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# SYNTHETIC FUELS FOR GROUND TRANSPORTATION
# WITH SPECIAL EMPHASIS ON HYDROGEN

By Jag J. Singh

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16. Abstract

The role of various synthetic fuels, for ground transportation in the United States, has been examined for the near term (by 1985) and the longer term applications (1985-2000 and beyond 2000). Feasible options, in their respective order of viability are: Synthetic oil, methanol, electric propulsion and hydrogen. It is concluded that the competition during the next 50 years will be <u>for</u> the fuels of all types, rather than <u>among</u> the fuels. The major conclusions of the present study are as follows: (1) Initiate extensive domestic oil and gas exploration concurrent with the development of several alternate fuels and related ancillaries; (2) hydrogen, as an automotive fuel, seems to be quite equivalent to the gasoline for optimum fuel to air mixtures. As a pollution free, high energy density fuel, hydrogen deserves serious consideration as the logical replacement for the hydrocarbons in the 21st century. Several research and development requirements, essential for the implementation of hydrogen economy for ground transportation, have been identified. (3) Extensive engineering development and testing activities should be initiated to establish hydrogen as the future automotive fuel, followed by demonstration projects and concerted efforts at public education. It should be resolved to meet all United States transportation fuel needs with hydrogen by the year 2025.

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# SYNTHETIC FUELS FOR GROUND TRANSPORTATION WITH SPECIAL EMPHASIS ON HYDROGEN

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## 1. ABSTRACT

The role of various snythetic fuels, for ground transportation in the United States, has been examined for the near term (by 1985) and the longer term applications (1985-2000 and beyond 2000). Feasible options, in their respective order of viability are: Synthetic oil, methanol, electric propulsion and hydrogen. It is concluded that the competition during the next 50 years will be <u>for</u> the fuels of all types, rather than <u>among</u> the fuels. The major conclusions of the present study are as follows: (1) Initiate extensive domestic oil and gas exploration concurrent with the development of several alternate fuels and related ancillaries; (2) hydrogen, as an automotive fuel, seems to be quite equivalent to the gasoline for optimum fuel to air mixtures. As a pollution free, high energy density fuel, hydrogen deserves serious consideration as the logical replacement for the hydrocarbons in the 21<u>st</u> century. Several research and development requirements, essential for the implementation of hydrogen economy for ground transportation, have been identified. (3) Extensive engineering development and testing activities should be initiated to establish hydrogen as the future automotive fuel, followed by demonstration projects and concerted efforts at public education. It should be resolved to meet all United States transportation fuel needs with hydrogen by the year 2025.

## 2. INTRODUCTION

It is now widely recognized that the country's growing liquid fuel demands can only be met if the domestic supplies are augmented by increasing oil and gas imports. The situation is particularly critical in transportation sector where about 96 percent of the needs are met by petrochemical fuels. Dependence on foreign imports is undesirable because of serious economic and national security repercussions resulting from unexpected interruptions. It is therefore necessary to try to find additional oil/gas resources in the country and develop alternate fuels for transportation vehicles. The former is only an interim solution that may provide enough breathing spell to develop alternate sources which will supply the long-term automotive needs. It calls for stepped up efforts to locate new oil/gas reserves. Besides the continental shelf areas, search for oil/gas should also be made on the continental slopes. These are the areas where the bottom of the ocean inclines downwards from the continental shelf towards the abysmal depths of mid-ocean. Conditions for the oil formation - presence of organic matter and the protection from oxidation - are likely to exist on the slopes. There is some stratigraphic evidence for the possible existence of oil in the deep sea areas. A survey of the Gulf of Mexico running from Texas to the Yucatan peninsula has yielded evidence of salt domes under the deep sea areas. Salt domes are a particular kind of salt deposits that often occur in conjunction with the petroleum deposits. It is thus possible that huge reserves of oil lie under the sea, more than are known to lie under the continents. Unless substantial new areas are opened to exploration for oil and production is developed quickly, the energy content of domestically produced hydrocarbons could drop by as much as 30 percent during the next decade. (Merely to maintain the current total energy consumption rate would require increasing imports of oil by 2-3 million barrels per day over present levels.) The alternate fuels should, ideally, be derived from non-fossil sources because of the finite nature of the United States (and the world, for that matter) fossil reserves. However, the currently known United States coal and oil shale reserves are large enough to warrant consideration of synthetic fuels (syncrude and methanol) derived from them. Most of the technology needed to convert coal and oil shale to liquid synthetic fuels is already in existence. These synthetic fuels will provide the cheapest alternate sources since the transportation and the distribution facilities for liquid fuels are already in existence.

The real long term solution to the automotive fuel needs - and all other energy requirements - will have to depend upon a fuel derived from an essentially inexhaustible energy source, such as the solar, nuclear, or the geothermal power. One such fuel is hydrogen derived from the electrolysis of water, another almost inexhaustible source. Hydrogen may be used to synthesize other fuels - methane, methanol, ammonia, hydrazine, and synthetic gasoline - or be used directly as the fuel. In this report, the potential of various synthetic fuels for ground transportation - with special emphasis on hydrogen - will be discussed. Comparison of liquid hydrogen fuel with the other synthetic fuels and electric propulsion methods will be made for the following time periods: Present → 1985; 1985-2000 and beyond the year 2000. Research and development needs for the implementation of synthetic fuel-based transportation industry will also be identified.

Whereas the long-run solution of the automotive fuel problem will have to depend on an essentially "un-exhaustible" energy resource, such as solar, nuclear or the geothermal power, the following interim measures should be adopted:

1. Increase the supply of petroleum, natural gas, and coal through advanced exploration, drilling, and recovery methods.

2. Begin to shift consumption from liquid fuels derived from petroleum to synthetic fuels.

3. Support the energy conservation measures by (a) improving energy efficiency of automotive engines and (b) optimizing freight/passenger transportation modes.

All of these steps combined are expected to result in considerable reduction in the United States fuel imports, thereby lessening the pressure on the conventional world oil supplies. (Thus, increasing the Unites States capability to meet its fuel demands is of great importance to the rest of the world also.)

In the immediate future (1975-1985), only those alternatives for which the technologies are already in existence or on the verge of commercial operation can make a contribution. In the case of transportation vehicles, this implies continued use of liquid fuels. These liquid fuels will have to be increasingly supplied by synthesis from coal and oil shale. There are two paths that can be followed to meet the liquid fuel needs for internal combustion engine-based transportation vehicles.

1. Some vehicles will be used on 100 percent petroleum-derived gasoline as now, while others will be operated on 100 percent synthetic liquid fuels ($C_xH_y$, $LH_2$, $NH_3$, and $NH_2NH_2$, etc.).

2. All vehicles will be operated on mixtures of natural and synthetic fuels (i.e., mixtures of petroleum-derived gasoline and synthetic fuels such as methanol and hydrogen, etc.). No differentiation is made between the normal gasoline and synthetic gasoline.

Of these two alternatives, the second approach appears to be more promising for the immediate future since all the reported laboratory and field tests indicate that the existing internal combustion engines can operate reliably on dilute mixtures of gasoline and synthetic fuels.

In the following pages, the discussion of these choices will be expanded. The synthetic fuels will include all hydrocarbons, hydrogen and its inorganic compounds, and electrical batteries.

## List of Symbols and Abbreviations

| | |
|---|---|
| Btu | British thermal unit |
| MW | Megawatt |
| $C_2$-$C_4$ alcohols | Higher alcohols |
| $C_8$-$H_{18}$ | Iso-octane (gasoline) |
| R-O-N | Research Octane Number |
| $C_xH_y$ | Hydrocarbons |

| | |
|---|---|
| $NH_3$ | Ammonia |
| $(NH_2)_2$ | Hydrazine |
| $VH_2$ | Vanadium hydride |
| $NbH_2$ | Niobium hydride |
| $FeTi\text{-}H_2$ | Iron titanium hydride |
| $LH_2$ | Liquid hydrogen |
| $LO_2$ | Liquid oxygen |
| $LN_2$ | Liquid nitrogen |
| $GH_2$ | Gaseous hydrogen |
| NPC | National Petroleum Council |
| ICE | Internal combustion engine |
| $\varphi$ | Reaction equivalence ratio |
| Syncrude | Crude oil synthesized from coal and shale, etc. |
| SCF | Standard cubic foot |
| LNG | Liquified natural gas |
| PSI | Pounds per square inch |
| FOB | Free on board (cost at the point of origin) |

## 3. DISCUSSION OF SYNTHETIC FUELS

The alternate (synthetic) fuels should meet the following criteria:

Low cost

Easy/plentiful availability

Compatibility with existing engine designs

Desirable physical properties of the fuel (smell, visibility, and toxicity)

Easy storage/safety/transportation

The above criteria will be applied to the following fuels:

1. Synthetic gasoline } Coal/oil shale-derived fuels
2. Methanol
3. Ammonia and hydrazine
4. Electrochemical batteries/fuel cells
5. Hydrogen

## 3.1 - Synthetic Gasoline

Let us begin by considering the cost of production of synthetic crude oil (syncrude) which can be prepared from coal as well as oil shale. Both coal and oil shale are plentiful in the United States and are "relatively" cheap. Syncrude is probably similar to "crude" oil - except for its higher aromatic/paraffinitic content - and should therefore be compatible with the modern internal combustion engine (ICE).

3.1(a). Syncrude from Coal - Under the existing technologies, the processes for converting coal to gas and oil are somewhat similar. It would thus seem appropriate to try to combine these two processes at one site. Chem. Systems, Inc. studied (ref. 1) the feasibility of such a combined oil and gas refinery (COG) in 1971 and quoted the following parameters:

Feed input: Coal = 57,000 tons/day
Oxygen = 7,740 tons/day

Output: Sulphur = 1,800 tons
High Btu pipegas = 7,660 tons
Liquified petroleum gas = 1,980 tons
Oil = 14,660 tons
Refined coal = 8,850 tons (used to run the refinery)
\+ 2,550 tons (for sale)
"Other" chemicals = 156 tons

Net efficiency = 75.5%, i.e., only a quarter of the energy potential is lost in processing

Capital investment for this combined oil and gas refinery was estimated to be:

| Investment | $ (Millions) |
|---|---|
| Land | 13 |
| Coal mine | 139 |
| COG refinery | 605 |
| Working capital | 29 |
| TOTAL | $786 millions |

Based on this investment detail, oil investment of $4200/barrel per day and gas investment of $\$770/10^6$ SCF per day are estimated. These figures are comparable to the current cost of finding and developing natural supplies of oil and gas. If the combined oil and gas refinery proves feasible - economically and technically - it could deliver:

$10^{12}$ SCF/year (synthetic natural gas) and

$330 \times 10^6$ barrels/year (oil)

Five such refineries could supply 5 TSCF/yr of synthetic natural gas and almost 5 million barrels per day (oil) - enough to meet the United States current gas and oil imports! It should, of course, be realized that five such refineries will use up 100 million tons of coal per year (about 1/6 of total annual production in the United States (ref. 2)). However, capital, material, and manpower constraints will limit syncrude from coal to $\lesssim$1 million barrels per day by 1985. The National Petroleum Council (NPC) has estimated that, given the most favorable circumstances, large scale commercial coal liquifaction plants will not appear on the scene much before the early 1980's. It has estimated a maximum syncrude from coal capacity of 680,000 barrels/day by 1985 (ref. 3).

A recent Massachusetts Institute of Technology (MIT) study has estimated the following figures for capital and operating costs for a syncrude-from-coal refinery (ref. 4):

Plant output = 40,000 barrels/day (oil)

Annual capital at 15% per year = $\$51 \times 10^6$

Annual operating costs = $\$22 \times 10^6$

Annual fuel costs = $\$37 \times 10^6$

TOTAL = \$110 million/year

Cost/barrel (oil equivalent) = \$7.70 (the probable price for coal liquids has been estimated by NPC to fall in the range of \$6-8/barrel (1970 dollars))

Capital cost: $\$350 \times 10^6$

Years to design and build: 5 years

Man-hours needed to build the plant: $\left.\begin{array}{l} 1.5 \times 10^6 \text{ (technical)} \\ 10 \times 10^6 \text{ (manual)} \end{array}\right\}$

3.1(b). Syncrude from Oil-Shale - According to a U.S. Bureau of Mines estimate (ref. 5) the capital cost to construct a plant to produce about 100,000 barrels/day of shale oil runs to several hundred million dollars. The oil will have to sell at about \$4/barrel to yield a reasonable return on investment. These figures are consistent with the MIT cost breakdown, for a syncrude-from-oil shale refinery (ref. 4), given below:

Plant output = 40,000 barrels/day

Annual capital at 15% per year = $\$37 \times 10^6$

Annual operating costs = $\$22 \times 10^6$

Annual fuel costs = $\$37 \times 10^6$

TOTAL = \$96 million/year

Cost/barrel (oil equivalent) = \$6.80

Capital cost = $\$450 \times 10^6$

Years to design and build = 4 years

Man-hours needed to build plant = $\left.\begin{array}{l} 1.0 \times 10^6 \text{ (technical)} \\ 10 \times 10^6 \text{ (manual)} \end{array}\right\}$

According to the 1972 NPC study (ref. 3), under favorable conditions - but short of an all-out national effort - the 1985 syncrude-from-shale capacity is estimated at 750,000 barrels/day. (It will be made up of one 50,000 barrels per day and seven 100,000 barrels per day plants.) Although water availability may limit production over the long run, sufficient water is available for the highest anticipated production through 1985. For a 15 percent annual interest on capital cost, the price of syncrude from 30 gallons/ton shale is expected to range from $5.60-$5.80/barrel.

A feasibility study conducted by Exxon Research and Engineering Company, under contract to the Environmental Protection Agency (EPA), gives the following cost breakdown for gasoline obtained from coal and oil shale (ref. 6):

| Source | 1982 Prices(*) | Capital Investment |
|---|---|---|
| Coal | $\$3.35/10^6$ Btu | $11.6K/barrel-day |
| Shale | $\$2.65/10^6$ Btu | $6.7K/barrel-day |

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(*) These prices are quoted in 1973 dollars and do not include any taxes. The prices are, of course, highly tentative because of the fluctuating raw fuel, materials, and manpower costs.

Beyond the year 1985, when first plants for syncrude will have been operational, other plants could be started rapidly in the following years - subject to the availability of capital, materials, and manpower. It is anticipated that by the year 2000, the syncrude capacity - both from coal and oil shale - will have reached (5-10) million barrels per day (ref. 3).

Syncrude can also be made from tar sands. As a matter of fact, tar sand is of major importance as the base fuel because there is already some commercial (tar sand → syncrude) production in Canada (ref. 3). However, the largest known tar sand deposits - and the only ones of commercial importance - are in the Athabasca regions of Alberta in Western Canada. According to the Alberta Oil and Gas Conservation Board estimates, there are some 300 billion barrels (oil equivalent) of potential resources, with about 6.3 billion barrels being easily recoverable. The technology for tar sand processing is relatively simple, though there are some environmental and economic problems associated with the mining of tar sand. The National Petroleum Council's U.S. Energy Outlook Study (ref. 3) estimated maximum syncrude production from tar sands at 1.25 million barrels per day by 1985. This limitation is imposed mainly by the problems of design and construction of large facilities and the availability of the capital. Tar sand technology and its impact on the United States energy resources has not been considered because of its foreign location, even though it is expected to have a strong influence on the energy balance sheet.

## 3.2 - Methanol

Methanol can be produced from coal and shale as well as organic wastes (municipal/agricultural). However, major sources of methanol are likely to be coal and shale (?).

According to the MIT study (ref. 4), methanol-from-coal cost estimate runs as follows:

Plant output = 40,000 barrels/day (oil equivalent)

Annual capital at 15% per year = $\$51 \times 10^6$

Annual operating cost = $\$44 \times 10^6$

Annual fuel cost = $\$48 \times 10^6$

---

TOTAL = \$143 million/year

Cost/barrel (or equivalent) = \$10.00

Capital cost = $\$350 \times 10^6$

It would require the same length of time to design and build a methanol production plant as an equal capacity syncrude-from-coal plant and would require the same number of skilled and unskilled man-hours. The expansion constraints on the methanol refineries are the same as those for syncrude-from-coal refineries.

The Exxon estimates (ref. 6) for methanol costs are $\$3.85/10^6$ Btu (for 1982-1985) in 1973 dollars. This cost is based on coal gasification with the Lurgi process followed by methanol synthesis from ($CO + H_2$). This scheme produces methanol and methane (SNG) as coproducts. Other gasification processes seem to be less efficient for this application. (The information on the alternate processes is limited.)

Methanol fuel distribution problems are expected to be significantly different from distributing petroleum products for two reasons:

1. If used in a 10-15 percent gasoline blend, blended at the pump, methanol must be distributed dry to avoid phase separation in the gasoline tank.

2. Methanol has about 50 percent of the energy content of hydrocarbon fuels, which leads to higher distribution costs per Btu.

The following table lists the production and distribution costs of syncrude (gasoline) and methanol in 1980-2000 time interval.

Table I - Cost Comparison for Synthetic Gasoline and Methanol (ref. 6)

| Fuel | 1982 | 1990 | 2000 |
|---|---|---|---|
| Shale → oil (gasoline) | $2.65/10^6$ Btu | $2.60 | $2.10 |
| Coal → oil (gasoline) | $3.35/10^6$ Btu | $3.15 | $2.65 |
| Coal → methanol | $3.85/10^6$ Btu | $3.40 | $2.95 |

Methanol is slightly more costly than coal liquids reflecting the higher distribution costs. (It would appear that methanol would be more suitable for fleet accounts and certain non-transportation uses.)

The capital investments cost for methanol is estimated at about $5.9K/barrel (oil equivalent) per day.

The relative efficiencies of processes for producing synthetic gasoline and methanol are summarized below.

Table II - Relative Production Efficiencies for Synthetic Gasoline and Methanol (ref. 6)

| Fuel System | Efficiency |
|---|---|
| Synthetic gasoline from shale | 55% |
| Synthetic gasoline from coal | 65% |
| Methanol from coal | 55-65% |

Efficiencies for shale fuel production are a little lower due to losses in shale retorting.

Methanol can be transported by almost all means - including oil and chemical pipelines. It is a colorless, odorless and water-soluble liquid at room temperature. Auto ignition temperature of methanol is 467°C - as compared with 222°C for gasoline. The following table compares the energy content of methanol with other fuels.

Table III - Relative Energy Contents of Various Fuels (ref. 7)

| Fuel Type | Kilojoules/gm | Kilojoules/cc |
|---|---|---|
| Gasoline | 44.3 | 30.9 |
| Methanol | 20.1 | 15.9 |
| Hydrogen | 124.7 | 8.7 |

Existing engines can be converted to use pure methanol, if sufficient quantities of it were available, if the air/fuel ratio is changed from about 14 (gasoline) to 6 (methanol). The conversion costs per vehicle are estimated at about $100.00 (ref. 7). A municipal vehicle so converted has been in operation at Santa Clara, California, for over 2 years (ref. 7). Besides the higher compression ratio, the methanol operated engines will also need a bigger fuel tank as seen from Table III. The best solution appears to be the use of a methanol-gasoline blend as fuel. Such a mixed fuel is expected to improve the engine performance, besides reducing air pollution (ref. 7). However, recent Exxon tests on 15 percent (by volume) of methanol in gasoline mixtures indicate the following problems with the blend (ref. 8).

1. Fuel economy occurs only in the older (1967 or earlier model) cars designed to run net rich. (This is because of the leaning effect of methanol on carburation.)

2. The addition of methanol, a polar molecule, to gasoline (non-polar) results in increase in the mixture vapor pressure. This usually results in vapor locking, evidenced by hesitation in response to throttle, stalling during the throttle, difficult hot starts and rough hot idle.

3. Water causes phase separation of the blend. The methanol water layer separates out at the bottom of the fuel tank. Hence a car adjusted to run on the blend will not run on the phase separated blend.

In view of these results, it is necessary to obtain extensive test data with blended fuels in all types of vehicles under field operation conditions before a decision on the use of methanol is made.

According to a recent report (ref. 9), there may exist a market for 18 methyl-fuel plants (via coal gasification, based on 1000 megawatts power plant potential) by 1975. This demand could rise to 28 by 1980 and to about 120 by 1990. The following table summarizes the market potential and uses for methyl-fuel plants.

Table IV - Summary of Market Potential and Uses for Methyl Fuel Plants (ref. 9)

| Market/Use | No. Plants Needed[†] (Based on 1000-MW Power Plant Potential) | | | |
|---|---|---|---|---|
| | 1975 | 1980 | 1985 | 1990 |
| Utility | 0 | 6 | 40(*) | 82(*) |
| Gasoline extender | 17 | 20 | 23 | 30 |
| Sewage de-nitrification | 1 | 2 | 4 | 7 |
| TOTAL | 18 | 28 | 67 | 119 |

(*) Notice the jump in the use of methyl-fuel for utilities in 1985 and beyond.

Methyl-fuel is a blend of methanol with controlled amount of $C_2$-$C_4$ alcohols. The presence of higher alcohols in the blend increases its gross heating value and significantly reduces the transportation and other handling costs. Clearly, methyl-fuel mixed with gasoline has a great potential as internal combustion engine automobile fuel. However, additional tests on the driveability, engine efficiency, and year-round operatability of (methyl-fuel + gasoline) blend operated vehicles of all types are required before a full commitment to this type of fuel is made.

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[†] These estimates may be over-optimistic in view of possible material, material technology, and manpower constraints attendant on a large scale energy base expansion. Lowering these estimates by a factor of 2-3 may give more realistic projections.

The following table summarizes the feasibility of producing synthetic fuels discussed so far.

Table V - Feasibility of Large Scale Production of Various Fuels

| Fuel Type | Prospects for Large Scale Production |
|---|---|
| Oil (from oil shale) | Design and construction can be undertaken <u>immediately</u>. |
| Oil (from coal) | 3-5 years development work needed before plant design and construction could be undertaken.<br>Demonstration plants for (coal → oil) conversion should be set up <u>immediately</u>. |
| Methanol (from coal) | Design and construction can be undertaken <u>immediately</u>. |

In view of the technological process uncertainties and the scale of the operation involved, it seems unlikely that any significant production of synthetic fuels (syncrude and methanol) can be expected before 1985. Even then, a tremendous effort will be required to replace a large fraction of petrol (gasoline) use with coal/shale-derived fuels.

### 3.3 - Ammonia and Hydrazine as Transportation Fuels

3.3(a). Ammonia - Ammonia is a feasible alternate fuel because of its potential availability (20 x $10^6$ tons/year in 1972), low cost (3¢/lb, industrial grade), low pollution and easy storage (ref. 10). It can be safely stored as a liquid in the same fuel tank as gasoline if copper, brass, and zinc are replaced by steel or aluminum. Ammonia has a very high octane rating (= 130 + R.O.N.). The basic process for the manufacture of ammonia is well-developed and has been in commercial use for many years. The only future significant changes would be in the use of new sources of hydrogen. The present low cost of ammonia is greatly dependent on the use of low-cost natural gas. However, the future hydrogen supplies will have to come - first from coal and oil shale and eventually from electrolysis of water. In the period up to 1985, these alternate sources are not expected to make any significant contribution to ammonia production. It is possible that the combined water electrolysis/coal gasification arrangements can come on board in significant numbers in the 1985-2000 period if the following questions about ammonia can be answered satisfactorily:

1. Does the use of ammonia truly represent an alleviation of air pollution problem? (Is the increased ammonia load on the atmosphere an environmental hazard?)

2. Is it realistic to expect that industrial grade ammonia production rates can be increased to meet the new market demands if ammonia is used as auto fuel?

In view of ammonia toxicity and tank rupture hazard, it does not appear likely that ammonia will be used as a direct fuel for internal combustion engines. Its use as a hydrogen carrier may deserve some further consideration, though the heating value of liquid ammonia, compared with liquid hydrogen is rather low ($8.1 \times 10^3$ Btu/lb (ammonia) vs $51.7 \times 10^3$ Btu/lb (hydrogen).

3.3(b). Hydrazine - Currently hydrazine is produced by two processes:

1. The Raschig process

2. The Urea process

In the Raschig process, one goes through the stage of producing ammonia first and then synthesizing it with sodium hypochlorite to produce hydrazine. In the Urea process, hydrazine is formed by the reaction of sodium hypochlorite and Urea. At high production levels ($\gtrsim$ 1.5 million pounds of $(NH_2)_2$ per year) the Raschig process can provide hydrazine at a cost of $\lesssim$ 50¢/lb. For a large plant (~ 1000 tons/day), with optimization of waste heat, etc., Olin Mathieson Company indicated the possibility of producing hydrazine to sell at 20¢/lb (ref. 10). The total United States capacity for $(NH_2)_2$ production in 1966 was only about $1.5 \times 10^4$ tons/year.

Like ammonia, hydrazine is a toxic element as seen from the following data.

Table VI - Toxicity Threshold for Various Fuels (ref. 10)

| Fuel | Toxicity Threshold (in parts per million) |
|---|---|
| Ammonia | 100 ppm |
| Hydrazine | 10 ppm |
| Gasoline | 500 ppm (for 8-hour period) |

Hydrazine vapors are irritating to the eye, nose, and throat. Contact of hydrazine with any body tissues will produce a caustic-like burn if not washed off immediately. Ingestion or absorption through the skin causes nausea, dizziness, headache and may even prove fatal. Hydrazine vapor in air is flammable between (4.7-100) percent hydrazine by volume. When burning freely in air, hydrazine behaves much like gasoline. But at elevated temperatures, hydrazine burns fiercely. The use of hydrazine as automotive fuel has the same limitations as ammonia, if not more so.

Ammonia and hydrazine have better future prospects in supplying fuels for fuel cells for use in electric propulsion. However, the current use of exotic noble metals as catalysts, coupled with high cost of production of ammonia ($NH_3$) and hydrazine ($N_2H_4$) fuels, makes standard production of fuel cells rather unlikely in the near future. In the following table, the relative heat content of $NH_3$, $(NH_2)_2$ and gasoline ($C_8H_{18}$) are compared:

Table VII - Relative Heat Contents of Ammonia, Hydrazine, and Gasoline (ref. 11)

| Fuel | Amount Needed to Provide 6.072 x $10^5$ Kcal | | Heat of Combustion (Kcal/gm) |
|---|---|---|---|
| | Volume | Weight (Kgm) | |
| Iso-octane, gasoline ($C_8H_{18}$) | 80 | 55.3 | 10.98 |
| Ammonia ($NH_3$) | 167 | 136.7 | 4.44 |
| Hydrazine ($N_2H_4$) | 151 | 152.5 | 3.98 |

## 3.4 - Electrochemical Batteries/Fuel Cells

Electric ground propulsion systems can provide a means of decreasing the atmospheric pollution as well as partially reducing automotive demands on the world's limited petrochemical supplies. All-electric and hybrid-electric vehicles have been proposed, and in some instances developed, in several countries. To develop competitive vehicles of this type, power sources with increased thermal, thermomechanical, and electrochemical energy conversion efficiencies and transfer systems must be developed. The electric propulsion system will have to meet the following minimum requirements before it becomes widely accepted (ref. 12):

(a) Average Family Car - (4000 lbs; 5-6 passengers; max. speed 80 mph, and 0 → 60 mph acceleration time $\simeq$ 13 seconds).

(1) Min. energy density(*) - 135 watt-hrs/pound

(2) Min. power density - 100 watts/pound

(3) Range - 200 miles/charge

(4) Speed - 60 miles per hour

(5) Service life - $\gtrsim$ 5 years

(6) Payload - 50% of gross weight

(7) Cost - \$10-20/KW-hr (comparable to the present day automobiles of comparable performance)

---

(*) The energy density in a gasoline powered car is $\simeq$ 1200 watt-hrs/pound.

(b) Other Road Vehicles -

| Vehicle Type | Range | Speed | Energy Density | Power Density |
|---|---|---|---|---|
| Commuter car | 100 miles | 60 mph | 28 watt-hr/lb | 31 watts/lb |
| Delivery van | 60 | 40 | 33 | 36 |
| City taxi | 150 | 40 | 64 | 30 |
| City bus | 120 | 30 | 55 | 25 |

The currently available lead-acid storage batteries cannot meet the specific energy and power requirements for either class of vehicles satisfactorily. However, the sodium-sulphur (Na-S) and the lithium-sulphur (Li-S) high energy batteries can provide sufficient energy and power to meet the needs of both classes of vehicles. The (Na-S) battery is expected to prove more economical if a reasonable service life ($\gtrsim$ 5 years) can be achieved. The service life of this battery depends upon the life of the ceramic separator. The performance of the presently available/feasible electrical vehicles does not measure up to the performance of internal combustion engine (ICE) vehicles as illustrated by the following comparison for a 3200 pounds weight vehicle:

Table VIII(a) - Comparison of Electrical Vehicles with the ICE Equipped Vehicles

| Vehicle Characteristic | Electric Propulsion | | Internal Combustion Engine |
|---|---|---|---|
| | (Lead-Acid) | (Sodium-Sulphur) | |
| Payload | 300 lbs | 300 lbs | 800 lbs |
| Motor power | 30 hp | 30 hp | 150 cubic inches |
| Range (at 20 mph) | 48 miles | 483 miles(*) | 273 miles |
| Range (city driving) | 28 miles | 280 miles(*) | 233 miles |
| Acc. dist. in 10 sec. | 365 feet | 365 feet | 373 feet |
| Fuel costs (¢/mile) | 1.1 | 1.0 | 1.4 (tax excluded) |
| Operating costs (¢/mile) | 4.2 | 1.7 | 2.1 |
| Total vehicle cost (¢/mile) (for city driving) | 8.3 | 8.2 | 5.6 |
| Energy density | 10 watt-hrs/lb | 100 watt-hrs/lb | 1200 watt-hrs/lb |

(*)Notice the jump in the range-related to the energy density of the power plant - as we go from lead-acid battery to sodium-sulphur battery.

An (Na-S) battery with the desired characteristics does not yet exist. The following table summarizes the objectives of the sodium-sulphur battery development program.

Table VIII(b) - Summary of the Objectives of (Na-S) Battery Development Program (ref. 13)

| Parameter | Electric Propulsion | Power System Load Levelling |
|---|---|---|
| Energy density (watt-hrs/lb) | 100 | 25 |
| Power density (watts/lb) | 100 | 25 |
| Durability (years) | 5<br>(1000 cycles) | 25 |
| Cost ($/KWH) | 20 | (5-15) |

The problems that remain to be solved before the sodium-sulphur (Na-S) battery system with the above characteristics becomes available are listed below:

(1) Containers to hold sodium polysulphide melt at 575°F, the temperature needed to keep the electrodes in liquid form.

(2) Thermal insulation and control of the temperature of the electrodes.

(3) Inexpensive processing methods for the manufacture of ceramic electrolyte.

In view of this formidable list, it appears that (Na-S) batteries will not be available for vehicular applications in the next 5 years. In the absence of durable (Na-S) battery - or equivalent - the ground electric propulsion will be limited to short range city driving - mainly in public transportation vehicles (buses and trains) for the next decade. Even with the availability of a battery with required power/energy characteristics, an electric vehicle will still suffer from reduced payload due to high weight of the battery.

The overall fuel utilization efficiency in electrically propelled vehicles is of the order of 13 percent (i.e., 7 → 21%), no more than that of the conventional gasoline powered internal combustion engine (ref. 14). Yet, there is some evidence that a small scale substitution of conventional mode of propulsion by electric propulsion may occur by 1985 - with gradually increasing substitution by the year 2000. Two, rather fanciful, scenarios (ref. 14) are stated below:

Scenario #1

(Based on a total of 125 million vehicles in 1985).

The no. of electrically propelled vehicles:

| | |
|---|---|
| (a) Limited performance vehicles (4000 miles/yr) | 5 million |
| (b) Standard performance vehicles (12,000 miles/yr) | 5 million |
| Calculated total electric energy consumption by electric vehicles in 1985 | $\simeq 56 \times 10^{9}$ KWH(e), i.e., only 1.4% of the projected U.S. electric consumption in 1985. |

Scenario #2

(Based on a total of 125 million vehicles in 1985.)

The no. of electrically propelled vehicles:

| | |
|---|---|
| (a) Limited performance vehicles (4000 miles/yr) | 60 million |
| (b) Standard performance vehicles (12,000 miles/yr) | 40 million |
| Calculated total electric energy consumption by electric vehicles in 1985 | $\simeq 480 \times 10^{9}$ KWH(e), i.e., 12.3% of 1985 electric energy consumption. |

This scenario calls for large scale changes in traffic patterns. It is obviously rather unrealistic. An intermediate situation where only one third of the second scenario comes close to realization may be more likely.

Vehicles using fuel cells as power plants can also compete successfully with those equipped with the conventional internal combustion engine. Such vehicles have been produced by Shell Thornton Ltd. (UK), ASEA (Sweden), and the General Motors Corporation, the Union Carbide Corporation, and several other companies in this country, for several years (ref. 12). These systems usually use ammonia, hydrazine, and hydrogen as fuels, are pollution free, reliable, and efficient. But the use of exotic noble metal catalysts makes fuel cells rather expensive for automotive applications. Perhaps the TARGET (Team to Advance Research for Gas Energy Transformation, Inc.) programs will lead to the development of fuel cells that do not use costly, poison-prone catalysts and have efficiencies in excess of 70 percent. It appears, however, that the first large scale ground applications of fuel cells will be electric power production and the railway locomotives where systems with overall efficiency of the order of 50 percent are possible.

The following table summarizes the outlook for the synthetic fuels described so far, as substitute fuels for internal combustion engine during the next decade.

Table IX - Prospects for the Alternate Fuels for Automotive Road Vehicles (ref. 15)

| Vehicle Type | Prospects/Comments |
|---|---|
| 1. Fleet type vehicles (trucks & buses) | Continue with present distribution system and introduce synthetic liquids (or EASILY LIQUIFIED GASES). |
| (a) Long haul commercial vehicles (trucks + buses) | Synthetic oil/present system (LIQUID HYDROCARBONS). |
| (b) Local commercial vehicles | |
| (1) Heavy hauling | Synthetic oil/present system. |
| (2) Light delivery (multiple | Electric propulsion (BATTERY POWERED). |
| 2. Private automobiles | |
| (a) Local/city | Electrical propulsion (BATTERY POWERED). |
| (b) Touring auto (including recreational vehicles) | Synthetic oil/present system (LIQUID HYDROCARBONS). |
| 3. Agricultural and construction vehicles | Synthetic oils (LIQUID HYDROCARBONS). |

## 3.5 - Hydrogen as Fuel

An assured long term supply of energy is essential for the economy of the United States. Even with the availability of synthetic alternate energy sources converted from coal/oil shale, the long range energy requirements of the United States cannot be met by the finite - and ultimately exhaustible - fossil fuel reserves. It is therefore essential to consider energy systems based on non-fossil fuels. The electrolytic hydrogen is one of the most attractive such fuels for the following reasons:

(1) It produces no air pollution - the main combustion product being water.

(2) It may be substituted for nearly all fuel uses and can be produced entirely from an almost infinite domestic resource - water.

(3) Any of the primary energy sources - solar, nuclear, geothermal - can be used for its production.

Major obstacles to the use of hydrogen as a universal fuel are:
(1) high cost, relative to current low prices for fossil fuels;
(2) unresolved problems of handling/tankage (gaseous or cryogenic fluid);
and (3) safety considerations, though they do not present serious technical obstacles to its widespread use. The hydrogen handling hazards, though definitely different, are no greater than gasoline hazards. This should be obvious from a comparison of safety parameters for hydrogen and gasoline detailed in the table below.

Table X - Comparison of Safety Parameters for Hydrogen and Gasoline (ref. 16)

| Property | Hydrogen | Gasoline | Remarks |
|---|---|---|---|
| Ignition energy (mj) | 0.02 | 0.25 | Negative |
| Quenching distance (cm) | 0.06 | $\gtrsim$ 0.25 | Negative |
| Ignition temp. (°K) | 858 | 530 | Positive |
| Combustion range (%) | 4-75 | 1.5-7.6 | Positive |
| Diffusivity ($cm^2$/sec) | 0.6 | 0.08 | Equal or (positive) |
| Flame velocity (cm/sec) | 270 | $\lesssim$ 30 | Negative |
| Flame emissivity | 0.1 | $\gtrsim$ 0.1 | Equal |

Hydrogen can, of course, be carried both in the gaseous and liquid state. In bigger vehicles - such as buses/trucks or trains - the weight of high pressure gas cylinder will not appreciably affect the payload. In smaller vehicles - such as delivery vans or private automobiles - the weight and volume of the compressed gas cylinder may dictate the use of liquid hydrogen ($LH_2$). In the case of $LH_2$, boil-off from cryogenic storage containers does present a problem. For example, a 150 liter liquid hydrogen container may loose (1-2) percent/day its charge by boil-off. Larger vessels have smaller losses, since the fractional loss is proportional to $(\text{volume})^{-1/3}$. The rates of liquid hydrogen boil-off are most serious in private automobiles, where containers with lower boil-off losses must be developed if the boil-off losses are to be kept to economical levels. Escaping hydrogen forms explosive mixture with air. However, the hydrogen fuel is still safer than gasoline because the escaping hydrogen vapors quickly diffuse away.

In view of the current high prices of gasoline, the cost of hydrogen production may be quite competitive. The following production costs, based on 8000 tons/day of liquid hydrogen, were estimated in a recent report (ref. 17):

(a) <u>$LH_2$ produced by steam-reforming with hydrocarbons</u>.

20¢/lb (FOB) - 30 tons/day plant

8¢/lb (delivered) - 2500 tons/day plant

(b) <u>$LH_2$ produced by electrolysis (conventional electric power)</u>.

$$\left.\begin{array}{l}11¢/\text{lb (gaseous } H_2) \text{ - FOB} \\ 13¢/\text{lb } (LH_2) \text{ - FOB}\end{array}\right\} \text{2500 tons/day plant}$$

Another computation (ref. 18) estimates (5-10)¢/lb price of liquid hydrogen (FOB) at a 2500 tons/day plant. Hydrogen costs have also been quoted at $\$(1.50\text{-}2.50)/10^6$ Btu (≡ (6-12)¢/lb) based on electric power costs of (0.4-0.7)¢/KWh. (Ref. 19 (a)) Nuclear electric power produced hydrogen costs are 4¢/lb for gaseous hydrogen and 7¢/lb for liquid hydrogen (including 3¢/lb cost of hydrogen liquifaction) (ref. 19(b)).*

The conventional process of (heat → electric power → electrolysis) hydrogen production is not very efficient. It can be replaced by a multiple step thermochemical cycle that uses heat and chemicals to break up water at (900-1000)°C, instead of 2500°C required for thermal decomposition (ref. 20(a)). Such power sources will essentially be hydrogen fuel cell substations and should produce hydrogen much more efficiently and relatively cheaply. At any rate, liquid hydrogen costs at (10-15)¢/lb at 2500 tons/day plants (delivered) appear to be quite competitive with the current gasoline prices (delivered). A recent study (ref. 20(b)) indicates that the cost of electrolytic hydrogen - not allowing for

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(*)See also figure 1 for nuclear electrolytic hydrogen price as a function of time up to 1985 (ref. 19(c)).

byproduct oxygen - will break even with the gasoline costs at 19¢/gallon at the pump, at electricity cost of 1.5 mills/KWh. (At the current electricity cost of about 12 mills/KWh, electrolytic hydrogen will cost approximately 3.4 times the gasoline cost.)

The major unresolved problem in the use of hydrogen as fuel in ground transportation involves fuel tankage. Gaseous hydrogen ($GH_2$) is out for smaller vehicles such as delivery vans and personal automobiles. For example, an automobile with a cruise range of 260 miles would require a compressed gas fuel tank weighing 3000 pounds and having a volume of 54 $(ft)^3$! Some improvements in gaseous hydrogen tanks may be possible by using high strength, low-density materials for pressure vessel fabrication. They are, however, unlikely to make significant impact on use of gaseous hydrogen for private automobiles for some time. Even liquid hydrogen, which also requires a bulky cryogenic storage tank, is not as efficient as gasoline as seen from the following table:

Table XI - Comparison of Heats of Combustion of Hydrogen and Gasoline (ref. 10)

| Fuel | Heat of Combustion (Btu/lb) | Relative Fuel to Equal Hydrogen Heat Content | |
|---|---|---|---|
| | | By Weight | By Volume |
| $H_2$ | 51,600 | 1.0 | 1.0 (liquid) |
| Gasoline ($C_8H_{18}$) | 19,100 | 2.7 | 0.3 |

It is clear that a liquid hydrogen tank will have to be more than three times the size of a conventional gasoline tank for the same energy content. The use of alternate forms of hydrogen storage, such as metal hydrides, may provide a solution to hydrogen tankage problems.

Before taking up a discussion of hydrogen-powered ground vehicles, the following two points should be emphasized:

(1) It is not intended to justify a very early replacement of conventional fuels with hydrogen disregarding the cost factor. Such a step is neither possible nor necessary. For example, just to meet only half of the projected transportation fuel needs even for the year 2000 with electrolytically produced hydrogen would require an additional

generating capacity of $10^{12}$ watts (at a cost of $350 billions) or about 2½ times the currently projected nuclear generating capacity in 2000 (ref. 10).

(2) Even though hydrogen as ground transportation fuel - or even as a source of energy at large - may be a long way down the road, R and D for hydrogen production and its use should be started without any further delay. This is necessary because it is not possible to predict how long it might take to resolve some of the problems inherent in the use of hydrogen as a universal fuel. It will be far better, from an economic standpoint, to have the technology ready in advance than to be late.

A discussion of hydrogen powered vehicles now follows.

## 4. HYDROGEN POWERED VEHICLES

4.1 General Considerations - Hydrogen is a highly desirable fuel because of its following characteristics:

Low weight

High energy density (per unit weight)

Clean burning

Low activation energy

Short term environmental recycling (i.e., $H_2 \rightarrow H_2O \rightarrow H_2 + O_2 \rightarrow H_2O$)

Hydrogen is the only fuel that can be used essentially for all fuel purposes, i.e., heating homes, generating electricity and providing transportation, power, etc. Ultimate elimination of the use of fossil fuels as common fuels will make these resources available for other petrochemical products (plastics and drugs, etc.). The main contemporary uses of hydrogen are: Ammonia and fertilizer production, ore reduction in metallurgical processes and, to a lesser extent, gasification of coal to obtain substitute natural gas. A big potential use, syncrude and methanol production from coal, should also be mentioned. In the following paragraphs, the problems associated with the use of hydrogen as an automotive fuel will be discussed.

Current technology appears to offer solutions to the problem of converting all fuel burning devices to the use of hydrogen. For non-compact vehicles, such as trains and ships, it would be possible to install currently available cryogenic storage vessels as fuel containers. External combustion steam turbine engines and gas turbines would require very simple modifications because the fuel feed and combustion are continuous. As with gas-fired stationary power plants, this change would involve only changing the fuel injection jet size to match the different fuel/air ratio.

The use of liquid hydrogen for automobiles would require replacement of fuel tank with an insulated liquid hydrogen tank, installation of heat exchanger to convert liquid hydrogen to an ambient temperature gas and the replacement of liquid gasoline carburetor with a gas/air mixer device. All other parts of the automobile, including the engine, would remain essentially unchanged. This conversion from gasoline to liquid hydrogen would cost about the same as current smog reducing modifications being added to the cars in California (ref. 21). Automobile performance would remain almost unchanged with these modifications. For private automobiles, the problem is more of fuel handling than motor conversion. There are two possible solutions to this problem.

(1) Replaceable (cryogenic fuel tank + hydrogen gasifier) assembly.

(2) Provision of fail-safe cryogenic transfer apparatus at local distribution centers to refill the depleted liquid hydrogen containers.

The second alternative would require a well-trained corps of cryogenic transfer technicians. However, in view of the large number of vehicles involved, the second alternative would still appear to provide a more acceptable solution to the private automobile fueling problem. In addition to the fueling capability, it will also be necessary to develop an easy venting capability of liquid hydrogen containers. One good method of safely providing this capability is to install a self-igniting catalytic burner on the vent line. This would permit slow, safe venting and combustion of any pressure buildup in the storage tank. As has been indicated earlier, a liquid hydrogen tank will have to be about three times as big and more than twice as heavy (when full) as the current full fuel tank on an average automobile (20 gallon gasoline capacity). Although undesirable, this increase in the size could conceivably be accommodated in the available tank space. (See figure 2(a))

So far, the discussion has been confined to liquid hydrogen as the form of fuel. However, the complications associated with the cryogenic containers, together with a supply of liquid nitrogen needed for cryogenic storage, make liquid hydrogen a less attractive fuel form. A possible solution to hydrogen storage/tankage problem may lie in the use of metal hydrides. It is well known that some hydrides contain far more hydrogen per unit volume than does liquid hydrogen. Considerable research has been done on hydrogen-metal systems - particularly those with low dissociation temperatures and high hydrogen content (ref. 22). Wiswall, et. al., have studied the magnesium alloy hydrides in detail. Results to date indicate that suitable hydrides can serve as hydrogen systems in automobiles. They will have to meet the following criteria for eventual use as automobile fuel carriers: (1) must have an appreciable decomposition pressure (at least one atmosphere) at the engine operating temperature; (2) must store large amounts of hydrogen on a unit weight or volume of the metal, and (3) the metal carrier must be cheap and abundant. The following hydrides meet some of the above criteria:

(a) Monohydrides of vanadium and niobium. An interesting feature of $VH_2$ and $NbH_2$ systems is that the hydrogen pressure is very sensitive to the presence of impurities in the reactant metal. Thus, by controlling the impurity content, one can obtain a wide spectrum of hydride pressure-temperature relationships. The disadvantages of vanadium and niobium systems are rather high costs of the metals.

(b) $Mg_2Ni$ - $H_2$ (with Mg + 5% Ni as the hydrogen storage medium).

(c) The rare earth-transition metal systems. Certain alloys of the type $AB_5$, where A is a rare earth metal and B is one of (Fe, CO, Ni, or Cu) metals, can absorb up to 7 hydrogen atoms per $AB_5$ unit. However, these hydrogen systems do not currently meet criterion-3 listed above.

The following table summarizes the pertinent properties of selected metal-hydrogen and alloy-hydrogen systems.

Table XII - Summary of Hydrogen Content and the Metal Costs for Selected Metal Hydrides (ref. 23)

| Hydride | Available Hydrogen (wt %) | Metal Cost dollars/pound |
|---|---|---|
| Magnesium hydride | 7.7 | 0.38 |
| Vanadium hydride | 2.0 | 4.00 |
| Magnesium-nickel hydride | 3.5 | 1.00 |
| Iron titanium hydride | 0.9 | 1.92 |

The use of metal hydrides, though it increases the fuel tank weight without appreciably affecting its volume compared with equal energy liquid hydrogen tank, eliminates the hazards associated with cryogenic tanks. Such a fuel system can be accommodated in the existing automobile design without excessive changes. (See figure 2(b))

The following table compares various hydrogen systems. (Energy equivalent: 120 lbs of gasoline (20 gallons) or 46 lbs of hydrogen.)

Table XII.- Comparison of Sizes of Fuel Storage Tanks for a Vehicle Range of 260 Miles (ref. 16)

| Storage System | Weight of the Container + Fuel | Tank Volume in $(ft)^3$ |
|---|---|---|
| Compressed hydrogen gas | 3030 lbs | 54 $(ft)^3$ |
| Liquid hydrogen at 20°K | 430 lbs | 10 $(ft)^3$ |
| Metallic hydrides (selected) | 500 lbs | 3 $(ft)^3$ |
| Gasoline(*) | 148 lbs | 3 $(ft)^3$ |

(*)Included as a reference only.

A typical hydride storage system may be arranged as shown in figure 3 below:

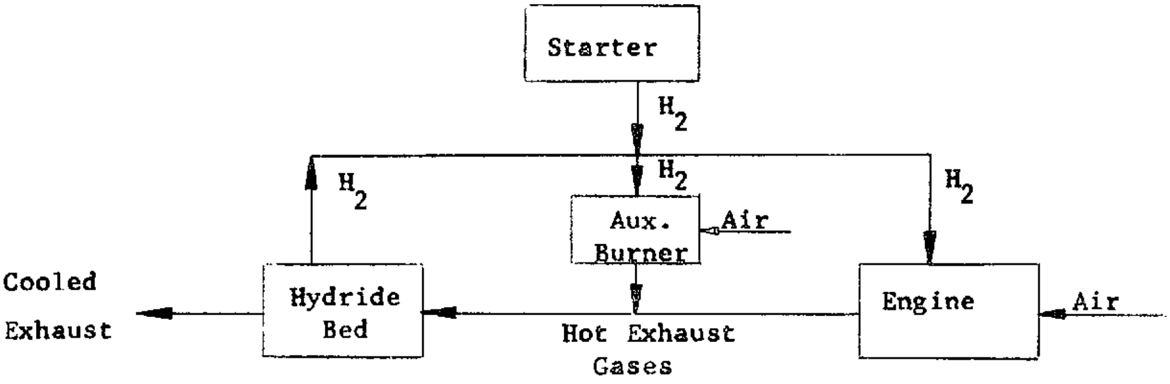

Figure 3 .- A typical metal hydride storage system for use in an automobile.

In order to provide energy for the auxiliary burner, it may be necessary to carry an extra amount of hydrogen. The results of a recent MIT study (ref. 23) on the performance of a metal hydride hydrogen system for an automobile lead to the following conclusions: (1) metal hydrides offer a reversible, chemical means for storing hydrogen in mobile and stationary vehicles; (2) for mobile sources, the hydride bed appears to be technically feasible, though problems associated with startup, recharging rates and the system safety need to be investigated further; and (3) most of the discharge and recharge problems are due to heat transfer limitations. A better heat exchanger design may eliminate these problems.

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4.2 Experience with Hydrogen Powered Vehicles - There have been several experimental attempts (refs. 24-31) to operate conventional automobiles, with various minor degrees of modifications, on hydrogen or hydrogen plus gasoline mixtures. Notable amongst them are:

(1) Hydrogen-air fueled automobile (ref. 25)

(2) The UCLA hydrogen car (ref. 25)

(3) The hydrogen-enriched gasoline powered car (ref. 26)

(1) The $H_2$/Air Fueled Car - A 1971 model 1600 Toyota Corolla station wagon with 4-speed manual transmission served as the test vehicle in this study. The 4-cylinder, 97.6 cubic inch displacement, 9 to 1 compression ratio engine was modified to accommodate the hydrogen induction technique (HIT). In this technique, the engine goes through the normal spark ignition otto cycle. Unthrottled air is inducted into the cylinder on the intake stroke. When the intake valve opens, the cylinder end of the hydrogen flow tube also opens, introducing hydrogen into the cylinder. The amount of hydrogen inducted is controlled by the throttle valve. Other modifications to the engine involved the use of sodium-filled exhaust valves, low operating temperature spark plugs, changes in ignition timing and decreased valve overlap. Even though the experience with this vehicle has been very limited (only 100 miles on and around the University of Miami campus) the authors claim that the HIT can be used successfully with the existing automobile engines with only minor modifications. The modified vehicle gives better performance and produces considerably less oxides of nitrogen ($NO_x$) pollutants. For the purpose of testing the technique, the hydrogen fuel was carried in a gaseous form in standard welders tanks. It was assumed that the availability of hydrogen fuel in gaseous state will not present any problems!

(2) The UCLA Hydrogen Car - A Ford "Boss" 351 cubic inch displacement, V-8. ICE was used in the model car in this investigation by the University of California at Los Angeles (UCLA) group. Its compression ratio was lowered from (11.7:1) to 8.9:1) by fitting low compression pistons from a 1972 Ford 351 cubic inch displacement, "Cobra Jet" V-8 engine and machining out the combustion chamber to a volume of 74 $cm^3$. To facilitate heat transfer from the valve head, the exhaust valves were filled with sodium. The original camshaft was replaced by a shorter duration, less overlap, higher lift unit. This shortened the period of time when both the intake and the exhaust valves are open, while retaining adequate power. A unique feature of the UCLA car is the use of substantial exhaust gas recirculation. This method is simpler and considerably cheaper than the HIT (used by the University of Miami group) and the technique used by Murray and Schoepell (refs. 28, 29). The fuel system met all the state of California regulations for natural gas fueled vehicles. The fuel system was sealed from the passenger compartment and vented to the side of the car.

The UCLA car performance was quite impressive. It met all 1976 Federal Emission Standards. It had adequate power for use in urban environment. Even though the internal combustion engine modifications were quite numerous, this study did prove that an internal combustion engine can safely operate on hydrogen fuel.

(3) Hydrogen-Enriched Gasoline Powered Car - A system designed to operate below the lean flammability limit of gasoline is currently being evaluated at Jet Propulsion Laboratory (JPL). It uses current fuels and engines. The gasoline-enrichment method is based on the addition of a small quantity of gaseous hydrogen to the primary gasoline to promote combustion of the fuel mixture at ultraclean conditions, i.e., with overall fuel-air mixtures significantly leaner than Stoichiometric. The gaseous hydrogen required is generated by the partial oxidation of a portion of the hydrocarbon fuel in an on-board hydrogen generator. Both the laboratory dynamometer tests and the road tests indicate that the addition of a small quantity of gaseous hydrogen to the primary gasoline significantly reduces CO and $NO_x$ exhaust emissions while improving engine thermal efficiency. The hydrocarbon emission results show need for further research to understand and devise methods of control. (The above feasibility tests were conducted with bottled hydrogen gas, instead of using actual generator-produced hydrogen. Ultimately, this bottled gas will be replaced by an on-board hydrogen generator.)

The only otto-cycle vehicle operated, to date, on (liquid hydrogen - liquid oxygen) mixture carried both cryogens in separate dewars (ref. 27). The operational approach involved use of very rich hydrogen to air mixture ratio and a recirculating system to recover the unburnt fuel from the condensed exhaust water for reuse in the cycle. The system has been tested on open roads and the following conclusions were drawn:

1. The $H_2$-$O_2$ system produced somewhat reduced acceleration, but could be made to attain its former top speed. (This may have resulted from source piping impedance limitations.)

2. A much improved economy of about 10 miles per pound of hydrogen was obtained. (This should be compared with an economy of about 2.5 miles per pound of gasoline.)

3. The $LH_2$-$LO_2$ mixture produces no $NO_x$ pollutants, the only exhaust product being water.

Although separate liquid hydrogen and liquid oxygen dewars were used in this study, the refrigeration in liquid hydrogen may be used to produce oxygen or oxygen-enriched air on-board the vehicle, thus eliminating the need for liquid oxygen dewar (ref. 32). An analysis of Vickers APU unit operated on hydrogen rich ($1.4 \leq \varphi \leq 7.0$) $H_2$-$O_2$ mixture indicates (ref. 33) that the thermal efficiency of the system is not notably high (0.125 - 0.356) without exceeding the design limits on the cylinder head temperature (ref. 34). Diluents, such as exhaust water, can be mixed with the reactants further development would be required to build dewars with capacities up to 4-5 million gallons. (Ref. 26) Thus, sufficient expertise in manufacturing, handling, and storage of liquid hydrogen is in existence in the United States now. This is well-attested by the safety record in liquid hydrogen handling operations during the last decade. As a matter of fact, the technology of handling liquid hydrogen is more developed than the technology of handling liquified natural gas (LNG) or even liquid nitrogen ($LN_2$).

A discussion of the magnitude of hydrogen handling operation that will have to be faced, if a complete switch is made to hydrogen fuel, is now given. Bartlit, et. al. (ref. 36) have analyzed the problem for the City of New York (projected 1985 population: 7.6 millions) with its projected energy demand in 1985 at $2.38 \times 10^{15}$ Btu/yr. A uniform hydrogen flow of $2 \times 10^{10}$ SCF/day would be required to meet such a demand. If hydrogen were to be used in the liquid form, over 800 of today's largest liquifaction plants at $6.13 \times 10^9$ watts of electrical power, would be required. (This electric power requirement should be compared with the total city electric demand at $12.26 \times 10^9$ watts.) Clearly, liquifying all of hydrogen needed is not practical, but that is not necessary either. It may be necessary to liquify only the amount needed for transportation. Considering transportation by mass transit, only 256 liquifaction plants at a power level of $1.88 \times 10^9$ watts, would be needed. Transportation needs of the city for 1 hour could be supplied from one storage tank at $2.3 \times 10^6$ gallons/tank. The problem of piping in $2 \times 10^{10}$ SCF/day of hydrogen is also manageable; it could conceivable be met by one high pressure (1000 psi) gas line of 7 feet diameter. It, thus, certainly appears that hydrogen is a feasible alternate fuel. Extending the above arguments to the country at large, Stewart, et. al., have estimated the following demand and cost figures for liquid hydrogen.

Table XIV - Summary of Liquid Hydrogen Requirements to Replace Gasoline in Automobiles (ref. 16)

| Item | Liquid Hydrogen Needed ($10^9$ Gallons/Yr) (Based on 1972 Usage) |
|---|---|
| Auto consumption | 250 |
| Losses: | |
| Produce → transport | 1.094 |
| Transportation boil-off | 0.234 |
| Transport → service station | 2.105 |
| Station boil-off | 8.322 |
| Station → automobile | 11.695 |
| Auto dewar boil-off | 18.250 |
| Auto dewar cool down | 0.310 |
| Total losses | 42 |
| Total production required | 292 billions of gallons/yr |

Table XV - Summary of Liquid Hydrogen Production/Distribution System Costs to Replace Gasoline in Automobiles (ref. 16)

| Item | Cost ($10^9$ Dollars) |
|---|---|
| $GH_2$ electrolysis facilities, 135 plants at $170M each (with 73 tons/hr capacity each) | 23(*) |
| Liquifaction facilities, 800 plants at $60M each (with 300 tons/day capacity each) | 48 |
| Service stations, 300,000 service stations at $0.2M each | 60 |
| $LH_2$ transportation trailers, 20,000 trailers at $0.1M each (with 13,000 gallons capacity each) | 2 |
| TOTAL COSTS | 133 x $10^9$ dollars |

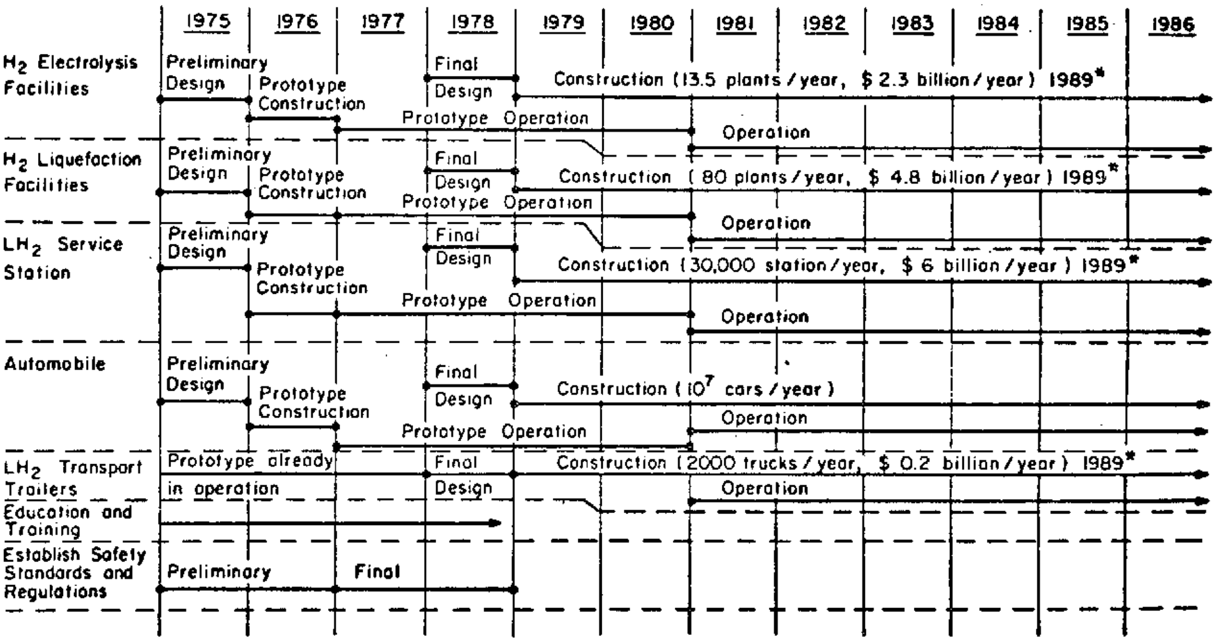
(*)This cost figure should be compared with $12 million for investment costs for a plant having a capacity of 40 x $10^6$ SCF/day (ref. 37).

Even though a cost figure of $133 billions is staggering, it should be compared with an NPC forecast of $110 billions over the next 13 years for the conventional exploration and capital investment, etc. (ref. 2).

However, the cost figures are not the only parameters that need consideration. There is the problem of practicability in the short range time interval. For instance, just to meet only half of the projected transportation fuel needs for the year 2000 (with electrolytically produced hydrogen) would require an additional electrical generating capacity of nearly $10^{12}$ watts (at a cost of about $350 billions) or about 2½ times the currently projected nuclear generating capacity at that time. Making full use of all available off-peak power in the year 2000, would reduce the required generating capacity by only about 20 percent. If coal were to be used in a coal gasification plant to produce enough hydrogen to meet this transportation need, about 1.3 billion tons of coal (- more than double the current coal production rate!) would be needed. (Ref. 10) In view of these enormous increases in "raw" material production rates needed for substituting hydrocarbons by hydrogen completely, it would be wiser to spread the process over the next 50 years or so, i.e., a tentative goal of 2025, by which all transportation needs could be met by hydrogen. Simultaneously, a parallel effort should be launched to substitute electricity for some selected uses - such as residential and commercial space heating. By the year 2000, such a switch could release enough fuel to meet about 30 percent of the total transportation needs. The additional electrical generating capacity to meet these heating needs would be about 0.3 x $10^{12}$ watts, i.e., 45 percent increase in nuclear generating capacity for the year 2000.

Stewart, et. al., have also projected a schedule for implementing the initiation of liquid hydrogen as the fuel for automobiles in the United States. Their projected schedule is reporduced in the following table.

Table XVI - Schedule for Installation of Hydrogen Production and Distribution Facilities (reproduced from ref. 16)



*Have adequate system in full operation by 1989

However, a complete replacement of hydrocarbon fuels by hydrogen in the years before 2000 is neither practical nor is it recommended. But the fact that hydrogen permits gasoline oxidation even in a very lean mixture points the direction for future automobile fuel texture - phasing out gasoline and phasing in hydrogen over the next 50 years. Furthermore, since hydrogen is essential in the production of synthetic oil and gas from coal/oil shale, first priority is warranted for its increased production. Hydrogen production, via hydrocarbon cracking and electrolysis, should be increased at a gradually increasing pace to meet all our transportation needs by the year 2025. This will provide the necessary base facilities and technology to switch to all-hydrogen economy when the hydrocarbon fuel reserves are exhausted or can meet only a small fraction of national energy needs. (In this context, it may be noted that, even with today's technology, it would be cheaper (ref. 38) to convert central power station electricity to hydrogen and to pipeline it below ground to the point of consumption than to transport electricity directly. This is illustrated in the table XVII below and also shown in figure 4. Demonstration plants for this process should be initiated forthwith. The experience thus gained will prove useful when an eventual conversion to all hydrogen systems is made - hydrogen being derived by electrolysis.)

Table XVII - Relative Costs of Delivered Energy in the United States in 1970 (ref. 38)

| Item | Electricity | Natural Gas | Electrolytic $H_2$ |
|---|---|---|---|
| | ← (Costs in $\$/10^6$ Btu) → | | |
| Production | 2.67 @ 9.1 mills/KWH | 0.17 | 3.23(†) |
| Transmission | 0.61 | 0.20 | 0.60 |
| Distribution | 1.61 | 0.27 | 0.34 |
| TOTAL | 4.89 | 0.64 | 4.17(††) |

(†)Computed from data in ref. 37.

(††)If part of hydrogen (15%) is to be reconverted to electricity at the user end ($150/KW in $H_2$-air fuel cells), the extra cost will make this alternative attractive only when compared with underground transmission of electricity for distances greater than 50 miles. (See figure 4)

It is recommended that development work in the following areas of liquid hydrogen economy be intensified to promote its integration into auto-fuel inventory as early as practical.

1. Development of a basic cycle improvement or new operating cycles that utilize high heating value, combustion characteristics and cooling performance of hydrogen fuel in an internal combustion engine. This improvement should result in the need for a smaller fuel tank. (A hydrogen-oxygen fueled engine may be more appropriate. More operating experience should be gained with such engines.)

2. Establishment of specifications for equipment needed in hydrogen handling for fueling ground transportation vehicles (i.e., thermal performance, structural integrity and other functional requirements for fuel tanks and fuel compartments). Ignition systems for hydrogen-fueled engines should also be standardized.

3. Development of new manufacturing techniques for mass producing cryogenic containers at low cost ($\leqslant$ \$500/tank).

4. Development of low heat leakage insulation to minimize boil-off losses in automobile size cryogenic tanks.

5. Development of new techniques for locating and sealing hydrogen leaks in transmission pipelines in automobiles.

6. The use of underground aquifers or depleted gas wells should be investigated for underground hydrogen storage. It may provide large potential savings in hydrogen economy.

## 5. SUMMARY DISCUSSIONS

The role of hydrogen as fuel for ground transportation vis-a-vis other synthetic fuels has been examined for near term (by 1985) and longer term applications (1985-2000 and beyond 2000). Options with reasonable chances of being feasible and practical, in their respective order of viability are: synthetic oil, methanol, electric propulsion and hydrogen. In the case of synthetic oil and methanol, only coal and oil shales have been considered as primary sources, though the Canadian tar sands can make an almost immediate impact on oil supply. The use of urban and agricultural waste products for the production of gaseous and liquid fuels (methanol), though highly attractive at the municipal level, has also been left out of consideration since these sources are not likely to make a significant impact on the national gas/oil needs. The overall cost analyses indicate that synthetic fuels - syncrude and methanol - are quite competitive with gasoline and can be expected to start contributing to our liquid fuel supplies by 1985. The initial use of hydrogen will probably involve enrichment of gasoline, hydrogen being produced by partial dissociation of a small fraction of gasoline on-board, because of improved fuel economy, better engine performance and reduced pollution. The electric propulsion is not likely to become significant in private automobiles before 1985-1990, i.e., until electrochemical powerpacks of the requisite power and energy density become available. The fuel cell concept, though highly efficient and having a potential of being 100 percent efficient, is not likely to be mass utilized until the problems associated with the use of exotic noble metals as catalysts are solved. Current fuel cell research may solve the problem by 1985 when the fuel cells using ammonia and hydrazine may become viable automobile power plants.

In the case of hydrogen, outstanding fuel tankage and associated logistics problems indicate a long time before hydrogen-fueled vehicles will become commonplace. Long haul motor freight and city buses would be the first users of hydrogen fuel. Private automobiles face a difficult logistics problem for handling liquid hydrogen due to the need for compact fuel tanks and general technical insophistication of the average driver. It is suggested that it may be more appropriate to redesign engines and automobiles for the optimum utilization of hydrogen properties. (Well developed methane and propane carburetors are now widely used in automobile-type engines. They could be redesigned rather easily to use hydrogen as the fuel without excessive economic impact on the automobile industry.) It is also suggested that ($H_2$-$O_2$) fuel be further tested because, besides minimizing pollution, it is expected to result in increased payload as well. The need for the following research and development (R and D) activities relevant to hydrogen-fueled private cars are identified:

1. Modification of the present internal combustion engine so that both the normal and the synthetic fuels can be used simultaneously as well as alternately. This will permit a smooth transition to hydrogen economy in the 21st century, besides reducing present gasoline consumption.

2. Development of the new manufacturing techniques for mass producing cryogenic containers at low cost, preferably less than $500 per tank.

3. Development of low heat leak insulators to minimize boil-off losses in automobile size cryogenic tanks.

4. Since most of the weight in a gaseous hydrogen tank comes from the container, the alternative of making these tanks from appropriate composites should be also investigated thoroughly. This will eliminate the need for cryogenic fuel tankage development, at least, for certain applications.

5. Development of efficient metal hydrides for hydrogen storage systems. Such systems must be based on cheap and plentiful elements and should provide significant improvement over liquid hydrogen fuel tankage. They should be able to withstand, at least, several hundred evolution-regeneration cycles without caking. It may also be worthwhile to explore the feasibility of a "combined fuel system" including a small hydride reserve tank for long-term stable storage with the major fuel supply contained in liquid hydrogen dewars.

6. Development of the specifications for equipment needed in hydrogen handling for fueling ground transportation vehicles. A refueling time of the order of 15 minutes should be a realizable goal.

7. Development of the new techniques for locating and sealing hydrogen leaks in transport pipelines and transmission tubes in automobiles.

8. Investigation of the feasibility of underground aquifers or depleted gas wells for underground hydrogen storage. This is expected to save large amounts of capital and materials that would otherwise have to be invested in manufacturing large capacity hydrogen storage tanks.

In making the above recommendations, it has been assumed that enough supply of hydrogen will be available to meet the growing demand. This, of course, is going to be a moot point as seen from the following data for 1985. At the present rate of energy consumption growth, the United States 1985 transportation energy demand will stand at about $30 \times 10^{15}$ Btu. Assuming that all of the fleet and commercial vehicles could be converted to hydrogen use by then, an annual hydrogen production capacity of $1.75 \times 10^{11}$ lbs will be required. If all of this were produced by electrolysis, an installed electricity generating capacity of at least $(970 + 180)10^{9}$ watts would be needed, i.e., an increase of about 17 percent over the currently projected total electric generating capacity in 1985 (i.e., an extra $42 billions outlay). If hydrogen were produced entirely by coal gasification, an increase in coal producing capacity by about 44 percent over the currently projected output capacity of 1100 million tons/year would be required by 1985 (i.e., an extra outlay of about $38 billions). In either case, major additional outlays will be involved. This will be the case even when the target date is pushed well into the nineteen nineties if all transportation needs were to be met by hydrogen. In view of the large demands on investment capital - and attendant manpower and materials demands - it appears more desirable to develop the whole spectrum of energy sources. It appears that the competition of the future (1975-2025) will be for fuels - fuels of all kinds - rather than among the fuels. After 2025, hydrogen is expected to be the most important of available general purpose fuels.

# 6. CONCLUSIONS

The major findings of the present study are summarized below:

1. Hydrogen, as an automotive fuel, seems to be quite equivalent to gasoline for optimum fuel-air mixtures. As a pollution free, high energy density fuel, it must be seriously considered as the logical replacement for hydrocarbons in the 21st century. Several research and development requirements essential for the implementation of hydrogen fuel for ground transportation have been identified (see table XVIII).

2. In the meantime, research and development work should proceed in several parallel directions simultaneously, i.e., undertake extensive domestic exploration for oil/gas concurrent with the development of several alternate fuels and their related ancillaries. This also includes examining the feasibility of redistributing our fuel consumption patterns with a view to relieving hard hit transportation industry, without excessively affecting our life style.

3. Deliberately pursue extensive research and development activities to establish hydrogen as the future automotive fuel, followed by several demonstration projects and concerted efforts at public education. It should be resolved to supply 1/3 of the fleet and commercial transportation needs with the hydrogen fuel by 1985, with the hydrogen share progressively rising to 100 percent by the year 2000. In the private automobile sector, the goal should be to have at least 1/2 of the vehicles on hydrogen by the year 2000 with this share rising to 100 percent by the year 2025. Realization of these goals will require increasing the United States electricity generating capacity well beyond the current projections for the years 2000 and after. As a psychological booster, the nation should set 2025 as the date by which all the transportation needs would be met by hydrogen fuel. This, of course, will require a national commitment of the scale of the Apollo program of the nineteen sixties.

Table XVIII - Summary of R and D Needs for Various Synthetic Fuels

| Fuel Type | R and D Needs |
|---|---|
| 1. Syncrude | 1. Adaptation of petroleum technology to syncrude refining. (Possible differences between <u>in situ</u> produced syncrude and above ground produced syncrude may require different modifications.)<br>2. Special treatments needed to reduce high sulphur/nitrogen content of the parent ores.<br>3. Development of viable <u>in situ</u> techniques for producing syncrude from coal and shale.<br>4. Environmental restoration procedures. |

In the case of both types of synthetic gasoline (coal and shale derived), long-time experience with auto operatibility with synthetic gasoline is required. Auto emission data from both types of synthetic gasoline should be acquired. (The high aromatic content of coal gasoline and high paraffinity of shale gasoline might have some adverse effects on the engine performance and emissions.)

More efficient methods to recover oil from the primary ore, in both cases, are needed.

| | |
|---|---|
| 2. Methanol | 1. Comprehensive study of methanol as an automotive fuel.<br>2. Thorough evaluation of changes required in internal combustion engine for methanol use.<br>3. Automobile tests on methyl-fuels. (Also determine the effects of different levels of methanol purity on the operating performance of internal combustion engine and emissions.)<br>4. Investigate problems of increased fuel volatility, vapor locking tendency, phase separation and corrosion in the tank holding the methanol-gasoline blends.<br>5. Develop more efficient methanol synthesis techniques (including improved goal gasification technology). |

| Fuel Type | R and D Needs |
|---|---|
| 2. Methanol (continued) | 6. Explore the uses of methanol as a fuel for fuel cell (i.e., impurity effects, etc.)<br>7. An unresolved problem - determining the long-term source of carbon required to produce methanol-needs solution. |
| 3. Ammonia and Hydrazine | 1. Explore cheaper synthesis techniques as well as cheaper - and more efficient (100% ?) - fuel cell technology.<br>2. What are the effects of increased ammonia burden on the atmosphere? |
| 4. Storage Batteries | 1. Development of high energy/power density batteries. (Develop a thorough understanding of the sodium-sulphur interactions at the surface of the ceramic, for example.)<br>2. Determine the optimal properties for the conductive ceramic. (Also develop low cost techniques for developing such ceramics.) |
| 5. Hydrogen | 1. Design/develop an engine that can operate alternately on either constituent or the blend of the constituent fuels.<br>2. Develop more efficient metal-hydrogen systems and obtain operating experience with them.<br>3. Develop better/cheaper cryogenic hydrogen containers.<br>4. Acquire more field operating experience with ($H_2$-enriched gasoline) and ($H_2$-$O_2$) fuel systems.<br>5. Investigate the feasibility of "combination fuel systems" (i.e., $LH_2$ + metal hydrides) for long-term stable use. |

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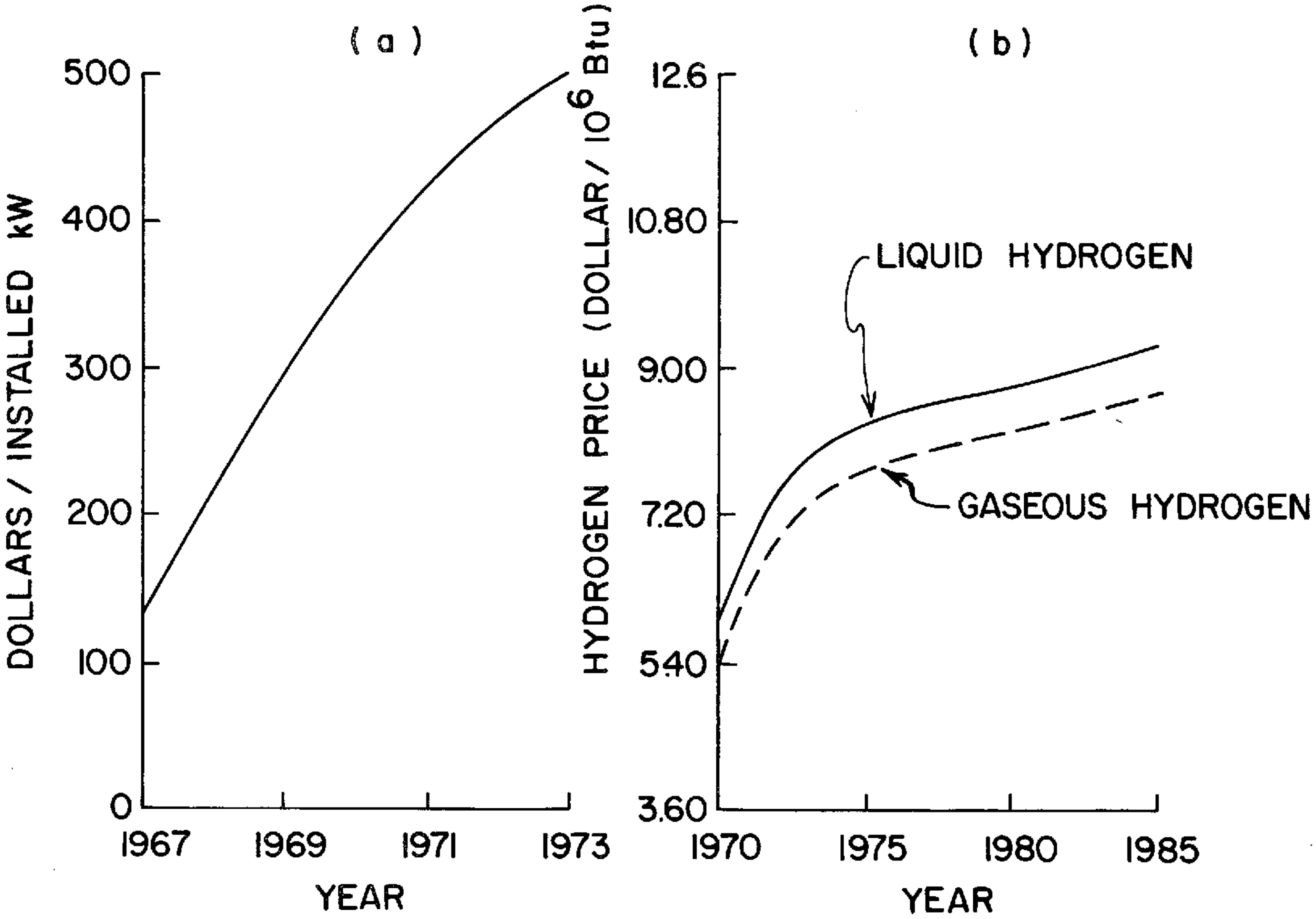

FIGURE - I. COST OF PRODUCING NUCLEAR ELECTRIC POWER AND NUCLEAR ELECTROLYTIC HYDROGEN.

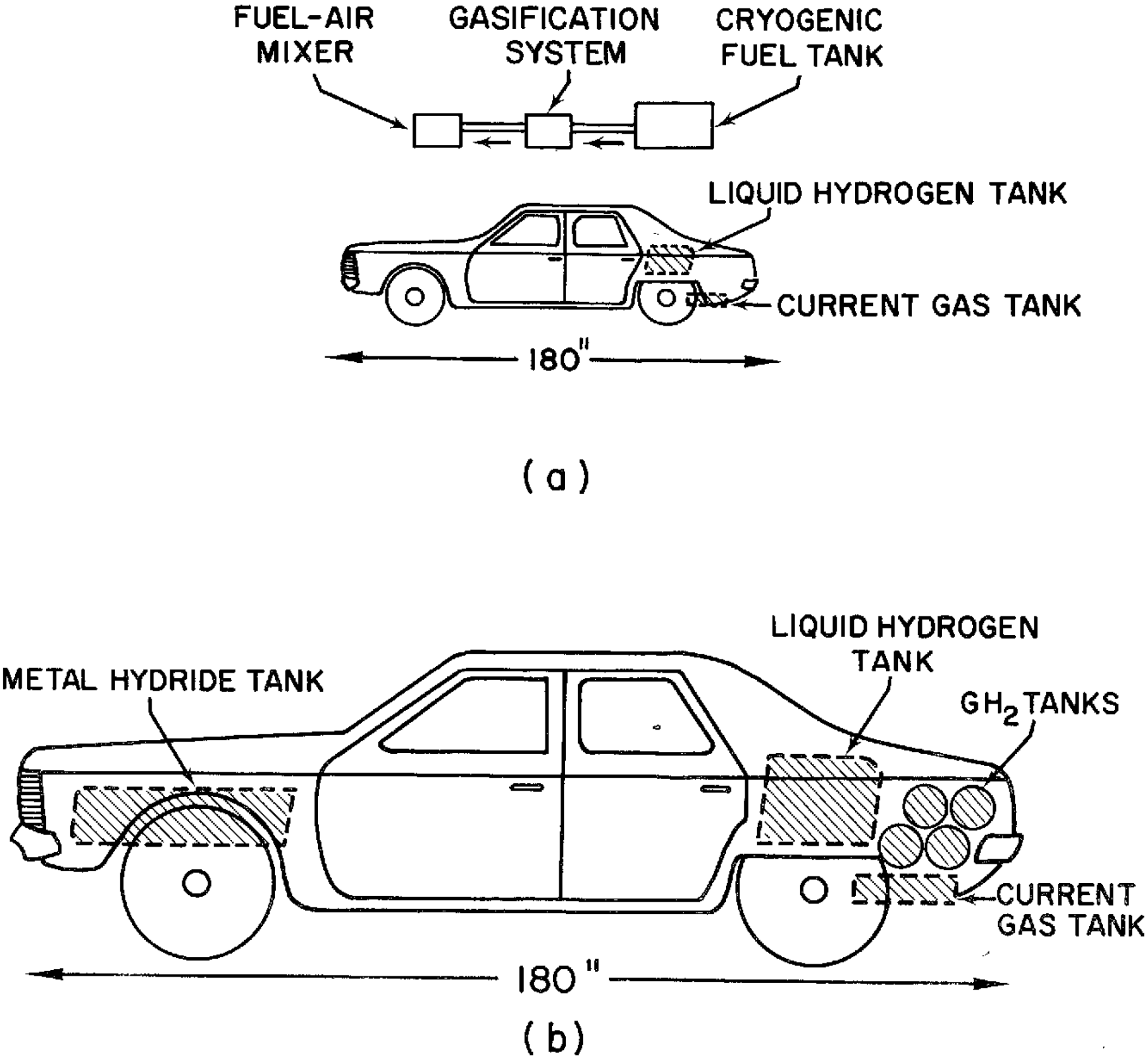

Figure-2. Hydrogen storage options in a conventional automobile

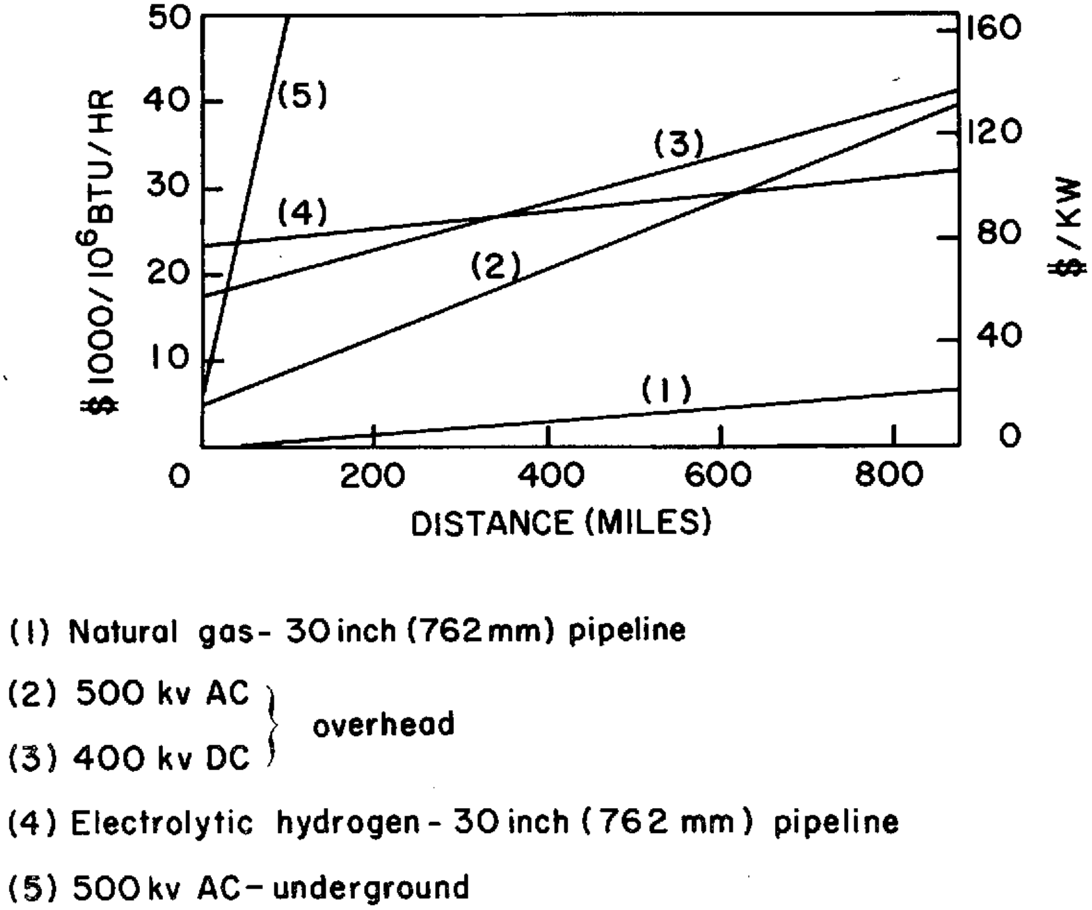

Figure-4. Comparison of transmission costs for various types of energy sources