EPA-460/3-74-012-a

July 1974

ALTERNATIVE FUELS FOR AUTOMOTIVE TRANSPORTATION - A FEASIBILITY STUDY

VOLUME I - EXECUTIVE SUMMARY

U.S. ENVIRONMENTAL PROTECTION AGENCY
Office of Air and Waste Management
Office of Mobile Source Air Pollution Control
Alternative Automotive Power Systems Division
Ann Arbor, Michigan 48105

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ALTERNATIVE FUELS FOR AUTOMOTIVE TRANSPORTATION - A FEASIBILITY STUDY
VOLUME I - EXECUTIVE SUMMARY

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Contract No. 68-01-2111

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Publication No. EPA-460/3-74-012-a

PREFACE

This report is the result of a research team effort at the Institute of Gas Technology. In addition to the authors, the major contributors to the study were J. Fore, P. Ketels, W. Kephart, and K. Vyas.

This report consists of three volumes:

Volume I — Executive Summary

Volume II — Technical Section

Volume III — Appendices.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

STUDY OBJECTIVES

The United States is becoming increasingly dependent on imported petroleum as an energy source; this country now imports about one-third of its crude oil and crude oil product supplies. Transportation is intensively dependent on petroleum, and this sector of the economy now consumes about 25% of the U. S. total annual energy supply and 55% of the U. S. crude oil supply. The automotive portion (cars, trucks, and buses) amounts to 75% of the transportation sector of the energy economy and, as such, consumes more than 40% of the crude oil supply. Because of international and domestic economic factors, political influences, and shortages due to petroleum resource depletion, alternative (non-petroleum-based) fuels for automotive transportation would be beneficial to our society.

The objective of this study is to assess the technical and economic feasibility of alternative fuels for automotive transportation, specifically —

- Identification and characterization of potentially feasible and practical alternative fuels that can be derived from domestic, nonpetroleum energy resources
- Technical and economic assessments of the most promising alternative fuels for three specific time frames
- Identification of pertinent fuels and research data gaps and recommendations of alternative fuel(s) to best satisfy future U. S. automotive transportation requirements.

Major emphasis in the selection of alternative fuels is placed on long-term availability from domestic resources. Economics, competition with other energy applications for limited energy resources, safety, handling, system efficiency, environmental impacts, and engine and fuel distribution system compatibility also are taken into account. This study provides background information for the development of U. S. energy programs pertaining to chemical fuels.

Working toward these objectives, we have generated a fuel selection methodology that can be applied to a potential alternative fuel. We have enlisted the factors of energy demand and supply, fuel availability, fuel synthesis technology, and certain physical, chemical, and combustion properties of the fuel. Apparent technology and information gaps bearing on a fuel's usefulness (for automotive purposes) are identified.

In this study, the petroleum resource base consists of crude oil, natural gas, and natural gas liquids (including LPG). Conventional gasoline from this petroleum resource base is the "reference" fuel. When possible, it is the basis for quantitative and qualitative comparisons. "Automotive transportation" refers to automobiles, trucks, and buses. The energy requirements for the remainder of the transportation sector are incidental to this study. We are primarily considering vehicles propelled by heat engines combusting chemical fuels. Electric vehicles – those storing and delivering energy electrochemically – are excluded from this study. However, vehicles that carry a chemical fuel and combust it in a fuel cell (to produce electricity for a motor) are included.

This study is concerned with three time frames: near term, 1975-1985; mid term, 1985-2000; and far term, beyond 2000. Because of the uncertainties in future energy availability, technological advances, economics, and public policy, forecasts or projections beyond the near term are very difficult. Two energy demand and supply projections (models) are detailed in the technical section (Volume II) of this report for two purposes: 1) to present an illustration of the methodology of fuel selection and 2) to provide an optimistic possibility of domestic energy self-sufficiency as well as a pessimistic possibility of continued dependence on energy imports. The projections are not intended as models of energy allocation; rather, they are intended to show quantitatively the deficits and excesses that could exist in future time frames. The assumptions inherent in our energy demand and supply models are specified, and the reader can change the projections by changing the assumptions.

To apply the methodology of alternative fuel selection to a reasonable number of fuels, we have studied 16 fuels in this program. As possible energy sources for fuel synthesis, we have studied 12 potential domestic sources of energy. Table 1 lists these energy sources, four abundant auxiliary material sources, and the potential alternative fuels. The conventional crude oil and natural gas resource base has been excluded. Also, we have excluded any fuel that would produce significant amounts of combustion products not found in (unpolluted) air. In the potential automotive fuel list, "distillate oils" refer to similar hydrocarbon mixtures – kerosene, diesel oil, and fuel oil (No. 1 or 2). Hydrazine is included as a fuel for fuel cells, and the coal is a solvent-refined product (low in ash and sulfur content).

Table 1. INITIAL-CONSIDERATION LIST

Energy Sources	Auxiliary Material Sources	Potential Automotive Fuels
Coal	Air (O_2, CO_2, N_2)	Acetylene
Shale oil	Rock (limestone)	Ammonia
Tar sands	Water	Carbon monoxide
Uranium and thorium	Land	Coal
Nuclear fusion		Distillate oils
Solar radiation		Ethanol
Solid wastes (garbage)		Gasolines (C_5-C_{10})
Animal wastes		Heavy oils
Wind power		Hydrazine
Tidal power		Hydrogen
Hydropower		LPG (synthetic)
Geothermal heat		Methanol
		Methylamine
		SNG
		Naphthas
		Vegetable oils

FUEL SELECTION METHODOLOGY

Candidate alternative fuels are selected from the initial-consideration list by evaluations, whenever possible, of certain fundamental areas of concern. The concerns that we have identified are as follows:

- Adequacy of energy and material availability and competing demands for fuels
- The existence of known or developing fuel synthesis technologies
- Safety (toxicity) and handling properties of fuels
- Relative compatibility with contemporary fuel-transport facilities and utilization equipment (tanks and engines)
- Severity of environmental impacts and resource depletion
- Fuel system economics (resource extraction, fuel synthesis and delivery, automotive utilization).

For the initial choice of candidate fuels, preliminary economic assessments have been made from various capital and operating costs published in the technical literature. These preliminary cost assessments have been combined with quantitative rankings for each fuel in the other areas of concern. The quantitative rankings and particular criteria by which fuels are evaluated have been derived during the course of the study, and they are discussed in Sections 2 through 9 and applied in Section 10 (Volume II) of this report. After the candidate fuels had been chosen from the initial-consideration list, the favored fuels for each time frame were selected by using more detailed and accurate information, particularly data on fuel-system economics. These economic data are derived in Appendix B (Volume III) and in Section 8 (Volume II) of this report. Again, a fuel ranking is constructed by numerically rating the above-listed concerns for each candidate fuel; in this case, assessments are made for each time frame. Some of the concerns, for instance, the safety and handling aspects (toxicity and physical and chemical properties), do not change with time. Others, such as the availability of a technology for fuel synthesis, can vary greatly during the three time frames of this study, so some assessments must be repeated. The different judgments for fuel selection must be as consistent as possible, and the criteria must be quantified when possible.

In this study, fuel system economics have been restricted to exclude vehicle utilization costs. The precision and accuracy of the data base on engine efficiency, vehicle weight, and fuel consumption for alternative fuels in conventional and unconventional power plants are inadequate to include this cost factor in fuel selection procedures. Further, the data base on efficiency and pollution aspects of resource extraction, fuel synthesis, and automotive utilization is incomplete. Therefore, the severity of environmental impacts could not be judged uniformly and could not be fairly applied to the selection of alternative fuels.

The alternative fuel evaluation procedure is outlined in Figure 1. According to this evaluation method, certain background information must be assembled before the evaluation can proceed. This background information consists of the following items:

a. Quantitative information on the U.S. domestic energy (and material) resource base. This must include the conventional petroleum resource base for reference. Assured, reasonably assured, and speculative quantities are sought.

b. Energy demand and supply model(s). These models are divided into market sectors to show deficits and excesses. The transportation sector is of prime concern.

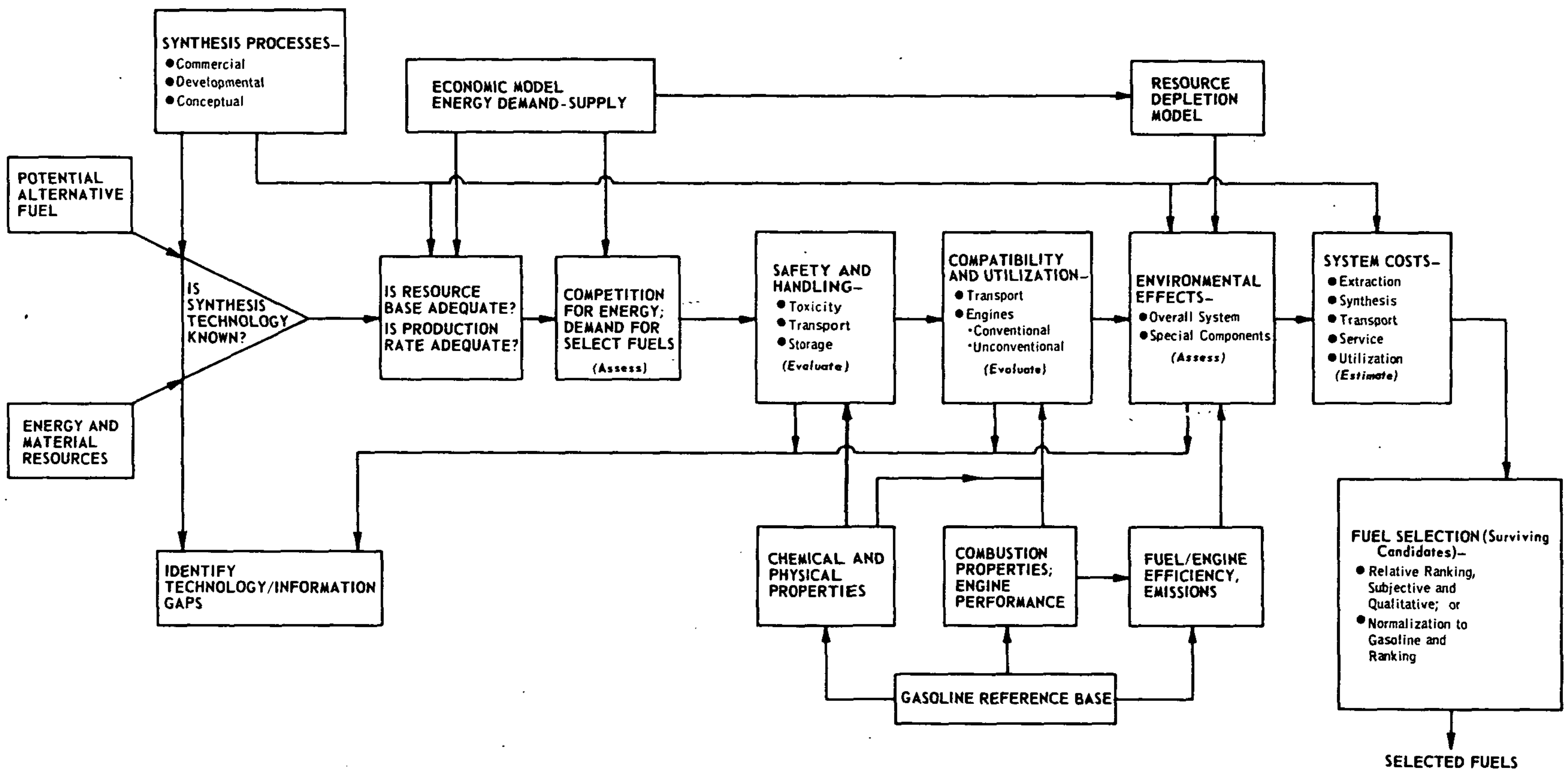

Figure 1. ALTERNATIVE FUEL EVALUATION METHOD

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c. Information on fuel synthesis processes. Needed are the availability of commercial processes, processes being developed, and conceptual processes for fuel synthesis from unconventional energy sources.

d. A bank of data on fuel properties – pertinent chemical, physical, combustion, and toxicity data. Also, prospects for fuel transport (handling) and fuel-engine compatibility and performance are needed. This also establishes the data for conventional gasoline, the reference fuel for this study.

e. A resource depletion model. This should integrate resource depletion due to automotive requirements with energy supply.

The evaluation procedure begins with a determination of whether a given fuel can be synthesized by some process from an available energy (and material) resource. If not, but if subsequent evaluations are satisfactory relative to conventional gasoline (selection criteria met), a synthesis technology gap is identified. Other technology gaps that may be identified concern fuel transport or tankage, fuel-engine compatibility, and correctable environmental effects. The energy demand and supply model determines for the various time frames how much energy (fuel) is required and whether that fuel will be available for automotive use, considering competing demands from other (higher priority) sectors of the economy. These assessments are followed by determinations of fuel safety and handling, and compatibility and utilization. The overall resource depletion due to the synthesis and use of a fuel is calculated, and the environmental effects due to potential material pollutants are assessed (if quantitative determinations can be made). Finally, the fuel is given a rating relative to conventional gasoline by normalization of the quantitative data and the semiquantitative judgments. As a result, the fuel has a certain ranking relative to the other potential alternative fuels.

DOMESTIC RESOURCE BASE

One prerequisite in the selection of an alternative automotive fuel is the determination of whether or not its domestic resources are adequate to support a substantial portion of the transportation demand for a period that allows major development and commercialization of a new industry. The term "substantial portion of the transportation demand" is quantified by using supply-demand projections for energy in the U.S. According to the Model I projections used in this study, the transportation energy shortfalls vary between 28 and 34% annually between 1975 and 2000, as shown in Table 2.

Table 2. TRANSPORTATION ENERGY DEMANDS AND SHORTFALLS ACCORDING TO MODEL I

	1975	1980	1985	2000	2020
Demand, 10^{15} Btu	19.4	23.0	26.7	40.4	70.1
Shortfall, 10^{15} Btu (domestic)	6.4	7.4	7.4	13.8	41.7
Shortfall, % of demand	33	32	28	34	59

Integrating the Model I shortfall from 1975 to 2000 results in a total shortfall of about 215 X 10^{15} Btu, or an average annual shortfall of 8.6 X 10^{15} Btu. In this study, we are interested in alternative fuel systems that could have a major impact on the projected shortfalls. Therefore, as a benchmark, we have chosen one-half of the shortfall, or an integrated value of 108 X 10^{15} Btu (1975-2000), as the level of energy supply that must be potentially achievable by a viable and important alternative fuel system. This benchmark corresponds to about 15% of the total transportation energy demand. Hence, to be adequate, a new (unconventional) energy source should have the potential to supply 3-6 X 10^{15} Btu/yr of fuel between 1975 and 2000.

For renewable resources, the rate at which a resource becomes available for conversion is a practical limiting factor. To be adequate, this energy resource also must be able to meet about 15% of the transportation demand for 25 years. Energy sources that are limited by a lack of required materials, conversion efficiency (to a fuel), or other factors to a production rate of less than 3-6 X 10^{15} Btu/yr are considered inadequate.

From a multitude of sources, but principally the NPC's U. S. Energy Outlook,[1] we have assembled and categorized the domestic energy resource base. Throughout this report, the following classifications are employed to uniformly categorize the resource base: "assured" reserves are adjacent to current producing areas and have been measured with a high degree of certainty. "Reasonably assured" reserves have a high probability of existing

[1] National Petroleum Council, U. S. Energy Outlook: A Report of the National Petroleum Council's Committee on U. S. Energy Outlook. Washington, D.C., December 1972.

based on geological and other information similar to that found in areas currently being produced. "Speculative" reserves assume a high degree of optimism and could possibly fall into one of the former classifications by means of extensive exploration and development activity. We have chosen this definition of resource base because, for various resources, the documentation is adequate and categorization can be uniform. Use of other classifications, such as "economically available" (minable), would result in less consistency, because these quantities have been reported on different economic bases.

We have summed the assured resource base, 75% of the reasonably assured resource base, and 25% of the speculative resource base for the finite domestic fossil and nuclear resources. These resources and sums are presented in Table 3, in which the adequacy of the resource is rated according to the requirement of 108×10^{15} Btu.

In the case of solar heat, we have taken one average state, or 2% of the U. S. land area, as that potentially available for agricultural production of a crop that could be converted to a fuel for automotive transportation. In the cases of municipal and feedlot wastes, we have taken the annual supply projected for 1985.

ENERGY SUPPLY AND DEMAND MODELS

This study uses two energy models to bracket future supply and demand. They show the fuel requirements resulting from different assumptions about the effectiveness of conservation efforts, changing demand patterns, and the drive toward domestic self-sufficiency. A third model, not fully developed, shows the effects of high fuel costs, extreme conservation, and Federally legislated vehicle efficiency (fuel economy) on automotive fuel demand. The effect of these models on our selection procedure is to define the minimum resource base requirements and fuel production rates that are required in a particular time frame.

These models are not intended for the purpose of energy allocation in the future, but merely as a quantitative indication of energy supply and demand deficits and/or excesses. The models show how much energy is needed and when it is needed for alternative fuels. They can be used as selection criteria

Table 3. ADEQUACY OF DOMESTIC RESOURCES

Finite Resource	Potential Supply, 10^{15} Btu	Adequacy*
Coal	67,100	Probable
Oil Shale	3,230	Probable
Uranium (Fission)		
Burner Reactors	550	Possible
Breeder Reactors	41,250	Moderate technology gap
Tar Sands	127	Not adequate
Deuterium (Fusion)	Unassessed	Serious technology gap

Renewable Resource	Potential Annual Supply (10^{15} Btu)	25-Year Fuel Supply (10^{15} Btu)	Adequacy*
Hydropower			
Total	1.8	37.5	Not adequate
Uncommitted	1.5 (as fuel)		Not adequate
Geothermal Heat	7.7 (as heat)		
Fuel Conversion	2.7 (as fuel)	67.5	Not adequate
Solar Heat (Total Area)	49,000 (as heat)		
2.0% U.S. Area	980 (as heat)		
Agricultural Production	9.8 (as crop)		
Fuel Conversion	4.9 (as fuel)	122.5	Speculative
Tidal Power	Negl	Negl	Not adequate
Wind Power	4.0 (as fuel)	100	Not adequate
Municipal Wastes	2.9 (as heat)		
	1.2 (as fuel)	30	Not adequate
Animal Feedlot Wastes	6.8 (as heat)		
	3.4 (as fuel)	85	Not adequate

* Not adequate = $>108 \times 10^{15}$ Btu.

because they indicate for a given time frame that, after several "best qualified" fuel systems are selected, other (additional) fuel systems are not needed.

The primary model of energy supply and demand for this study, denoted Model I, is based on a slightly modified (supply) Case I of the NPC report[1] and on the low level of demand from the NPC report. The assumptions upon which the Case I energy supply quantities are based closely approximate an optimistic situation in which a maximum effort is undertaken to make the United States self-sufficient in terms of energy supply at the earliest possible date. These conditions best fit the ground rules of this study, i.e., to assess the feasibility of alternative automotive fuels based on U.S. domestic resources.

The projected quantities of energy supply and demand from Model I are presented in Table 4. For each time frame, these quantities are categorized by type of energy available to each sector of the economy based on historical use patterns, assumed rates of future consumption, and priorities in allocation. The transportation sector is assumed to have the lowest priority. Considering practical energy conversion efficiencies in the synthesis of fuels and in the generation of electricity, Table 2 is formulated to determine alternative fuel needs.

FUEL SYNTHESIS TECHNOLOGY

The resource base assessment and energy demand and supply Model I indicate that the domestic energy sources available for large-scale automotive fuel production are coal, oil shale, nuclear energy (fission), and maybe solar energy. However, the other energy sources (winds, tide, waste materials, geothermal heat, etc.) deserve the development as contributors to the overall U.S. energy supply, and local or limited use of these unconventional energy sources may result indirectly in more (conventional) fuel being available for transportation.

Considerable effort is being directed toward developing processes that will convert coal to clean fuels — gaseous, liquid, or solid. As shown in Figure 2, coal can be gassified by means of two routes. The first route produces clean gas of either medium (250-550 Btu/CF) heating value or high (950-1000 Btu/CF) heating value. The latter is a supplement to pipeline-quality natural gas (SNG). The second route to clean gas produces only low

Table 4. MODEL I ENERGY SUPPLY AND DEMAND BY MARKET SECTORS

	1970	1975	1980	1985	2000*	2020*
	10^{15} Btu					
Demand						
Residential/Commercial	15.8	18.2	21.1	23.9	36.2	62.8
Industrial	20.0	22.2	24.7	27.1	41.0	71.2
Transportation	16.3	19.4	23.0	26.7	40.4	70.2
Electricity Conversion	11.6	15.5	20.7	26.7	40.4	70.2
Nonenergy	4.1	5.0	6.2	8.1	12.3	21.3
Total	67.8	80.3	95.7	112.5	170.3	295.7
Supply						
Oil						
Conventional (Wellhead)	21.0	23.7	27.3	31.7	31.0	31.0
Oil Shale	0	0	0.6	1.9	6.7	6.7
Coal Liquefaction	0	0	0.2	1.1	10.2	13.0
Total	21.0	23.7	28.1	34.7	47.9	50.7
Gas Production						
Conventional (Well)	22.4	24.5	24.6	28.0	22.0	15.0
SNG From Coal	0	0	1.0	2.0	8.0	10.0
Total	22.4	24.5	25.6	30.0	30.0	25.0
Coal (Traditional Uses)	13.1	16.6	21.1	27.1	35.0	64.0
Hydro and Geothermal	2.7	3.1	4.0	4.7	5.0	5.0
Nuclear (Heat)	0.2	4.0	11.3	29.8	102.0	275.0
Total	59.4	71.9	90.3	126.3	219.9	419.7

* The assumed rate of growth for 2000-2020 is 2.8% /yr, which is the same for the 1985-2000 period except for nuclear power supply figures.

(100-250 Btu/CF) heating value gas because the gas contains a considerable amount of nitrogen. The nitrogen is introduced when air is used in the system for combustion to furnish the heat for the gasification reactions.

Production of clean liquids or clean solids from coal is carried out by three principal routes. In the first route, clean gas containing appropriate proportions of carbon monoxide and hydrogen (synthesis gas) is converted by the Fischer-Tropsch Process to hydrocarbon oil. The second route involves heating the coal to drive out the naturally occurring oils in it (pyrolysis) and

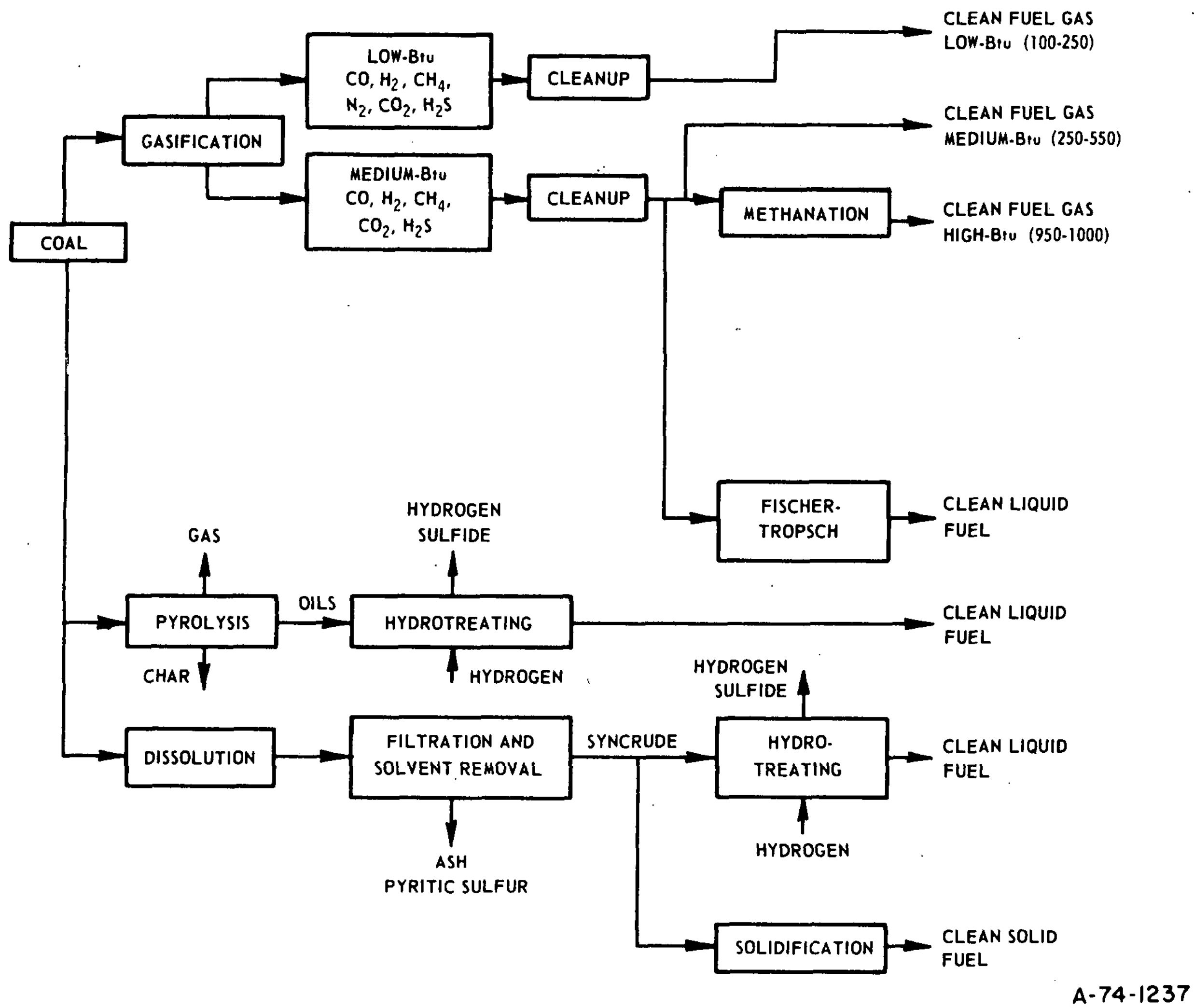

Figure 2. PRODUCTION OF CLEAN FUELS FROM COAL

then treating these oils with hydrogen for desulfurization and quality improvement. Pyrolysis processes produce significant quantities of by-product gas and char, which must be disposed of economically. The third route to clean liquid fuel involves dissolving the coal in a solvent and filtering out ashes, which include the pyritic sulfur. After the solvent has been removed, the resulting heavy crude oil (syncrude) is treated with hydrogen to remove organic sulfur and to improve its quality. In one process, a solid fuel (solvent-refined coal) is produced if the syncrude is allowed to cool before the hydrotreating step.

Many processes exist for making gaseous or liquid fuels from oil shale. Some processes are on the pilot-plant scale (e.g., TOSCO II Process, Gas Combustion Retort Process, Union Oil Process) and some are in commercial use (e.g., Petrosix Process, GCOS Process). As shown in Figure 3, oil shale can be hydrogasified to gaseous fuel or it can be retorted to make liquid fuel.

The processed (spent) shale is a fine, granular, dark residue – dark due to residual carbon that coats the particles because the low temperature in the processing retort does not produce any significant agglomeration into clinkers. More than 75% (by weight) of the feed shale becomes spent shale. Therefore, disposition of spent oil shale is a major problem, and once this spent shale has been deposited, there remains the problem of re-vegetating the deposit. Studies are being conducted to resolve this problem.

Appendix B (Volume III) contains detailed descriptions for four processes that produce candidate alternative automotive fuels from coal and oil shale. These "pattern" processes have been chosen because they consist of demonstrated technology and because sufficient information is available for process characterizations and detailed economic assessments. The economic assessments are used to aid in the evaluation of alternative fuel systems by providing fuel production costs. The pattern processes are as follows:

- Gasoline and distillate hydrocarbons from coal via the Consol Synthetic Fuel (CSF) Process plus product refining including catalytic cracking
- Gasoline and distillate hydrocarbons from oil shale via the Gas Combustion Process (Bureau of Mines) plus hydrotreating and refining of the product
- Methanol from coal via a Koppers-Totzek gasifier and Imperial Chemical Industries (ICI) methanol synthesis
- SNG (methane) from coal via a Lurgi gasifier with methanation.

In addition, Section 5 (Volume II) includes brief descriptions of many processes based on coal and oil shale to produce synthesis gas (hydrogen and carbon monoxide) and several alternative fuels. Required material and energy inputs, operating conditions, product streams, and potential environmental pollutants are listed. Also, Sections 5 and 8 (Volume II) include descriptions of fuel synthesis technologies based on nuclear heat, solar energy (including agricultural crops), and waste materials.

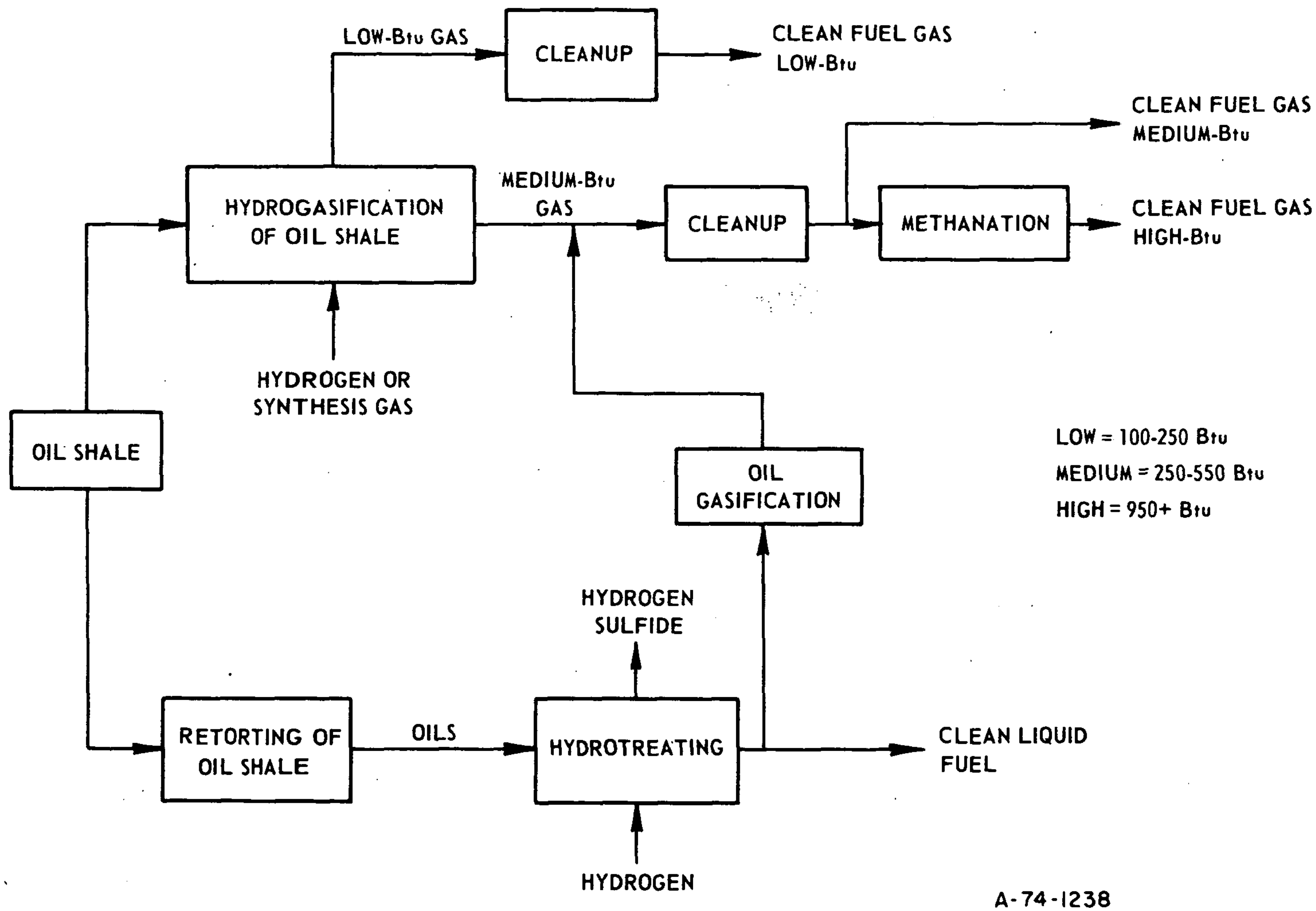

Figure 3. PRODUCTION OF CLEAN FUELS FROM OIL SHALE

Recently, attention has been given to the possibility of the use of process heat directly from the core of high-temperature, gas-cooled nuclear reactors to drive a chemical process. The production of hydrogen for use as an automotive fuel by this means is a distinct possibility. With water as a raw material, the products of thermal decomposition are hydrogen and oxygen. Because of the temperature limitations of nuclear reactors and conventional process equipment, direct single-step water decomposition cannot be achieved, but sequential chemical reaction series have been devised in which hydrogen and oxygen are produced, water is consumed, and all other chemical products are recycled. This multistep thermochemical method offers the potential for processes that can use high-temperature nuclear heat and be contained in chemical process equipment.

ALTERNATIVE FUEL PROPERTIES AND SYSTEM COMPATIBILITY

This subject encompasses physical, chemical, and combustion properties, safety (toxicity), transportability and storability, and compatibility with engines. Appendix A (Volume III) contains a listing of the pertinent chemical, physical, and combustion properties of potential alternative fuels. Section 6 (Volume II) deals with the details of transportability, storability, tankage, and engine compatibility.

Safety assessments might be made by considering combinations of the combustion properties and toxicity of fuels. Combustion properties that are indicative of the likelihood of accidental fire are flash point, ignition energy, limits of flammability in air, and ignition temperature. Gasoline and distillate oils are handled safely; however, these fuels have very low lean flammability limits and low ignition temperatures. Gasoline also has the lowest flash point of any of the liquid fuels. Thus, we find only minor (insignificant) distinctions evident between fuels that are potentially safer than gasoline in terms of combustion when gasoline is handled safely in the reference system.

Toxicity is a different matter, and distinctions should be made. In our investigation, we have sought the following fuel concentrations in air: least amount for detectable odor, least amount causing eye irritation, least amount causing throat irritation, and maximum concentration allowable for prolonged (8-hour) exposure. Concentrations above this last value cause a variety of symptoms, differing with different fuels, but on the average, the effects are deleterious and incapacitating. We have quantified alternative fuel toxicity relative to gasoline by using the "toxicity ratio," which we define as the ratio of the 8-hour exposure concentration (in air) of the fuel in question to that of gasoline:

$$\text{Toxicity ratio} = \left(\frac{\text{ppm fuel}}{\text{ppm gasoline}}\right)^{-1}$$

It would be inconvenient and expensive to introduce a fuel that has physical and chemical properties unsuited for the equipment now used for energy supply. The great economic incentive to retain existing facilities would have to be overcome. Fuels that can be handled in existing petroleum-product-distribution equipment have an enormous advantage.

At present, four separate transport systems handle four classes of fuels. About 10×10^{15} Btu is delivered as gasoline by the liquid-fuels-distribution system each year. The solid-fuel (coal) transmission system handles about 12×10^{15} Btu annually. Gaseous fuels, primarily natural gas, have their own pipeline system, which accounts for about 20×10^{15} Btu yearly. The last class of distribution system, which moves condensable gases like LPG, is relatively small and would need a considerable (but possible) investment to accommodate the huge quantities of fuel required to supplement gasoline supplies.

The compatibility of each fuel is judged against the changes and additions to each of these four distribution systems that it would necessitate. The best situation allows the continued use of the liquid-fuel pipelines, trucks, and service stations system. A switch to one of the other three systems requires, at the least, a substantial amount of new distribution equipment and service-station facilities.

We have estimated automotive tankage weights and volumes after consultation with manufacturers. Fuel energy content alone does not necessarily indicate the true weight of a fuel system. Because fuel tankage weights influence total vehicle weight and hence fuel consumption, we have calculated the tankage weights of alternative fuels at the energy equivalent of 20 gallons of gasoline. Fuels requiring a fuel storage system weighing in excess of 500 pounds are poor alternatives to gasoline. Tankage weights in the range of 200-500 pounds are considered good, and those in the range of 140-200 pounds (comparable to that of gasoline) are excellent. Tankage volume does not affect performance or fuel consumption, but can affect passenger and payload space. For example, at 600 gallons, gaseous carbon monoxide is unacceptable, and at 110 gallons, acetylene is awkward. To quantify this criterion, we have used the tankage index defined as:

$$\text{Tankage index} = \left(\frac{\text{fuel tankage weight}}{\text{gasoline tankage weight}}\right) + \left(\frac{\text{fuel tankage volume}}{\text{gasoline tankage volume}}\right)$$

Just as it would be impractical to introduce a fuel that in the near term is incompatible with the present distribution system, it would be impractical to introduce a fuel that is incompatible with automotive power plants, present or planned. The compatibility of fuels with engines is judged on an arbitrary numerical scale. Details are presented in Sections 6 and 10 (Volume II). In the near-term time frame, fuels are judged for compatibility with conventional spark-ignited and diesel engines; for the mid term, stratified-charge engines are included; and for the far term, Brayton, Rankine, and Stirling-cycle engines and fuel cells are included along with conventional, stratified-charge, and diesel engines.

Table 5 summarizes the tankage and safety properties of the potential alternative fuels.

FUEL SYSTEM ECONOMICS

To further evaluate alternative fuels, we have applied a costing procedure to the potential fuel systems. This method sums the calculated costs of resource extraction and synthesis, the costs of refining or liquefying, and the costs of transmission and distribution. This procedure yields a delivered fuel cost ($/Btu) to the service station.

The determination of fuel system costs has been done in two phases. An initial "rough cut," using published estimates of resource extraction and synthesis costs, was done first. Transmission and distribution costs for similar fuels or chemicals were used. For the several attractive candidate fuels (those ranking most favorably with respect to gasoline), a second, detailed determination of costs was made. Section 8 (Volume II) and Appendix B (Volume III) contain pertinent details. The candidate fuels were found to be gasoline and distillate hydrocarbons (coal and oil shale), methanol from coal, SNG from coal, and nuclear-based hydrogen.

Table 5. TANKAGE AND SAFETY PROPERTIES OF POTENTIAL FUELS

Fuel	Chemical Formula	Lower Heating Value, Btu/lb	Tankage Weight,[c] lb	Tankage Volume,[c] gal	Flammability Limits in Air, %		Ignition Temperature, °F	Dangerous for Prolonged Exposure, ppm
					Lean	Rich		
Acetylene	C_2H_2	20,780	800	390	2.8	80	581	Nontoxic[e]
Ammonia	NH_3	8,000	385	45	15	28	1200	100
Carbon Monoxide[a]	CO	4,350	2000	600	12.5	74	1128	100
Coal	C	10,000	200	18	d	d	d	Nontoxic
Diesel Oil or No. 2 Fuel Oil	Mix	18,480	150	22	--	--	494	500
Ethanol	C_2H_5OH	11,930	235	30	4.0	19	793	1000
No. 6 Fuel Oil	Mix	17,160	165	22	--	--	765	500
Gasoline	Mix	19,290	145	22	1.4	7.6	430	500
Hydrazine	N_2H_4	7,000	710	65	4.7	100	518	1
Hydrogen (ℓ)[b]	H_2	51,620	200	105	4.1	74	1085	Nontoxic[e]
Kerosene	Mix	19,090	145	22	0.7	5	491	500
LPG (synthetic)	C_3H_8	19,940	180	27	2.1	10	808	Nontoxic[e]
Methanol	CH_3OH	9,080	280	41	6.7	36	878	200
Methylamine	CH_3NH_2	12,860	260	35	4.9	21	806	10
Methane SNG (ℓ)[b]	CH_4	21,250	165	45	5.0	15	1170	Nontoxic[e]
Naphthas (approx)	Mix	18,850	150	22	1.1	6	430-530	500
Vegetable Oil (Cottonseed)	Mix	16,110	165	22	--	--	530	Nontoxic

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[a] Gaseous.

[b] Cryogenic liquid.

[c] Energy equivalent of 20 gallons of gasoline.

[d] For coal dust, the flammability data vary with the type of coal. For dust of coal of medium volatility, the ignition temperature is about 1100°F. The minimum explosive concentration is about 50 oz/1000 cu ft.

[e] Asphyxiant.

For these candidate fuels, the economics have been calculated by using discounted cash flow (DCF) financing in accordance with the method contained in The Supply-Technical Advisory Task Force — Synthetic Gas-Coal report.[2] The basis of this financing process is outlined in Table 6.

For resource extraction and fuel synthesis, we have made careful determinations of all components of capital and operating costs. Table 7 presents the results for those candidate fuels and synthesis routes that could be characterized in sufficient detail.

Similarly, the capital and operating costs have been derived for transmission and distribution of the candidate alternative fuels to service stations. These costs are combined with the fuel production costs to arrive at the fuel system costs in Table 8. The corresponding reference (domestic crude) gasoline costs are $\$1.60/10^6$ Btu for crude production and refining, and $\$1.20/10^6$ Btu for product transmission and distribution, for a total of $\$2.80/10^6$ Btu delivered.

The system costs of Table 8 are the base costs used for candidate fuel evaluation in the future time frames. These costs are in terms of late-1973 dollars. They are the predicted fuel costs at the service station and vehicle interface, but they do not include Federal and state sales and other taxes normally imposed on gasoline and alcohol.

In the future, coal, oil shale, and fissile (nuclear) fuels will escalate in real costs because of the necessity for deeper mining, the use of lower-assay-material deposits, longer distance transport of materials including water, and environmental and safety regulations. Synthesis costs also will escalate because of the necessarily increased amounts of processing per unit of product. Breeder processing of nuclear fuels also will be a necessary expense if the nuclear energy supply is to be sizable (as predicted) after 1985. Economies of scale cannot be expected to reduce costs because all plants and resource extraction sites have already been considered in sizes above the range in which economies of scale apply. Further, up-to-date technology and some technological advances, particularly in resource extraction, were assumed in deriving the base costs. Additional technological advances were assumed

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[2] Synthetic Gas-Coal Task Force, The Supply-Technical Advisory Task Force — Synthetic Gas-Coal. Prepared for the Supply-Technical Advisory Committee, National Gas Survey, Federal Power Commission, April 1973.

Table 6. BASES FOR FUEL COST CALCULATION BY THE DCF METHOD

Basis

- 25-year project life
- 16-year sum-of-the-years'-digits depreciation on total plant investment
- 100% equity capital

Essential Input Parameters

- 12% DCF return rate
- 48% Federal income tax rate

Handling of Principal Cost Items

- Total plant investment and working capital are treated as capital costs at start-up completion.
- "Return on investment during construction" (equal to total plant investment X DCF return rate X 1.875 years) is treated as a capital cost at start-up completion.
- Start-up costs are treated as an expense at start-up completion.

* See Appendix B (Volume III) for detailed calculations.

Table 7. PATTERN SYNTHESIS PROCESSES AND FUEL PRODUCTION COSTS (1973 Dollars)

Raw Material	Synthesized Fuel	Pattern Process	Production Cost (12% DCF)*	
			Volume Basis, \$/gal	Energy Basis, \$/10^6 Btu*
Coal	Gasoline	Consol Synthetic Fuel (CSF) plus refining with hydrocracking	0.33	2.81
Coal	Gasoline and distillate oils	Consol Synthetic Fuel (CSF) plus refining with catalytic cracking	0.31	2.51
Oil Shale	Gasoline and distillate oils	Gas Combustion Process (Bureau of Mines) plus hydrotreating and refining	0.25	2.05
Coal	Methanol	Koppers-Totzek gasifier and ICI synthesis	0.23	3.88
Coal	SNG (CH_4)	Lurgi gasifier with methanation	1.84/10^3 SCF†	2.14

* If 10% SCF financing is used, the resulting fuel synthesis costs are 88% to 91% of the costs presented in this table.

† Basis: the low heating value of the fuel.

Table 8. SYSTEM BASE COSTS FOR CANDIDATE FUELS
(1973 Dollars)[a]

Resource Base and Synthetic Fuel	Resource Extraction and Fuel Synthesis ($/10^6 Btu)	Transmission and Distribution ($/10^6 Btu)	Total Cost ($/10^6 Btu)	Total Cost, $/gal
Coal				
Gasoline (Primarily)	2.81	1.06	3.87	0.49
Gasoline and Distillate Oil[b]	2.51	1.06	3.57	0.47
Methanol	3.88	1.34	5.22	0.32
SNG[c]	2.14	2.04	4.18	0.31
Oil Shale				
Gasoline and Distillate Oil[b]	2.05	1.06	3.11	0.39
Nuclear Heat				
Hydrogen[d]	4.55	3.83	8.38	0.25
Hydrogen[e]	4.55	2.21	6.76	--
Reference Gasoline	1.60	1.20	2.80	0.33

[a] Basis, low heating values of the fuels.

[b] 50:50 product mix, average price.

[c] SNG transmission and distribution as a gas, liquefied at service stations.

[d] Thermochemical hydrogen transmission to terminal as a gas, liquefied, and distributed in liquid-hydrogen trucks to service stations.

[e] Thermochemical hydrogen transmission and distribution as a gas, combined as a metal hydride at the service stations.

in the cost projections for future time frames. However, the cost of domestic petroleum also will increase for many of the same reasons. The expected real cost increases for each candidate fuel in each time frame are detailed in Section 8 (Volume II). Figure 4 illustrates the projected fuel costs throughout the time frames of this study.

SELECTED FUELS AND STUDY RESULTS

The selected alternative fuels for automotive use according to time frame are presented in Table 9.

Table 9. SELECTED ALTERNATIVE FUELS

Near Term (1975-85)	Mid Term (1985-2000)	Far Term (Beyond 2000)
Gasoline from oil shale and water or coal and water	Gasoline from coal and water or oil shale and water	Gasoline from coal and water or oil shale and water
Distillate (diesel) oils from oil shale and water or coal and water	Distillate (diesel) oils from coal and water or oil shale and water	Distillate (diesel) oils from coal and water or oil shale and water
	Methanol from coal and water	Nuclear-based hydrogen (from water)
		Methanol from coal and water

According to a scenario based on Model I energy demand and supply, the production rates of synthetic fuels for automotive transportation and the required fuel imports are presented in Table 10. The additional coal- and nuclear-based energy included in this table is that fuel (converted from heat at 35% until 2000, at 42% in 2020) that is potentially available according to Model I energy supply. By 2000, part of the nuclear portion of this could be hydrogen. Methanol is not included. Because of water limitations in the Western coal fields, full-scale gasoline-plus-distillate-oil production and full-scale methanol production are mutually exclusive. Of course, part-scale production of both to some coal-industry product mix of gasoline, distillate oils, and methanol is possible. According to the pattern process studies, methanol synthesis requires 60% more water than gasoline and distillate oil synthesis. Therefore, in terms of ultimate industry capacity, methanol from coal is a less favored fuel. Nuclear plants for producing hydrogen from water may be sited in areas where water is more abundant and not a limitation to production rates.

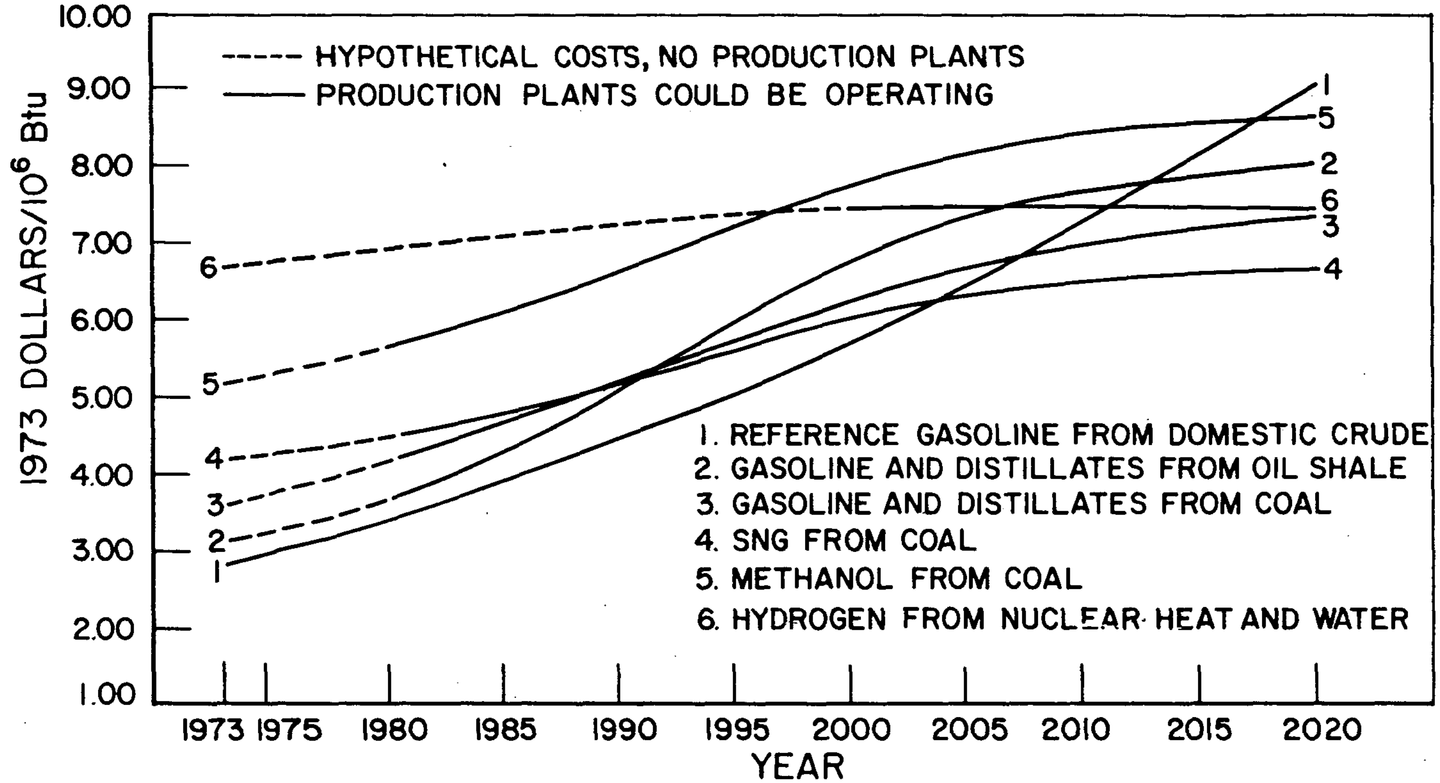

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Figure 4. CANDIDATE AUTOMOTIVE FUEL COSTS AT SERVICE STATIONS FOR CURRENT AND FUTURE TIME FRAMES (1973 Dollars/Million Btu; Basis: Low Heating Value; 12% DCF Financing)

Table 10. ALTERNATIVE AUTOMOTIVE FUEL SUPPLY CORRESPONDING TO ENERGY DEMAND AND SUPPLY MODEL I

Year	Conventional Gasoline and Diesel Oil*	Oil Shale Fuels†	Coal Fuels†	Potential Additional Coal- and Nuclear-Based Fuels‡	Required Fuel Imports
	10^{15} Btu				
1975	9.7	Nil	Nil	Nil	4.9
1980	11.2	0.2	0.1	Nil	5.6
1985	13.1	0.7	0.4	6.5	(0.9)
1990	12.9	2.0	1.5	7.5	(1.4)
2000	12.7	2.8	4.2	10.1	0.2
2020	12.7	2.8	5.3	30.1	1.1

* Automotive portion (75%) of the transportation supply (55% of the domestic crude fuel).

† Gasoline and distillate hydrocarbons; automotive portion of the transportation supply.

‡ Hypothetical fuel production, automotive portion, in addition to the energy industry growth of the scenario based on Model I.

The important conclusions that we have reached on the basis of this study are as follows:

- It is feasible to produce alternative automotive fuels from domestic resources within the foreseeable future and in quantities sufficient to alleviate petroleum imports. The adequate energy resources are coal, oil shale, and fissionable nuclear fuels. The preferred automotive fuels are gasoline and distillate hydrocarbons, methanol, and hydrogen. If it were not for higher-priority uses, SNG and SLPG also would be favored fuels for automotive use.

- The production of fissionable fuels (uranium and plutonium) from fertile materials (thorium or depleted uranium) is a practical requirement for nuclear energy to be assured as a major energy supply beyond 1985. The breeding of U^{233} or Pu^{239} has been demonstrated, and limited production of U^{233} from Th^{232} occurs in the newly commercialized high-temperature, gas-cooled reactors. However, a demonstration of a fast breeder reactor is needed to show commercial potential for net production of fissionable fuel.

- As a potential source of energy in the far-term time frame and beyond and almost without raw material limits, fusion reactors promise an eventual solution to the continuing energy crisis. Aside from capital investment limitations, reactors creating the fusion of deuterium nuclei and extracting some of the produced energy could be used for electricity generation, hydrogen production from water, and process-heat applications. However, demonstration of net energy production from a continuously operating fusion mechanism is not anticipated in the near future. This required demonstration of concept constitutes a serious technology gap. Therefore, it cannot be considered as an energy source for automotive fuels before the year 2000.

- With present agricultural technology, solar energy is converted to plant material at an efficiency of about 1%. After conversion to a chemical fuel, the overall efficiency is about 0.5%. Although the energy is free, the land area and capital investment are not. To be practical, solar plantations need higher energy efficiencies and must not reduce necessary domestic food-crop capabilities.

- A nonfossil and nonelectric process for producing a chemical fuel from a renewable material resource is highly desirable. Such a process might be coupled to solar energy, nuclear fusion process heat, or nuclear fission process heat, to provide supplemental amounts of a chemical fuel such as hydrogen or methanol. Methane or alcohol from water and a renewable carbon resource (e.g., carbon from vegetation) or an extensive resource (limestone) are other possibilities.

- At present, there is no satisfactory method to tank sufficient hydrogen on-board a vehicle. Three options have been considered:

  a. Liquid hydrogen is bulky, requires vacuum-jacketed tanks, and suffers from the problems enumerated earlier.

  b. Metal hydride storage is too heavy and, in most cases, requires moderate- or high-temperature heat for decomposition to "generate" the hydrogen. The logistics of hydride regeneration have not been defined sufficiently, and the most practical and cost-effective scheme has not been delineated. A systems study is in order.

  c. Hydrogen can be carried by chemical bonding as another material, preferably as a liquid, such as methanol, formaldehyde, acetic acid, methyl formate, or gasoline. These chemicals can be decomposed (reformed) on-board the vehicle to produce hydrogen. Feasibility studies and experimental programs are in order.

Section 9 (in Volume II) contains a listing of technology and information gaps related to alternative fuels for automotive use. Included are the aspects of vehicle efficiency and fuel consumption, emissions and pollutants from alternative fuels, and engine operating problems. Further, the need for social and economic impact studies is expressed.