA could purchase large volumes of liquid hydrogen at an average weighted price of $.165 per pound. If, fore example, the demand from one buyer averages between two and four million pounds per month—as has happened at various

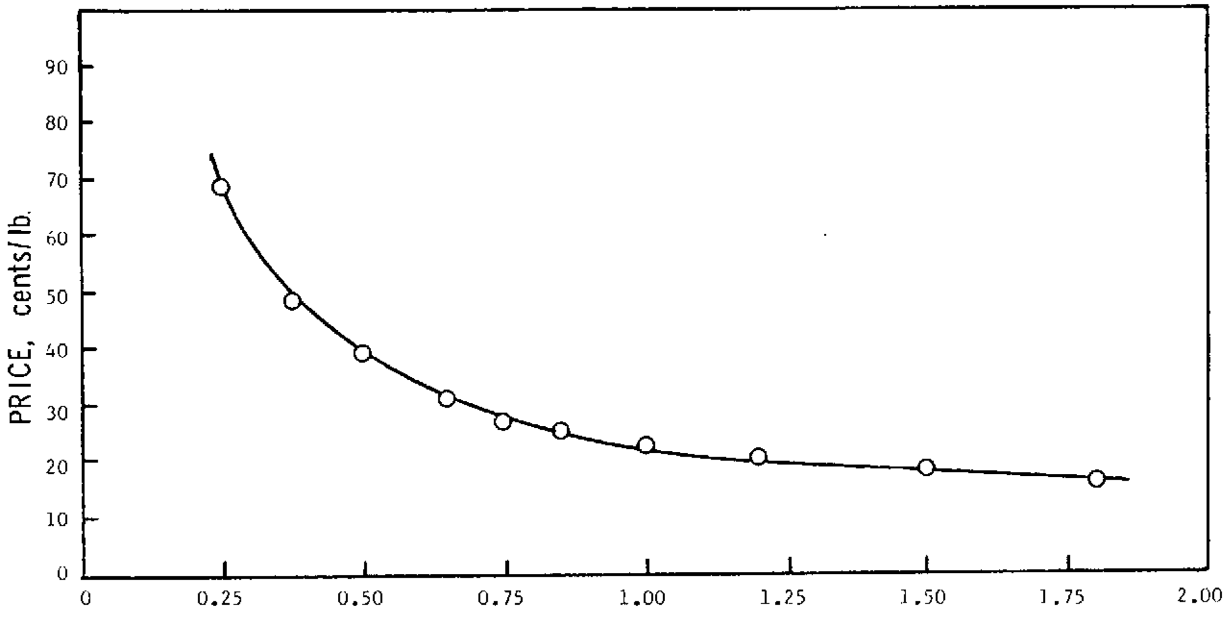

FIGURE J-2
LIQUID HYDROGEN PRICE-OUTPUT RELATIONSHIP

times in the past—the price would be as low as $.16-$.20/lb. The converse would be the case on low volumes. Currently (summer, 1973), part of the combined NASA-DOD demand amounts to some 250,000 lb. per month and, therefore, the price runs around $.44/lb., f.o.b. plant—or around $1/lb. delivered to Kennedy Space Center.[5]

Other factors, besides economies of scale, affect the price. Among them, the location of the buyer (and seller), the nature of the market, and the amortization policy.[6]

Given the present location of the plants[7] and the prices quoted above the cost of delivery can exceed the f.o.b. plant price. Then, the market has monopsonistic elements. The behavior of one or two institutional buyers cannot only raise or lower the price, but can influence the entry or exit of firms in the industry. Lastly, and depending of course on all other factors, it is possible to obtain a lower price from a supplier whose plant is fully amortized. Concerning the 1973 price of $.44/lb., it may be maintained that it reflects the fact that a small volume is being produced and that with increased output liquid hydrogen could still be purchased at prices in the $.17-$.20/lb. range.

The situation concerning JP-4 is definitely one of rising prices. Its 1970 price was $.09/gallon; it jumped to $.095 in 1971 and in 1973 it has been around $.115/gal.[8] Furthermore, nobody seriously believes that this trend is going to be reversed, therefore, if it is assumed that the function in Figure 1 for hydrogen will remain monotonic, it

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[3]**Lawrence Lessing, "The Coming Hydrogen Economy," Fortune,** November, 1972, p. 140.

[4]See John E. Johnson, op. cit., p. 11

[5]Another supplier reports similar prices: $.44/lb., f.o.b. plant, and $.69/lb. delivered.

[6]A more detailed cost analysis is presented in what follows.

[7]The location (and capacity) of the plant is the following: Long Beach, Cal. (30); Fontana-Ontario, Cal. (30); New Orleans, La. (30); Ashtabula, Ohio (7); Pedricktown, N. J. (6).

[8]Michael L. Yaffee, "DOD, Airlines Face Energy Crisis," **Aviation Week and Space Technology,** November 20, 1972, pp. 54-55.

is not unreasonable to expect that at some future time the situation may reverse itself, hydrogen becoming the cheaper fuel. The conditions under which this would take place are examined in the following table.

TABLE J-II
COMPARATIVE PRICES OF HYDROGEN AND JP-4

H_2 Price		JP-4 Price	
¢/lb.	$/10[6] BTU	¢/g.	$/10[6] BTU
35	6.78	15	1.22
30	5.81	14	1.14
25	4.84	13	1.06
15	2.91	12	.98
10	1.94	11.5	.94
9	1.74	11	.89
8	1.55	10.5	.85
7	1.36	10	.81
6	1.16	9.5	.77
5.5	1.07	9	.73
5	.97	8.5	.69
4.5	.87		
4	.58		

Units: 51,600 BTU/lb. for H_2
123,000 BTU/g. for JP-4

Plotting some of the above data the conditions under which hydrogen would become the cheaper fuel can be seen more clearly.

If the price of hydrogen is $.165 per pound and the price of JP-4 is $.115 per gallon, then hydrogen is more costly: $3.20 per million BTU against $.94 for JP-4. Given the different slope of the lines, however, hydrogen could be the cheaper fuel for certain range of prices. Figure J-3 illustrates one possibility. In the case of hydrogen, a price of $.043 per pound is equivalent to $.83 per million BTU, which is the same cost if the fuel is JP-4 at a price of $103 per gallon. Thus, if JP-4 were to remain at the latter price, *hydrogen would have the advantage at prices below* $.043/lb. In fact, this advantage would remain even if JP-4 were also to decline in price. Beyond the crossover point the advantage would of course lie with JP-4. Thus the question is, given the aforementioned price trends for these two fuels, under what conditions is hydrogen likely to become the cheaper fuel? It is likely that the average cost curves have the shape shown in Figure J-4?

To answer the question some considerations must be given to the method of production. At the present time, the raw material most commonly used for both fuels is hydrocarbons (natural gas and oil). A case can be made for the fact that the main factor that explains the increase in price of JP-4 is the increase in the price of the raw *material (oil). Until the late 1960's, the average price of* crude oil remained below $3/barrel at the well, but in January, 1972, the price was up to $3.75. The same situation prevails in natural gas. In 1965, the weighted average price (including old and new contracts) was $.156 per 1,000 of at the wellhead, but, in 1972, this figure had climbed to $.21 per 1,000 €f. So far as the future is concerned the price trends of these fuels are not likely to be reversed, and it is questionable whether the two curves would intersect if in both cases the same raw material is used. A more likely case is one where the JP-4 average cost curve turns up without intersecting the hydrogen curve. Economies of scale are not likely offset a price differential of three to one.[10]

The situation is different if the feedstock for hydrogen is neither gas nor oil, an alternative with much merit within the context of the energy crisis. To facilitate the discussion, the costs of hydrogen will be broken down following the manufacturing process from raw material to finished product. The following stages will be considered: gas production, liquefaction, transmission, storage, and distribution. As the discussion proceeds, the costs will also be broken down as capital-operating costs, and fixed-variable costs.

Concerning the first step, the production of gaseous hydrogen, the most important cost factors are the manufacturing method employed, which is of course interrelated with the required raw materials (including electric power), and plant size. So far as the method of production is concerned, it may be noted that at every step of the process, from the selection of the raw materials to the method of handling and storage,

[9]Gilbert Burck, "The FPC is Backing Away from the Wellhead," **Fortune**, November, 1972, pp. 109-11. For oil and natural gas prices going back to 1880 see Sam H. Schurr, et. al., **Energy in the American Economy, 1850-1975,** (Baltimore: Johns Hopkins Press, 1960), pp. 546-48. See also Office of Emergency Preparedness, **Report on Crude Oil and Gasoline Price Increases of November 1970,** April, 1971, Annex C.

[10]$3.20 per million BTU against $0.94 as indicated on page 7.

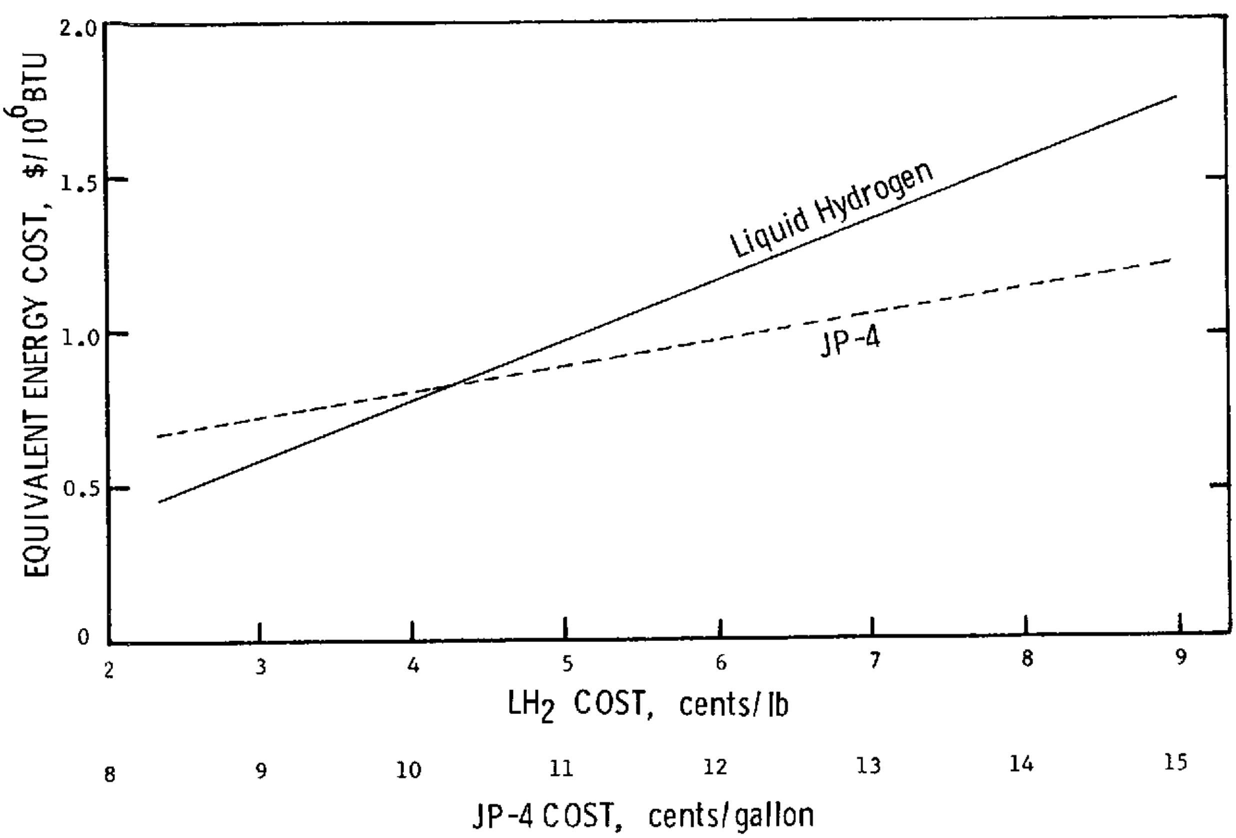

FIGURE J-3
LIQUID HYDROGEN - JP4 FUEL COST COMPARISON

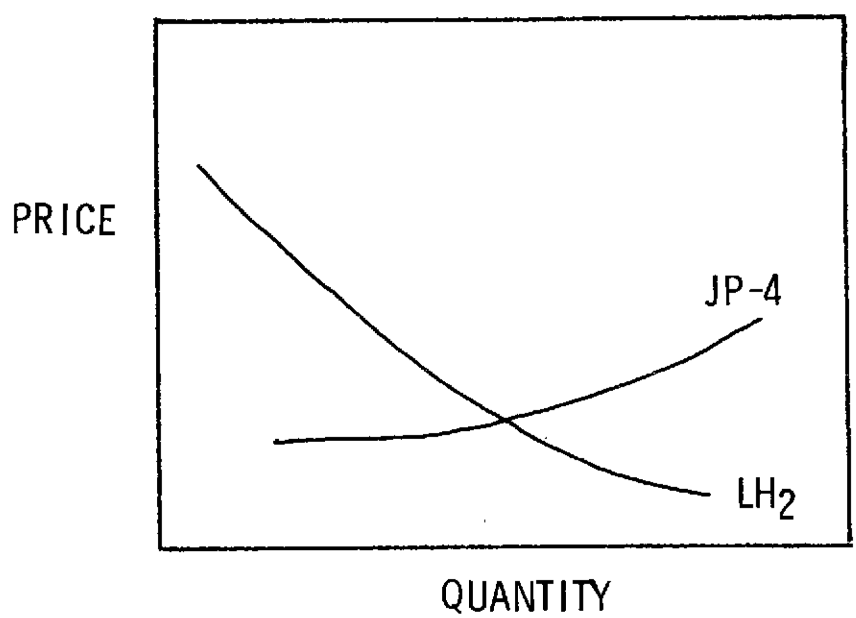

FIGURE J-4
HYPOTHETICAL PRICE-QUANTITY RELATIONSHIP
FOR LIQUID HYDROGEN AND JP-4

technological variations are possible and, therefore, variations in cost will result. It should also be mentioned that while in times of relative price stability cost estimates will, by definition, undergo minor change, and certain caution must be exercised when cost estimates made at different times are compared. What may have been a reasonable cost estimate in 1967, particularly if it were made in current dollars, may need careful revision in 1973.

Another consideration to be kept in mind is the location of the plant. This is important, not only because it affects transportation costs, but also because local costs (real estate, electric power, raw materials, local taxes, etc.) vary between locations.

In what follows attention will be centered primarily on hydrogen, but liquid methane and liquid propane will also be considered, using as a point of reference the current and foreseeable price of JP-4. The costs of three methods of production will be discussed: steam reforming, using natural gas as the feedstock, and coal gasification, using both lignite and bituminous coal as the feedstocks. Comparisons will be made with the partial oxidation, the water electrolysis, and the hydrogen halide processes.

Some of the previous studies on the economics of liquid hydrogen production have been directed toward a specific question. For instance, what are th liquid hydrogen requirements for an HST network that would be operational in the 1980's? Or, what are the liquid hydrogen propellant requirements for the NASA shuttle program? This discussion is also specific in that it is applicable to the demonstration project suggested in chapter IV of the report—but it is at the same time more general. It raises the question of economic feasibility, the matter of specific application being a corollary. There are various reasons for following this approach, reasons that will be made clear as the discussion proceeds.

If, as a point of departure, one considers Johnson's price of liquid hydrogen of $.21/lb for the largest plant ever built (60t/d) under a fully loaded system,[11] what plant size would cut this cost in half? At this figure liquid hydrogen would probably begin to be competitive with JP-4. Using the relationship

$$\text{Total Cost} = [\text{Rate of Production}]^{3/4}$$

as a rough guideline, it can be established that the rate of production would have to be increased from 60t/d to 960t/d.[12] Therefore, using a plant with a capacity of, say 1,000t/d, what are the costs of production?[13]

Examining investment costs first, it is assumed, for purposes of evaluation, that the plant is to be built in New York City and that it is designed with a capacity of 1,000t/d for 365-day/year operation.

Investment costs are considered in two stages: gaseous hydrogen production and purification, and liquefaction. Use is made of Williams' formula, which, as Hallett notes, [14] is applicable to chemical industries.

It states that

$$X = I\left(\frac{C}{C_B}\right)^M$$

WHERE
X = Investment cost
I = Investment cost of base plant
C = Capacity of desired plant in t/d
C_B = Capacity of base plant in t/d
M = Scale factor.

Furthermore, following Hallett's analysis, [15] the capacity of the base plant is taken to be 250t/d, the value of C being 1,000t/d.

The estimated I and M constants are

	Steam Reforming	**Coal Gasification**	
		Lignite	**Bituminous**
I ($)	7.65×10^6	16.9×10^6	20.8×10^6
M	0.7	0.7	0.7

Therefore, the capital investment costs for gaseous hydrogen production are

Steam Reforming	**Coal Gasification**	
	Lignite	**Bituminous**
$20,188,000	$44,599,000	$54,891,000

Adding the investment costs for the liquefaction plant, the relevant constants are

$$I\ (\$) = 31.5 \times 10^6$$
$$M = 0.8$$

Therefore, the investment cost amounts to $95,490,000. Adding both costs yields the total investment costs as follows:

Steam Reforming	**Coal Gasification**	
	Lignite	**Bituminous**
$115,678,000	$140,089,000	$150,381,000

To arrive at an annual investment charge two adjustments must be made, one for plant location and a second one for amortization. For the first the adjustment factor developed by the Department of Defense can be employed; in the case of New York City it is 1.3, Washington, D.C. being 1.[16] The investment costs become $150,381,000 for steam reforming, $182,115,000 for lignite and $195,495,000 for bituminous coal.

As mentioned before, the amortization policy can have a significant effect on the price of the product. This is illustrated with the aid of Figure J-5 which was estimated for a 60t/d plant but which nevertheless brings out the relation between amortization and unit cost.[17]

The curves of course illustrate the effect that plant utilization can have on average cost, but it can also be seen that the amortization rate is no less significant. At full capacity the difference in cost can be as large as $.10/lb; at less than full capacity the difference increases. The problem is that in recent years plants have been built on the basis of short term contracts and, therefore, amor-

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[11]John E. Johnson, **op. cit.**, Figure 10, p. 20.

[12]See C. Marchetti, **op. cit.**, p. 16.

[13]In some of the studies done for NASA a capacity as large as 2,500 t/d has been used in the cost estimates of liquid hydrogen production. See N.C. Hallett, **Study, Cost, and System Analysis of Liquid Hydrogen Production, Summary Report,** NASA, June 1968. See also his **Final Report** under the same title and date. Darrell E. Wilcox and Cynthia L. Smith, "Future Cost of Liquid Hydrogen for Use as an Aircraft Fuel," NASA Working Paper, OART, Mission Analysis Division (Moffett Field), April 1968, summarize Hallett's results.

[14]N. C. Hallett, **Final Report,** p. 12.

[15]The parameters used in the computations are taken from Hallett's **Summary Report,** Section 3, pp. 9-20.

[16]See N. C. Hallett, **Final Report,** p. 151.

[17]See also Figure III-2. Data taken from J.W. Terbot, "Liquid Hydrogen Propellant Logistics Study," NASA Contract NAS8-25147, March 1970, figures B-7 and B-8, pp. 36, 37.

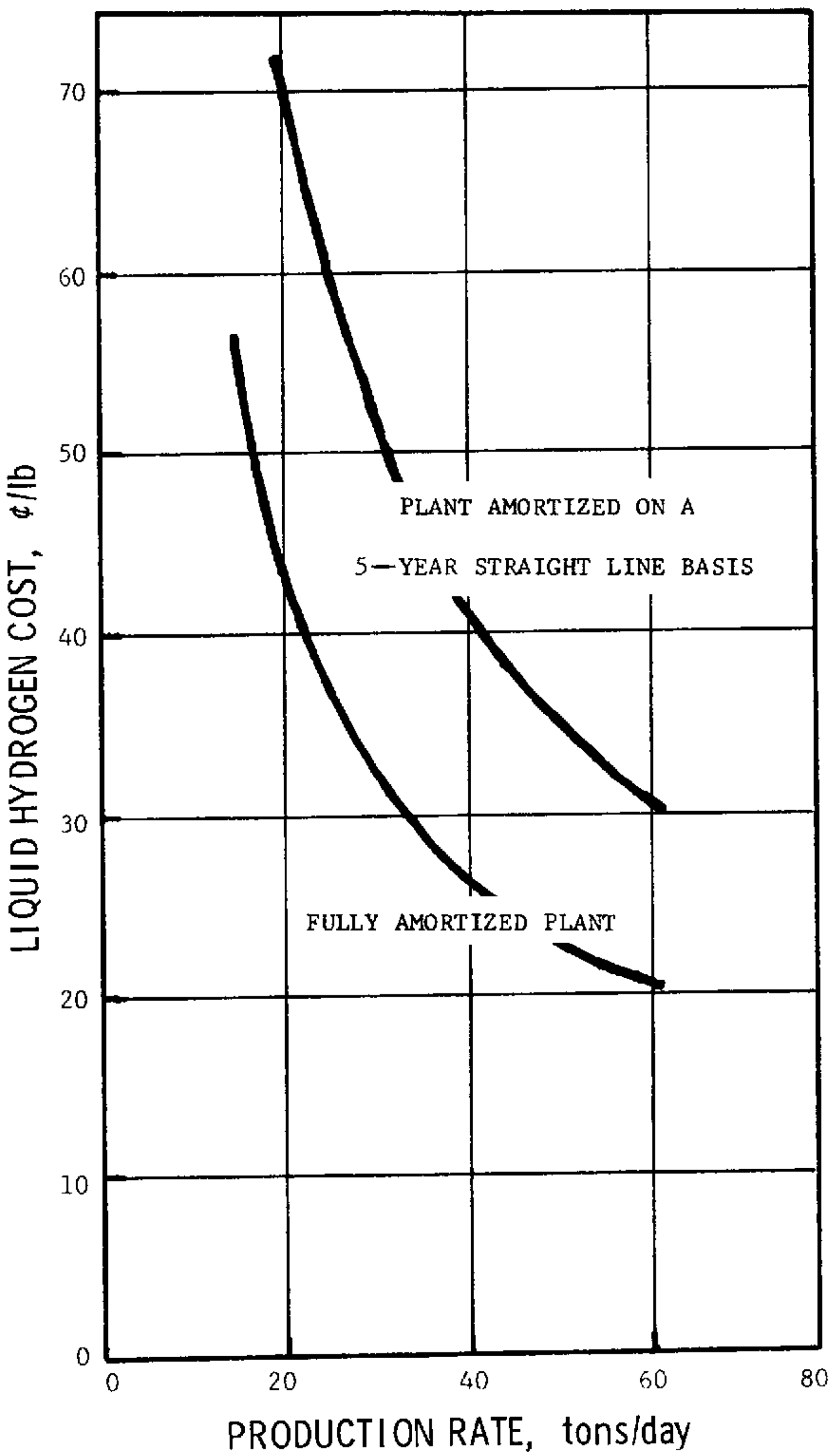

FIGURE J-5
LIQUID HYDROGEN PRODUCTION COSTS
AT KENNEDY SPACE CENTER - (60 tons/day plant)
Source: Terbot, J. W., "Liquid Hydrogen Propellant Logistics Study," 1970

tization rates of 20 percent have been acceptable. What happens if, to reflect a more stable market, a longer amortization period is introduced, say 15 years? Amortization on a straight line basis would call for a rate of 6.67 percent per year, a rate which would have a less pronounced effect on average cost. Such rate will be assumed; *however, it will be combined with other charges to arrive* at an estimate of fixed costs. These charges are taken as percentages of total investment cost and are insurance (0.33 percent), interest (3 percent) and general and administrative (1 percent). Thus, the total to be charged against investment cost on an annual basis is 11 percent. This is designated the fixed charge. The annual fixed charge for the three alternatives is

Steam Reforming	Coal Gasification	
	Lignite	Bituminous
$12,724,000	$15,409,000	$16,541,000

These figures are the first component of total annual cost.

The next step consists of the calculation of the annual operating costs. Included here are the following items: labor, chemicals, lubricants, catalysts, maintenance, general and administrative costs, home and field office allocations, and other miscellaneous expenditures. There are various ways of calculating these costs; [18] the method used here relies on the use of Williams' formula with the following constants:

Gaseous Hydrogen Production and Purification

	Steam Reforming	Coal Gasification	
		Lignite	Bituminous
I($)	1.28×10^6	2.57×10^6	2.89×10^6
M	.73	.65	.65

Liquefaction

I ($/yr) = 1.91×10^6

M = 0.65

The following are the annual operating costs obtained.

	Steam Reforming	Coal Gasification	
		Lignite	Bituminous
Gas Production	$3,521,000	$6,328,000	$7,116,000
Liquefaction	4,702,000	4,702,000	4,702,000
TOTAL	$8,223,000	$11,030,000	$11,818,000

The next item to be computed is the cost of raw materials. These are feedstock, fuel, water, and process energy. The requirements are the following: [19]

Gas Production and Purification

	Steam Reforming		Coal Gasification: Lignite	Coal Gasification: Bituminous
Feedstock	$1.9 \frac{\text{lb } CH_4}{\text{lb } GH_2}$		$8.84 \frac{\text{lb } H_2O}{\text{lb } GH_2}$	$20.3 \frac{\text{lb } H_2O}{\text{lb } GH_2}$
Fuel	$1.44 \frac{CH_4 \text{ lb}}{\text{lb } GH_2}$	$-4.4 \times 10^{-5} CH_4$	$12.10 \frac{\text{lb (coal)}}{\text{lb } GH_2}$	$8.74 \frac{\text{lb (coal)}}{\text{lb } GH_2}$
Water	$39 \frac{\text{lb}}{\text{lb } GH_2}$		$35 \frac{\text{lb}}{\text{lb } GH_2}$	$26 \frac{\text{lb}}{\text{lb } GH_2}$
Energy	$0.47 \frac{\text{Kwh}}{\text{lb } GH_2}$		$.57 \frac{\text{Kwh}}{\text{lb } GH_2}$	$.57 \frac{\text{Kwh}}{\text{lb } GH_2}$

Liquefaction

Refrigerants	$.04 \frac{\text{lb } N_2}{\text{lb } LH_2}$
	$.01 \frac{\text{lb } CH_4}{\text{lb } LH_2}$
	$.02 \frac{\text{lb } C_3H_8}{\text{lb } LH_2}$
	$.02 \frac{\text{lb } C_2H_4}{\text{lb } LH_2}$
Energy	$4.46 \frac{\text{Kwh}}{\text{lb } LH_2}$

[18] See N. C. Hallett, **Final Report,** p. 67.

[19] N. C. Hallett, **Summary Report, pp. 12, 15.**

The computations for the raw materials follow.

Steam Reforming, Gas Production and Purification

Required Feedstock	$\frac{0.0457}{\text{lb } GH_2}$ MCF CH_4 = 33.361x10^6 MCF
	Unit Cost = \$0.363/MCF
	Total Annual Cost = \$12,110,000
Fuel, CH_4 (oil equivalent)	.005 $\frac{\text{BBL}}{\text{lb } GH_2}$ = 3,650,000 BBL
	Unit Cost = \$1.85/BBL
	Total Annual Cost = \$6,752,000
Water	39.0 $\frac{\text{lb } H_2O}{\text{lb } GH_2}$ = 14,235,000 T
	Unit Cost = \$0.072/T
	Total Annual Cost = \$1,024,000
Energy	0.47 $\frac{\text{Kwh}}{\text{lb } GH_2}$ = 343,100,000 Kwh
	Unit Cost = \$0.00288/Kwh
	Total Annual Cost = \$988,000

Liquefaction

Refrigerants	
Nitrogen	.04 $\frac{\text{lb } N_2}{\text{lb } LH_2}$ = 14,600 T
	Unit Cost = \$6.50/T
	Total Annual Cost = \$94,900
Methane	24x10^{-5} $\frac{\text{MCF } CH_4}{\text{lb } LH_2}$ = 175,000 MCF
	Unit Cost = \$0.363/MCF
	Total Annual Cost = \$63,500
Propane	0.02 $\frac{\text{lb } C_3H_8}{\text{lb } LH_2}$ = 7,300 T
	Unit Cost = \$25/T
	Total Annual Cost = \$182,500
Ethylene	0.02 $\frac{\text{lb } C_2H_4}{\text{lb } LH_2}$ = 7,300 T
	Unit Cost = \$80/T
	Total Annual Cost = \$584,000
Water	24.7 $\frac{\text{No. } H_2O}{\text{No. } LH_2}$ = 9,015,000 T
	Unit Cost = \$0.072/T
	Total Annual Cost = \$649,000

(CONTINUED)

Energy
(hydrocarbon feedstock)

$$4.46 \frac{\text{Kwh}}{\text{No. LH}_2} = 3.256\text{x}10^9 \text{ Kwh}$$

Unit Cost = $0.00288/Kwh

Total Annual Cost = $9,376,000

TOTAL COST OF RAW MATERIALS—LIQUEFACTION, $10,949,900.

Cost Summary: Steam Reforming Process:

Fixed Charges	$12,724,000	(24.07%)
Operating Costs	8,323,200	(15.74%)
Raw Materials	31,823,900	(60.19%)
TOTAL COST	$52,871,100	

Average Cost = $0.07
(Excluding taxes and profits, f.o.b. plant)

The computations for the coal gasification process using lignite follow.

Gas Production and Purification

Required Feed Water

$$8.84 \frac{\text{lb } H_2O}{\text{lb } GH_2} = 3,226,600 \text{ T}$$

Unit Cost = $0.072/T

Total Annual Cost = $232,315

Fuel

$$12.10 \frac{\text{lb lignite}}{\text{lb } GH_2} = 4,416,500 \text{ T}$$

Unit Coal = $2/T

Total Annual Cost = $8,833,000

Oxygen

$$5.20 \frac{\text{lb } O_2}{\text{lb } GH_2} = 1,898,000 \text{ T}$$

Unit Cost = $5/T

Total Annual Cost = $9,490,000

Cooling Water

$$26 \frac{\text{lb } H_2O}{\text{lb } GH_2} = 9,490,000 \text{ T}$$

Unit Cost = $0.072/T

Total Annual Cost = $683,280

Energy

$$.57 \frac{\text{Kwh}}{\text{lb } GH_2} = 416,100,000 \text{ Kwh}$$

Unit Cost = $0.00288

Total Annual Cost = $1,198,368

Cost Summary: Coal Gasification—Lignite:

Fixed Charges	$15,409,000	(26.65%)
Operating Costs	11,030,000	(19.08%)
Raw Materials*	31,386,000	(54.28%)
TOTAL COST	$57,825,000	

Average Cost = $0.08
(Excluding taxes and profits, f.o.b. plant)
*Includes cost of raw materials for liquefaction.

Coal Gasification—Bituminous
Gas Production and Purification

Required Feed Water	$20.3 \frac{\text{lb } H_2O}{\text{lb } GH_2} = 7{,}409{,}500$ T
	Unit Cost = \$0.072/T
	Total Annual Cost = \$533,400
Fuel (Equivalent of W. Va. bituminous)	$13.15 \frac{\text{lb coal}}{\text{lb } GH_2} = 4{,}799{,}750$ T
	Unit Cost = \$7.92/T
	Total Annual Cost = \$38,014,020

The costs of oxygen, cooling water and energy are the same as in the preceding case.

Cost Summary: Coal Gasification - Bituminous:

Fixed Charges	\$16,541,000	(18.54%)
Operating Costs	11,818,000	(13.25%)
Raw Materials	60,868,968	(68.22%)
TOTAL COST	\$89,227,968	

Average cost = \$0.12
(Excluding taxes and profits, f.o.b. plant)

And the average costs per pound are,

Steam reforming	Coal gasification	
	Lignite	Bituminous
\$0.07	\$0.08	\$0.12

Thus the answer to the original question is affirmative; if capacity could be increased from 60 tons per day to 1000 tons per day the average cost per pound could indeed be cut in half. The results call for some analysis but before this is done some comments on transmission, storage and distribution are in order. This will complete the discussion of the major cost components as liquid hydrogen follows the production-consumption route.

It is frequently mentioned in the literature that the technology for transmission of gaseous hydrogen is basically the same as that for natural gas. It is noted of course that hydrogen has a lower heating value (one-third the heating value of natural gas) and that consequently compressor size and horsepower would need to be increased by a factor of 3 to handle the larger volumetric flow. The compressor stations would be spaced at intervals of 100 miles and while they would be more expensive no serious construction problems would arise since they would be above ground. Estimates of the transmission cost run from \$0.018 to \$0.04 per million BTU per 100 miles.[20] For natural gas the transmission cost runs between \$0.01 and \$0.024 per million BTU per 100 miles. In addition to the larger compressors two other factors would contribute to higher costs, the pipeline would need a higher degree of leak tightness and the compressors would be powered by a more expensive fuel.[21]

Marchetti casts doubt on these estimates. The pumping stations can be father apart; some 300 miles (500 km.) rather than 100 miles.[22] For short distances, in fact, no pumping may be necessary if hydrogen can be produced at high pressure. In his view, "The optimized cost of transporting energy is not substantially different for the two cases . . ."[23] Examples are cited of currently operating pipeline networks in this country (between some refineries) and abroad (Germany).[24] The Synthetic Fuels Panel's Report makes clear that at least in this country there is no existing hydrogen transmission or distribution system in which booster compressors are in use.[25] Be this as it may, it can readily be estimated that a difference of one or two cents in the transmission rate would not cause a significant change in the delivered price of the gas. The hydrogen-producing plants, moreover, would not be located in Texas or Louisiana and the distances involved would be shorter than in the case of natural gas.

The use of pipelines to transport hydrogen in liquid form does not appear economical at this time, except perhaps over very short distances or for transfer of energy in much greater amounts than those in use today.[26] Gregory notes that even in the case of natural gas no

[20]D.P. Gregory, et al, **op. cit.**, p. 31; **Hydrogen and Other Synthetic Fuels**, Report of the Synthetic Fuels Panel, September 1972, p. 61; and W.E. Winsche, K.C. Hoffman, F.J. Salzano, "Hydrogen: Its Future Role in the Nation's Energy Economy," **Science**, 29 June 1973, p. 1326.

[21]The Synthetic Fuels Panel expressed concern that the admission of gaseous hydrogen into old natural gas pipelines would create leaks. See their Report, **op. cit.**, p. 63.

[22]C. Marchetti, **op. cit.**, Table 2, p. 17.

[23]**Ibid.**, p. 15.

[24]**Ibid.**, p. 15, and Synthetic Fuels panel's Report, p. 56.

[25]Synthetic Fuels Panel's Report, p. 56.

[26]See Synthetic Fuels Panel's Report, p. 63.

liquid transmission systems have been developed on a nation-wide basis.[27]

So far as storage is concerned, it has been suggested that it could be accomplished underground in depleted oil and gas wells and mined caverns. Marchetti mentions the vast Groningen gas field in Holland as a case in point.[28] In France, the Baynes aquifer storage system ". . . has been in operation for over ten years, first with manufactured gas and now with natural gas."[29] Gregory mentions that helium, which is a low-density gas with leadkage characteristics similar to those of hydrogen, is being stored successfully in an underground reservoir near Amarillo, Texas.[30]

Other storage possibilities include the use of pipelines designed for operation under varying pressure, the use of metal hydrides, and the conversion of hydrogen to other chemicals such as ammonia and methanol. Furthermore, progress in cryogenic storage will offer additional possibilities.[31] Due to low specific volume and high production costs the storage of gaseous hydrogen in pressure vessels appears quite uneconomical.[32]

Concerning distribution, current articles call attention to the distribution of "city gas" in the old days which consisted of up to 80% hydrogen.[33] It is thought that with proper precautions the distribution of hydrogen should prove to be no more hazardous than the distribution of manufactured gas. In order to meet city codes it will, of course, be necessary to increase the tightness of the pipes and to introduce more rigorous inspection and supervision. It seems that it will be desirable to mix the hydrogen with other gases prior to distribution in order to make it odorous and to narrow its flammable limits, increasing at the same time the energy needed for ignition, the visibility of the flame, and also the heating value.[34]

The cost of distribution by pipeline is given as 0.66/10⁶BTU by Winsche, which compares to a similar cost for methane of $0.60/10⁶ BTU. Cost estimates are scarce and some seem to be inconsistent.[35]

Returning to the average costs per pound of liquid hydrogen of $0.07, to 0.08 and 0.12 for the three alternatives examined (methane, lignite and bituminous coal), it is, of course, possible to alter the results by changing the stated conditions. This of of some interest because when, as currently, price instability prevails, cost estimates quickly get out of date. What would be the result if, in order to get a closer approximation to present circumstances some unit costs were changed? What if interest on borrowed money were 7% instead of 3%? Similarly, what is the effect of changing the cost of electricity from 2.88 mills per kwh to, say 6 mills, of changing the price of lignite from $2 to $3 per ton, and of changing the price of oxygen from $5 to $8 a ton?[36]

Carrying out the required calculations it can be shown that the new average costs are $0.116 per pound for the coal gasification process using lignite and $0.154 per pound if the raw material is bituminous coal. Thus one may conclude that the coal gasification process is not as appealing as it seems at first sight.

Several comments are in order:

1. There is no question but that if the raw material is natural gas, the steam reforming method is the most economical. If this were not the case, it would not be so popular. The drawback, and it is a very serious drawback, is that its continuous use offers no solutions; it simply prolongs the dependence on a fossil fuel that is at the heart of the energy crisis.

2. The same comment applies to the partial oxidation method. It leads to an average cost somewhat greater than by steam reforming but the difference is minor.[37] Thus while the computations are not shown the conclusion is the same: a method based on the partial oxidation of oil offers no viable alternative. JP-4 fuel shares a common fate. Recent cost data show that the prices of natural gas and oil are moving upward and they are not going to come down. We know from Ricardian economics that the cost of production will increase as the more inaccessible deposits are tapped, or as the underdeveloped countries in possession of the richer fields believe that it is a matter of justice that they receive higher prices; therefore, it seems over-optimistic to think that the price of any fuel that uses natural gas or oil as the raw material will ever be cheap again.

3. Calculations for the water electrolysis method were not worked out because it offers little promise for the immediate future. It is still in need of R&D work and it is going to be much more costly. In his 1972 study Alexander used a current price of electricity of 2.6 mills per kwh and a future price of 1.6 mills based on the development of fast breeder reactors.[38] This point of view is frequently encountered: liquid hydrogen will be economical because off-peak nuclear power will be cheap. The argument can be overdrawn. Alexander found that either because of safety or because of environmental factors the nuclear investment has been taking upward jumps: $135 per kw in 1967; more than $300 per kwh in 1971.[39] The current figure

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[27]D. P. Gregory, et al, **op. cit.**, p. 31.

[28]C. Marchetti, **op. cit.**, p. 15. In Chapter IV the storage and distribution costs of one concrete application are covered in some detail. That discussion is not repeated here.

[29]Synthetic Fuels Panel's Report, p. 56.

[30]D. P. Gregory, "The Hydrogen Economy," **Scientific American,** January 1973 (Volume 228, Number 1), p. 16.

[31]The Synthetic Fuels Panel reported that very large underground storage in aquifers or plowshare caverns would cost between $3 and $6 per 10⁶ BTU, figures which are entirely incompatible with the transmission costs discussed in the text. See its Report, Table 6, p. 57. Care should be exercised concerning some of the cost data. A price of $2 per ton for lignite is quited on p. 11 but this figure is changed to $7 on p. 48. A comparison between capital costs (p. 47) and operating costs (p. 48) shows that in one case the operating costs are greater than the capital costs—this in a capital-intensive industry.

[32]**Ibid,** p. 56.

[33]D. P. Gregory, et al, pp. 33, 34, and "The Hydrogen Economy," op. cit., p. 21. See also C Marchetti, **op. cit.,** p. 14.

[34]**Ibid.,** p. 33.

[35]Compare Winsche's cost for methane of $0.60/10⁶ BTU with Gregory's $0.17/10⁶ BTU. See the D. P. Gregory, et al, **op. cit.,** p. 6.

[36]In the preceding set of computations the price of water was taken as $10.072 per ton instead of Hallett's $0.0072/T, which seems rather low.

[37]When the cost is not the same the difference remains within fractions of a cent. See estimates by Hallett in his **Summary Report,** pp. 42-51. See also D. E. Wilcox and C. L. Smith, op. cit., p. 25.

[38]Arthur D. Alexander, III, **Economic Study of Future Aircraft Fuels (1970)2000),** NASA Technical Memorandum, September 1972, p. 20.

[39]Arthur D. Alexander, III, "Description and Appraisal of LH^2 Production Methods and Costs—Current, Immediate Future (to 1985) and Future," Working Symposium on Liquid-Hydrogen-Fueled Aircraft, LRC, May 1973, p. 418.

is undoubtedly higher. Thus, the cost of fast breeder nuclear power will probably be around 15 mills per kwh or higher. What will be the off-peak power rate? 30% off? 50%? Certainly not two or three cents per kwh. Hence, in the 1973-85 time span, coal gasification is a better bet. It is *more feasible technologically* and also much more economical. True, coal gasification does not sever the dependence on fossil fuels but in this case there will be no shortage of supply for a good many years. Furthermore, if the raw material is lignite there are few environmental difficulties.

4. What has been said about water electrolysis also applies to the hydrogen halide method, with the additional disadvantage that a greater amount of R & D work is involved and that its cost will be even higher. These remarks should not be taken to mean that the eventual solution to the fossil-fuel depletion problem does not lie with methods such as water electrolysis or hydrogen halide; what is asserted is that they do not provide a near term or interim solution. It is the same situation with respect to thermochemical processes[40] or to the application of solar or tidal energy to the production of hydrogen; the possibilities still lie in the future and cost estimates would be rather speculative.

Before closing this discussion the question may be raised whether other synthetic fuels may not offer greater promise than hydrogen. Liquid propane, for instance, could be produced at a cost of $1.462 per million BTU in 1970,[41] a cost that puts it in competition with liquid hydrogen at $0.08/lb. The problems is that the cost (putting technological disadvantages aside) is based on the use of oil as the raw material and the source of the difficulty remains. So far as liquid methane is concerned there is no doubt that if the base is natural gas it can outprice both JP-4 and liquid hydrogen,[42] but again the dependence on a fossil fuel continues.

Other possibilities suggest themselves. What is the economic picture if say, methane or methanol were to be produced from coal? Again it is a case of the cost of the final product exceeding the cost of one of the ingredients. Hydrogen must be produced as "the initial step"[43] and therefore it would have the cost advantage. Of course, this does not rule out the production of these other fuels *from coal since there may be applications where their* higher cost would present no serious disadvantage.

It is not entirely unlikely that at some future date Americans will face a situation similar to that of Europeans, that is, that the cost of fuel is not the issue but its availability. Coal gasification can buy time and postpone the day when such possibility becomes real.

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[40]See the discussion of hydrogen production by these methods in Chapter

[41]**Ibid.**, p. 417.

[42]A. D. Alexander, III, **Economic Study**, Fig. 17 (page not numbered).

[43]John E. Johnson, "The Economics of Liquid Hydrogen Supply for Air Transportation," Paper presented at the Cryogenic Engineering Conference, Atlanta, Georgia, August 1973, p. 7.

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