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The Hydrogen Fuel Economy:
An Early Retrospective

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Abstract

Liquid hydrogen has been proposed as a fuel to replace hydrocarbons such as kerosine, gasoline, and diesel fuel in the transportation sector of the energy economy. The motivation for this solution is reviewed from the standpoint of fossil fuel resources, environmental pollution, and the practical operation of engines and vehicles. The difficulties of cryogenics storage and alternative hydrogen storage options are discussed, and other, broader possible roles of hydrogen in the energy economy are noted. It is concluded that hydrogen fuel is indeed a promising and practical fuel for the future.

I. Introduction

It is by now recognized by all perceptive environmentalists that (1) fossil fuels are being consumed at an exponentially-rising rate, and will be largely exhausted sometime during the 21st century, and (2) the consumption of fossil fuels leads to environmental pollution. Alternative energy sources in the form of fission and fusion nuclear reactors, as well as solar and geothermal power plants, are envisioned as replacing fossil fuels. It is less universally noted that, while these alternatives fully suffice for the supply of fixed-station power for generation of electricity, they cannot address directly the problem of energy for vehicles and aircraft, and furthermore the transportation sector currently consumes about 25% of our fossil fuels. In order to provide a long-range solution to the energy requirements for transportation, either electric storage batteries or synthetic chemical fuels must be developed. The thesis of this article is that hydrogen, probably as a liquid, is the most promising synthetic fuel, and that a hydrogen fuel economy has many other attractive features beyond the transportation sector.

The concept of using liquid hydrogen as a vehicular fuel occurred to some of us at the University of Michigan about four years ago in the course of informal conversation. We were stimulated by the remarkable drop in the price of liquid hydrogen occasioned by its extensive use as a rocket fuel. My thoughts were organized and presented at an environmental teach-in at the University of Michigan in March 1970, and subsequently published[1,2]. I was quickly made aware of a surprising number of widely-separated individuals and groups with very similar thoughts[3]. Subsequent correspondence and meetings have lead to the formation of an informal group calling itself the "H_2indenburg Society," founded on the 35th anniversary of the end of the Hindenburg, and "dedicated to the safe utilization of hydrogen as a fuel." It is appropriate to briefly recapitulate the main aspects of the "energy crisis" before turning specifically to a discussion of hydrogen fuel.

II. The Energy Crisis

The energy crisis is not a crisis of an abrupt, precipitous nature; it is really an alarmist term which should serve to remind us that, due to finite fossil fuels and pollution, our pattern and scale of use of energy must change very significantly over the coming decades. The present and projected consumption of energy by the United States is presented in Figure 1, where the exponential growth character is clearly evident.* The per capital use of energy in the U.S. currently is about 100 times the per capita energy consumed as food, while the corresponding ratio in India is only about 2.

The sources of energy in percent of the total are also given

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*The statistics used here and below will generally refer to the United States, as statistics were more readily available to me and its pattern of energy usage is typical of advanced, industrialized countries.

in Figure 1, again for the U.S.[4] Clearly, petroleum and natural gas have grown to dominate the current sources of energy. However it is just these sources which are in shortest supply; Figure 2 presents on a bar graph the world's readily recoverable reserves of coal, oil, and natural gas, and superposed on these graphs are the fractions of the total already consumed: about 16% in the case of petroleum and natural gas. While larger quantities of oil are available in tar sands, oil shales, very deep wells, etc., the recovery of this oil will be at much greater cost. Ultimately the cost factor will force the usage of petroleum products for fuel downward until at sometime in the next century it is probable that oil will be too dear for any use other than as a petrochemical feedstock.

Of course just the realization of this situation has lead to the evolution of nuclear fission reactors as alternate power sources and is now stimulating development of breeder reactors and research on fusion devices. Solar[5] and geothermal[6] power sources are alternatives which are obviously attractive and for which remarkably good cases can be made by their articulate spokesmen.

It has been too easy, however, for enthusiasts for these alternatives to ignore the transportation sector. None of these options seems capable of providing a <u>direct</u> solution to the problems of vehicular propulsion. Specifically, the requirements for vehicular power are that (1) the power plant (and its fuel) be available in small unit packages, (2) that it have high specific power and high specific energy (power- and energy-per-unit-weight), and (3) that it be relatively safe - as safe as current practice at least. While nuclear reactors may provide power for ocean vessels and direct electric power is practical for railroads, road vehicles and aircraft are by far the dominant consumers of petroleum for transportation. This is illustrated in Figure 3 where the pattern of petroleum consumption for transportation in the U.S. is shown. One notable feature is the growing fraction of the total for aircraft in the coming decades.[7]

One aspect of petroleum usage which contributes to the crisis nature of the problem is the source distribution. Historically, the United States has supplied her own petroleum needs, but in the future she will join Western Europe in reliance on the Middle East for petroleum. This is illustrated in Figure 4 where the U.S. petroleum supply and demand are projected into the next decade. From this figure it appears that by about 1980, half of the petroleum for the U.S. economy will be imported; just about the fraction of the total required for transportation.[8]

III. Hydrogen for Transportation

The alternative energy sources discussed for transportation include the electric storage battery, the fuel cell, and various engines employing synthetic fuels. I should state clearly that all of these options should be vigorously pursued; all will find application and warrant diligent research and development. For the case of the automobile, Bolt has prepared the graph of Figure 5, where specific power and specific energy are plotted logarithmically and possible ranges of parameters for various energy systems are indicated.[9] The best specific power and specific energy are clearly available with the internal or external combustion using chemical fuels; while the fuel cell is attractive on an energy basis, it is poor in specific power. Storage batteries are simply not able to supply energy-per-unit weight competitively with chemical-fueled engines, although some light element, exotic battery systems are promising.

It is not my purpose to downgrade nor demean the significant progress being made in battery and fuel cells systems; it may develop that the small, personal commuter vehicles will be battery powered. I would only point out that, at present, chemically-fueled engines lead the pack. Further, if a future energy system can build on the engineering experience of our current automobile and aircraft industries we will be able to make any transition more expeditiously and efficiently.

Table I itemized possible light, synthetic fuels which may be considered as replacements for petroleum products in the future. Any of them, and many more, could be synthesized using fixed-station nuclear (or other) energy. The two reasons for favoring hydrogen from this list are (1) it contains the greatest energy per unit weight of any, and (2) it is completely cyclic.

The properties of hydrogen, as a liquid, are noted in Table II, and its energy contents per unit weight and per unit volume are compared with gasoline and with fuel oil in Table III.

IV. Environmental Considerations

The appeal of hydrogen to me is that, as a fuel, it is completely cyclic. Water drawn from the oceans is electrolyzed using fixed-station energy, the resulting hydrogen is subsequently burned leading to water which is returned to the biosphere whence it came (Figure 6). Energy from coal is possible through coal gasification, however this leads ultimately to the release of CO_2 into the atmosphere and to a continuing build-up of atmospheric CO_2. Other fuels containing carbon are objectionable to me for this reason, unless they draw their carbon from the atmosphere for synthesis. Only ammonia and hydrogen are free from this problem, and ammonia is not attractive on an energy per unit weight basis; the nitrogen does not carry its own weight, literally.

As a direct corollary, burning hydrogen cannot result in the production of the common, noxious pollutants such as carbon monoxide and unburned hydrocarbons. The only undesirable emissions are oxides of nitrogen, and combustion conditions can be tailored to minimized these alone. Tests by Murray and Schoeppel have demonstrated that under practical hydrogen operating conditions, the nitrogen oxides are reduced about an order of magnitude relative to gasoline engines.[10]

V. Storage Options

The principle difficulty with hydrogen as a fuel is the storage in the "gas tanks" of the consuming vehicles. As seen in Table II, storage as a liquid involves the cryogenics technology concerned with temperatures of 20°K (-423°F). This then involves dewar vessels: double-walled containers with the inner flask and outer jacket separated by an evacuated space and containing a "superinsulation" (aluminized mylar) radiation shield. With such containers it is possible to store liquid hydrogen with losses of only 2% per day for a 150 liter container and less for larger volumes. On the other hand, such specialized tanks are costly, heavy, and bulky. The properties of two tanks suitable in capacity for automobiles and for trucks or buses available from the Linde division of Union Carbide, Inc. are given in Table IV[11]. The "efficiency" of storage for the 150 liter tanks, a size roughly comparable to a 15 gallon gasoline tank in stored energy, is noted in Table V . The retail cost of this tank is comparable to the cost of a small automobile in the U.S.: about $1800. Hence the intrinsic advantages of hydrogen as a fuel in terms of weight and cost are quickly lost when the container is included. The gap between present, economic technology and a practical liquid hydrogen fuel system is less for larger units (aircraft, diesel railroad engines, large trucks) than for automobiles. In any case the fuel tank problem will require serious technological research and development when the liquid hydrogen fuel economy is taken seriously.

There are at least two alternative fuel storage systems: compressed gas and metal hydrides. While compressed gas is simplest in principle, the hydrogen storage per unit weight and per unit volume is far from competitive. Standard 2000 pounds-per square-inch gas cylinders (the type generally supplied to users of compressed gases such as nitrogen, oxygen, helium, etc., as well as hydrogen) are compared with liquid storage in Table VI.

The third storage medium, metal hydrides, has been studied in detail by a group at the Brookhaven National Laboratory in the U.S. They have observed that magnesium or metal compounds of Mg, Ni, and Cu may hold the same mass of hydrogen in a given volume as liquid hydrogen, however at a significant weight deficit.[12] The hydrogen is stably bound at ambient temperatures and is dissociated from the metal at a few hundred degrees Centigrade. This dissociation could be accomplished with heat from the engine exhaust. A comparison between the energy storage efficiencies of hydrides, compressed gases, and liquid hydrogen is made in Table VI, taken from the work of the Brookhaven group. It appears that very considerable development remains before a hydride fuel storage system is developed to the point where its technical and economic possibilities can be realistically appraised. While my personal taste style favors the aesthetically simpler liquid system, I would heartily endorse an accelerated study and pursuit of the hydride approach.

VI. Practical Experience

If hydrogen is the be seriously considered as a fuel for internal combustion engines, it is appropriate to inquire as to its practicability. Indeed there is now a wide spectrum of experience in this field, dating back to German experiments with dirigible gas.[13] Quantitative experiments are documented by R.O. King, who notes difficulties with pre-ignition using hydrogen.[14] More recently Murray and Schoeppel have conducted extensive experiments with hydrogen-fueled one-cylinder engines, using fuel injection and reporting very favorable results, both in operating properties and in exhaust emissions. In particular they reported significantly reduced exhaust concentrations of oxides of nitrogen in the exhaust, compared with gasoline-fueled engines.[10]

One of the most enterprising early groups to operate automobiles on hydrogen is the Perris Smogless Automobile Association. This pioneering group of men in Perris, California invested their own time and money in a series of automobile experiments. Their particular approach has been to carry both hydrogen and oxygen (as fuel and oxidizer) so that only water is exhausted, and in this they have been quite successful.[15]

The recent environmental awareness on college campuses has stimulated an annual series of "clean air car races" and (most recently) an urban vehicle design competition. University groups in different parts of the U.S. have modified automobiles for hydrogen operation for these competitions. At Coral Gables, Florida, Swain and Adt have operated a Toyota engine with hydrogen introduced through the intake valve seats, and with no intake manifold or carburator otherwise.[16] A group at U.C.L.A. in Los Angeles have modified an American Motors Gremlin to burn hydrogen with pressurized gas storage. This car was displayed at the recent 7th Intersociety Energy Conversion Engineering Conference in San Diego, where it attracted considerable interst. The urban vehicle design competition was won by Roy Billingsly of Brigham Young University with a Volkswagon modified to burn hydrogen. A group at the Illinois Institute of Technology undertook to build an automobile wherein hydrogen was burned to drive an electric generator, with electric motors on each wheel. One cannot but be impressed by the creative energy and enthusiasm of these young groups.

The Brookhaven group has operated a Mazda Wankel engine successfully on hydrogen, and reports that its operation is, if anything, smoother with hydrogen than with gasoline.

Conventional gas turbines and aircraft jet engines have operated on hydrogen, and indeed there is no reason why any fuel-burning engine should not work well with hydrogen. I have been frankly surprised to note that apparently every serious effort to run an engine or an automobile on hydrogen fuel has been successful.

VII. Safety

It would be wrong to minimize the safety hazard incumbent in the use of hydrogen, and indeed there have been serious accidents through the years involving hydrogen. The most famous of these was the fire which destroyed the German dirigible, the Hindenburg, at Lakehurst, New Jersey in 1937 where many lives were lost. On the other hand, it is equally wrong to discount the use of hydrogen on these grounds. The safety problems with hydrogen are different than with gasoline or with methane; they are not necessarily worse.[17] Very large quantities of liquid hydrogen have been handled in the U.S. space program without serious accidents.

In any modern transportation technology there are inevitable risks and hazards: ship sinkings, automobile collisions, and airplane crashes. Electricity is used by society in spite of the shock hazard, and indeed occasionally fatal electrocutions occur. These are all examples of the prices our society appears willing to pay for these technological conveniences. In other words, we adopt any new technology with an accompanying calculated risk; in the case of hydrogen this risk certainly exists, but it is not clearly greater than the risks attendant on the fuel it replaces.

VIII. The H_2indenburg Society

It was with recognition of the public concern with these safety considerations, with the "Hindenburg Syndrome", that some of us founded an informal group, the H_2indenburg Society, following a synthetic fuels session of the American Chemical Society annual meeting in March. Through Derek Gregory of the Institute of Gas Technology in Chicago[18] and Bill Escher of Escher Associates in Michigan[19] this expanding group of enthusiastic scientists, engineers, and administrators is in remarkably close contact. Some of the group have obvious professional interaction with hydrogen technology, such as A.K. Stuart of the Electrolyzer Corp., Ltd. (manufacturers of water electrolysis equipment) and J.E. Johnson of the Linde Division of Union Carbide (operator of large-scale hydrogen liquifaction facilities). Others are at government laboratories where interests in hydrogen developed, such as F. Salzano (Brookhaven National Laboratory) and J. Michel (Oak Ridge National Laboratory). Still others have been in other related fields of science or technology and have turned their attention to hydrogen fuel systems on their own initiative when the appeal of a hydrogen fuel economy became apparent. R. Schoeppel and myself from the university environment and L.O. Williams[20] from Martin Marietta fall into this category. Our discussions are characterized by a general enthusiasm for the subject, and the stimulus of new ideas in a new field, rather than by reflections of parochial interests or territorial concerns.

IX. Economics and Efficiency

The key to any major change in our energy use patterns must be economics. Long before fossil fuels are exhausted their prices will rise, and when this price exceeds that of synthetic alternatives the latter will come into widespread use. I am reluctant to quote the costs of hydrogen fuel explicitly because they depend on many variable factors, such as the cost of energy used to electrolyze hydrogen, the scale of the operation, whether liquified or not, etc. Currently the cost of liquid hydrogen in the U.S. is about three times the cost of gasoline at production (not including distribution, marketing, etc.). Large-scale production could reduce this ratio to two. As it is certain that the price of gasoline will only rise in the future, a crossover will occur even if hydrogen costs remain constant. The economic use of liquid hydrogen as a motor vehicle fuel is adversely affected by the added costs of the cryogenic storage and handling, even though these may be significantly reduced in the future. On the other hand, the increasing requirements for emission controls on automobiles lead to reduced engine efficiency and greater first costs; both factors effectively forcing up the costs of gasoline operation.

Perhaps more relevant is the efficiency of converting electrical energy to chemical energy through the electrolysis of water. This is currently about 70% although it could be made higher through advancements in electrolysis technology. The added costs in liquifying the hydrogen are about 25% of the electrolysis costs, both in capital equipment and in energy.

It should be possible to reap some benefits from the latent and sensible heats of liquid hydrogen in an engine by using incoming fuel to cool the exhaust and hence to increase the engine efficiency over that possible with ambient temperature fuels.

A practical objection to the production of hydrogen by electrolysis is that the overall efficiency of generating stored, chemical energy in the form of hydrogen from, say, nuclear fuel is only about 20% because the nuclear energy is used to produce heat which in turn produces electric power through a thermal cycle which in turn is limited by the Second Law of Thermodynamics. There are at least three alternative approaches to the production of hydrogen (other than steam-reforming of hydrocarbons).

C. Marchetti and G. de Beni have proposed a chemical sequence, the end products of which are H_2 and O_2 from water using heat from a reactor directly to drive the chemical reactions.[21] Alternatively, B.L. Eastlund of the U.S. Atomic Energy Commission proposes using ultraviolet radiation, perhaps from a fusion reactor, for direct photolysis of water vapor. In addition, L.O. Kramptnitz of Case Western Reserve University is studying a photosynthesis process whereby the energy conversion capabilities of algae would be used to dissociate water. While I will follow these developments enthusiastically, I strongly suspect that hydrogen will continue to be produced by steam reforming of hydrocarbons or by electrolysis well into the era when it becomes a widely used fuel.

Of course the limited efficiency of heat enegines and Carnot cycle constraints mentioned in connection with hydrogen generation apply equally to the consumption of hydrogen in internal combustion engines for vehicles, so that present technology would involve two Carnot cycles in the conversion of, say, nuclear energy to shaft power in an automobile. (Electrical storage batteries and fuel cells would not incur the energy inefficiency of a heat engine and might convert electricity or fuel energy to shaft power with 50%-75% overall efficiency.)

Another alternative stressed by W.J.D.Escher and the Perris group is the use of byproduct oxygen in the combustion process.[19] After all, oxygen is produced with hydrogen in the correct stoichiometric ratio, and might well be preserved also, rather than being released to the air. If it were then also carried with the hydrogen fuel and the two components combined in a heat engine, the much higher flame temperature of up to 6000°F could be considered. While this is well in excess of any current engine operating temperatures, the aircraft turbine developments using cooled turbine blades suggest approaches that might be used to go to temperatures and corresponding thermal efficiencies well above those possible with hydrogen-air combustion. Escher likes to refer to his hydrogen-oxygen fuel system as H_2O^*, or "water-star"; the excited state or higher energy form of water.

X. Other Uses of Hydrogen

The emphasis in this discussion has been on the use of liquid hydrogen in the transportation sector. A very significant parallel effort has been concerned with the replacement of pipeline gas (both natural gas - methane - and manufactured gas) by hydrogen for space heating and industrial use.[18] Given existing pipelines this is a very straightforward technological step, and only requires hydrogen production facilities near to present natural gas well sites. There are several desirable extensions of this basic idea. Future nuclear plants may be most economical in very large sizes (e.g., 30,000 Megawatts) and in any event pressures are mounting to locate them well apart from population centers, perhaps at off-shore locations.[20] On the other hand electric power transmission is costly over great distances, both in initial costs and in power transmission efficiency. Gregory suggests that power might be used at large-scale nuclear plants to produce hydrogen and hydrogen distributed as the energy carrier to local communities. For the delivery of energy as heat, such an alternative would already be economically advantageous to electric power generation for energy delivery over 400 km. Hydrogen could then be used locally to power turbines or fuel cells to generate electricity for non-heating uses of energy. Here again the problem of the Carnot cycle thermal efficiency at both ends of the hydrogen pipeline is an aesthetic and economic drawback, however fixed-station fuel cells would alleviate even that problem.

Hydrogen has been proposed as a replacement for coke in the processing of iron ore and for other industrial processes. The use of byproduct oxygen for everything from sewage treatment, waste disposal, and steel refining to the on-board oxidant in "water-star" systems has been mentioned as the least explored of the aspects of the hydrogen economy. This will undoubtedly receive attention in the future.

XI. Perspective, Recommendations, and Conclusions

At the present time we have experience in the reasonably large scale production of hydrogen (current world consumption is 6 trillion standard cubic feet per year), both from steam reforming and by electrolysis of water. The space program has dramatically escalated our cryogenics capability, and plants of 30- and 60-ton per day liquid hydrogen production capacity have operated successfully. Liquid hydrogen has been widely transported by railroad tank cars and highway trucks and has been stored in dewar vessels of up to 850,000 gallons capacity. A variety of internal combustion engines has been run successfully on hydrogen, as have gas turbines and jet engines. Some automobiles have been modified to run on hydrogen as demonstration vehicles with dramatic reductions in exhaust emissions. Technologically, there is no question that hydrogen is a feasible alternative to natural gas, gasoline, and diesel fuel in our energy economy.

What should now be done? I would like to see a more extensive demonstration vehicle program developed and pursued.

Up to this time, the engine modification efforts have been comparative shoe string operations, done through the considerable ingenuity and enthusiasm of the several young groups. It seems appropriate that a deliberate support program be established which will permit various technically interesting alternatives to be systematically modeled and tested; I would hope that this program could involve jet aircraft and large highway vehicles (trucks or buses) as well as automobiles.

Beyond the feasibility stage, then, I believe that pilot programs should be set up to study genuine practical applicability. For example, several freight jet aircraft could be modified for hydrogen with external fuel tanks, and be placed in regular operation between two particular terminals, each equipped for hydrogen storage and refueling. An exercise of this sort for several months would involve all aspects of the storage, refueling, and practical use of liquid hydrogen fuel. Similarly, a few large trucks could be equipped for hydrogen-burning and operate between two cities where liquid hydrogen fuel terminals would be established. Again a similar pilot project involving a fleet of delivery vans, taxi cabs, or similar smaller vehicles operating out of one fixed terminal could be operated on hydrogen. Two such programs could permit a practical comparison between liquid hydrogen fuel and, for example, a metal hydride system.

Such a series of pilot programs would accomplish three objectives: firstly, they would exercise several aspects of a practical fuel economy: production, distribution, storage, and refueling, as well as operation with hydrogen fuel. Secondly, they would permit comparisons between hydride and liquid systems or other options in practical situations. Thirdly, the visibility and operation of such pilot programs would stimulate public familiarity with and acceptance of the hydrogen fuel economy.

The early use of hydrogen as an aircraft fuel appears most promising because of the high premium on weight carried aloft and (from the safety aspect) the control possible on the storage and refueling systems. Large trucks and buses would be less concerned with the weight and volume of fuel storage, but would stand to gain very much from the freedom from pollution of hydrogen fuel. At the other end of the spectrum, small two-cycle engines, as used in motorcycles, lawnmowers, snowmobiles, etc. would most probably remain fueled by liquids, either gasoline or a synthetic fuel such as methanol. The private, family automobile represents both the largest consumer of fuels and the most uncertain candidate for hydrogen. Perhaps smaller, "commuter type" automobiles will operate most economically on an advanced type of storage battery. It is in the private automobile sector that the metal hydrides also appear to have the greatest promise, although considerable development remains before a practical fuel tank is ready to place in a vehicle. Nevertheless I still believe that liquid hydrogen even here is the most promising fuel of the future.

Change comes slowly in society; in spite of the successful operation of a power-generating nuclear reactor about 20 years ago, nuclear power generation is only now beginning to make a dent on the large-scale pattern of electric power generation. Considering the vast scale of the energy economy, it appears clear that the time required for a major change in the overall pattern of energy production and usage will be measured in decades. In view of this and of the global petroleum situation, I am convinced that we must begin vigorous implementation now of demonstration vehicle engineering and of pilot programs if we expect to accomodate to the petroleum shortages which will develop over the coming decades. Hydrogen should not be considered to the exclusion of other fuel and energy alternatives, but it is impressive to note the growing number of independent students of the energy scene who have become hydrogen enthusiasts. For my own part, I have reached the conclusion that the use of liquid hydrogen is not only feasible technically and economically, but it is desirable and may even be inevitable.

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Table 1

Synthetic Fuels

Hydrogen	H_2
Acetylene	C_2H_2
Ammonia	NH_3
Hydrazine	N_2H_4
Methane	CH_4
Methanol	CH_3OH

Table II

Properties of Liquid Hydrogen

Boiling Point	20.4°K
Liquid Density	0.0708 g/cm^3
Latent Heat of Vaporization	108 cal/g
Energy Release upon Combustion	29,000 cal/g or 2050 cal/cm^3 or 1.21×10^5 joule/g
Flame temperature	2483°K
Autoignition temperature	858°K

Table III

Energy and Cost of Fuels

Fuel	Energy/Mass (cal/g)	Density (g/cm^3)	Energy/Volume (cal/cm^3)	Cost (dollars/cal)
Liquid Hydrogen	29,000	0.07078	2,050	8×10^{-9} at \$0.11/pound*
Gasoline	11,500	0.74	8,500	4.2×10^{-9} at \$0.12/pound
Fuel Oil	10,500	0.96	10,000	

*Estimates for large scale electrolytic production of hydrogen.

Table IV

Properties of Two Sizes of Commercially Available Liquid Hydrogen Dewar Tanks

(From the Linde Division of Union Carbide Corp.)

		LSH-150	LSH-1000
Capacity	liters	150	1000
	gallons	40	264
Dimensions, inches	height	58	59
	width	20	54.5
	length	-	117.5
Weight empty, lbs.		166	2400

Table V

Efficiency of Liquid Hydrogen Storage in the 150 Liter Dewar of Table IV in Terms of Hydrogen Weight/Total Weight and Hydrogen Volume/Total Volume

	Hydrogen Stored	Empty Dewar	Efficiency
Weight	10.6 kg 23.4 lb	75 kg 166 lb	12.4%
Volume	150ℓ 39.7 gal	304ℓ 10.7 ft^3	49.3%

Table VI

Hydrogen Storage Systems*

Each example corresponds to 45 lbs. hydrogen, or an energy equivalent to 120 lbs. gasoline.

Storage System	Wt. of Carrier and Fuel, lbs.	Contained Volume, ft^3
Gas at 2000 psi	2250	66
Liquid	353	10.2
Magnesium Hydride	692	10.8

*From K.C. Hoffman _et_ _al_. (B.N.L.) SAE 690232

Figure Captions

Figure 1. U.S. Energy consumption for the 150-year period 1850-2000. The energy sources are also given. (From C. Starr, p. 5, "Energy and Power," A Scientific American Book, W.H. Freeman and Co., 1971.)

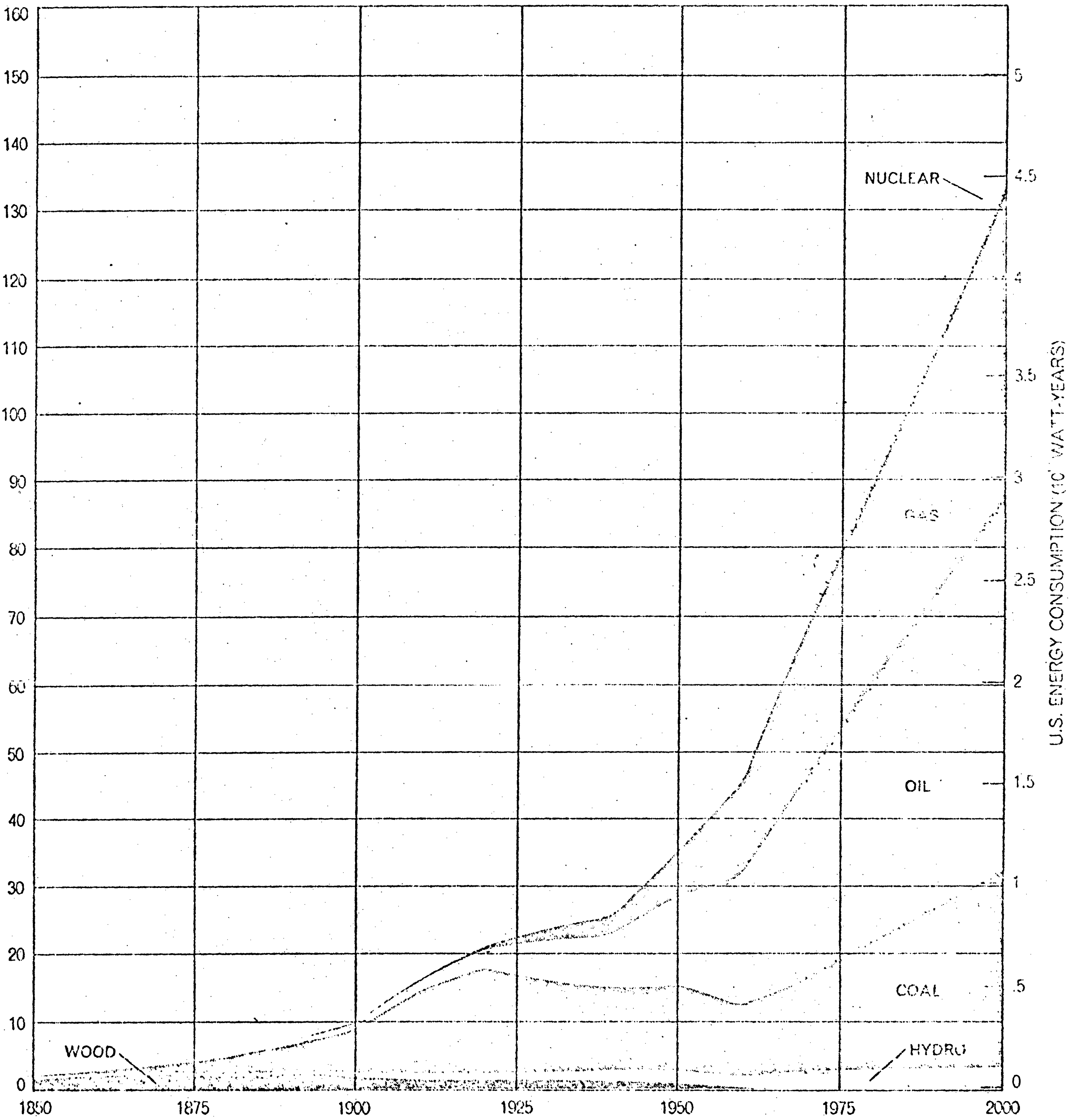
Figure 2. Fossil fuel supplies remaining in the world are indicated by a scheme wherein the entire gray bar represents original resources, light gray portion shows how much has been extracted and dark gray areas show what remains. Figures reflect estimates by M. King Hubbert of the U.S. Geological Survey and could be changed by unforseen discoveries. (From S.F. Singer, p. 111, "The Biosphere," A Scientific American Book, W.H. Freeman and Co., 1970.)

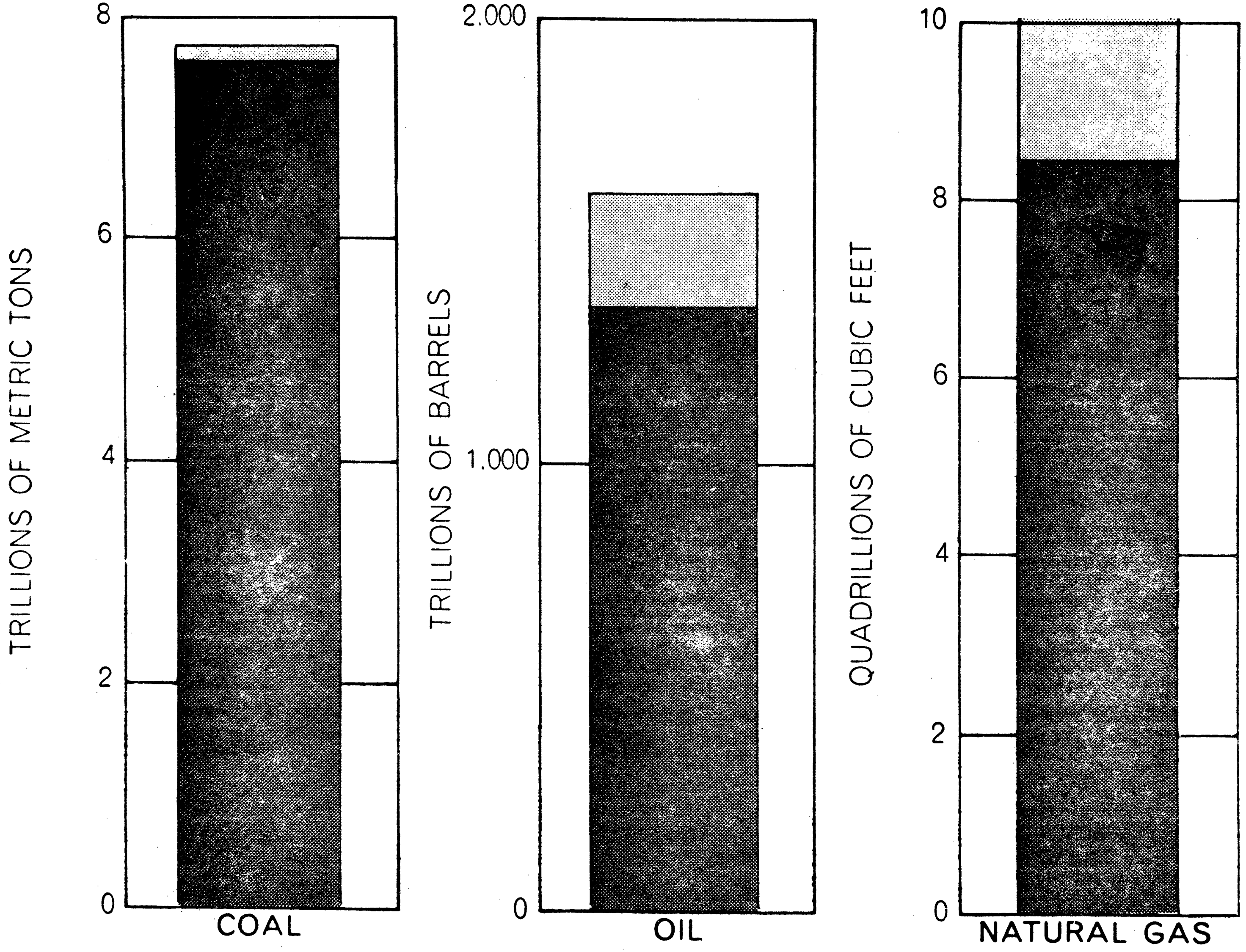
Figure 3. Pattern of U.S. petroleum consumption for transportation. (From W.E. Fraize and J. Dukowicz, "Transportation, Energy, and Environmental Issues," Mitre Corp. McLean, Va., Rept. M72-25, 1972.)

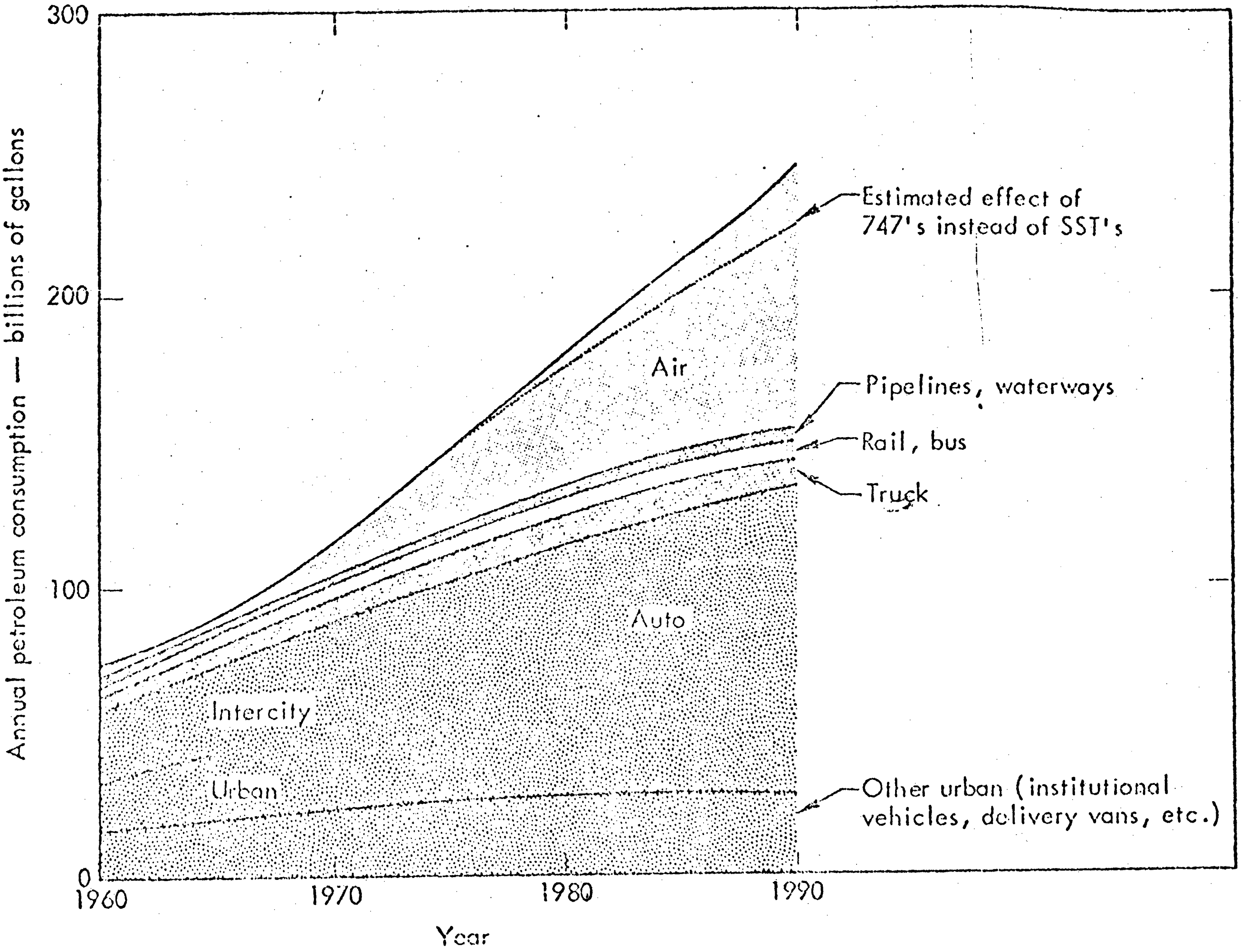
Figure 4. U.S. petroleum supply and demand. (From A.L. Austin, "A Survey of Hydrogen's Potential as a Vehicular Fuel," Lawrence Livermore Laboratory Report UCRL 51228, 1972.)

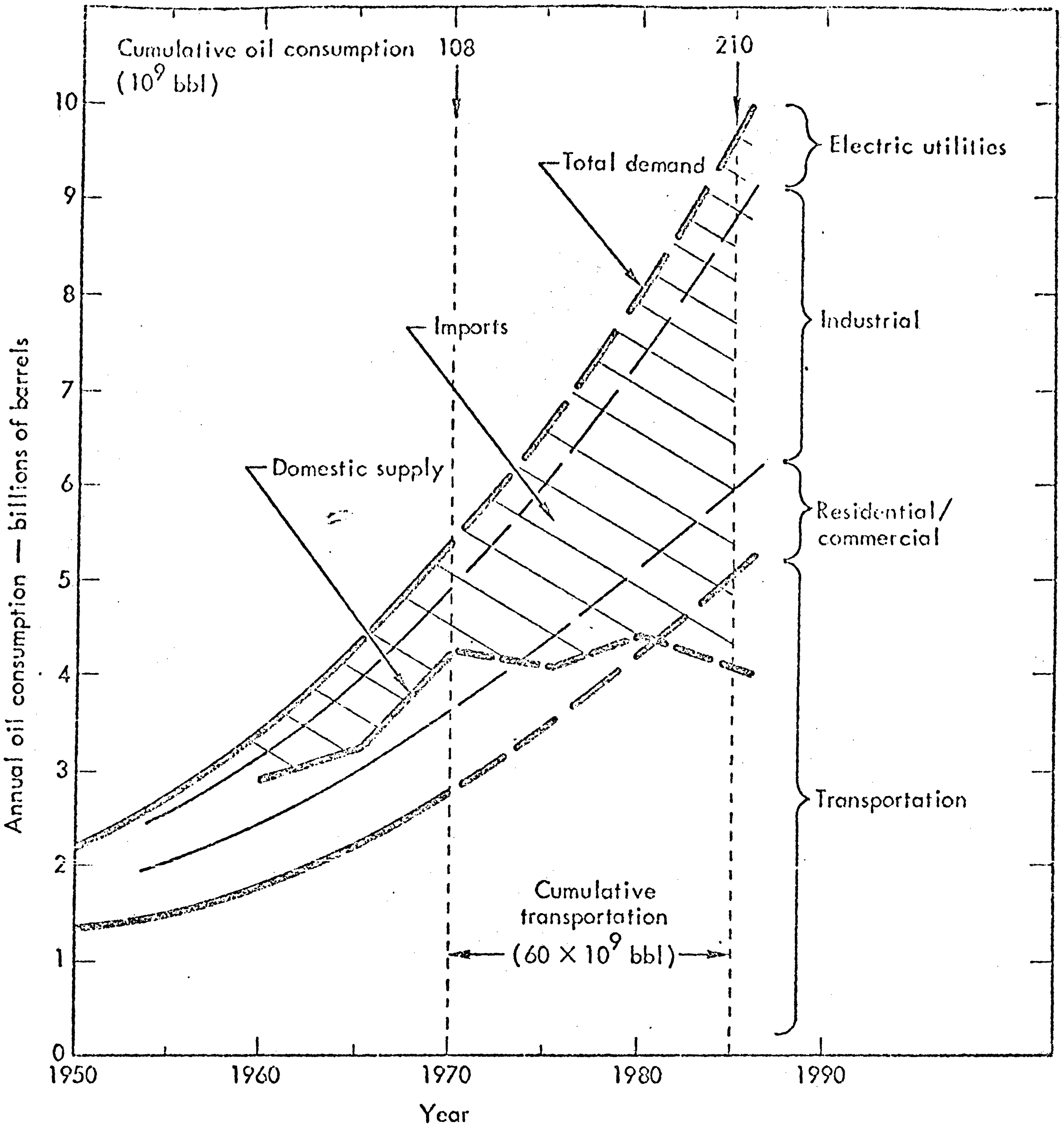
Figure 5 Vehicle requirements for a 2000-pound vehicle and the capability of power plant systems. Solid lines indicate the ranges in miles corresponding to different constant speed in miles per hour (mph) transformed onto the specific energy - specific power coordinates. (From J.A. Bolt, Soc. Automotive Eng. Paper 680191, 1967.)

Figure 6. The hydrogen fuel cycle as applied to transportation.

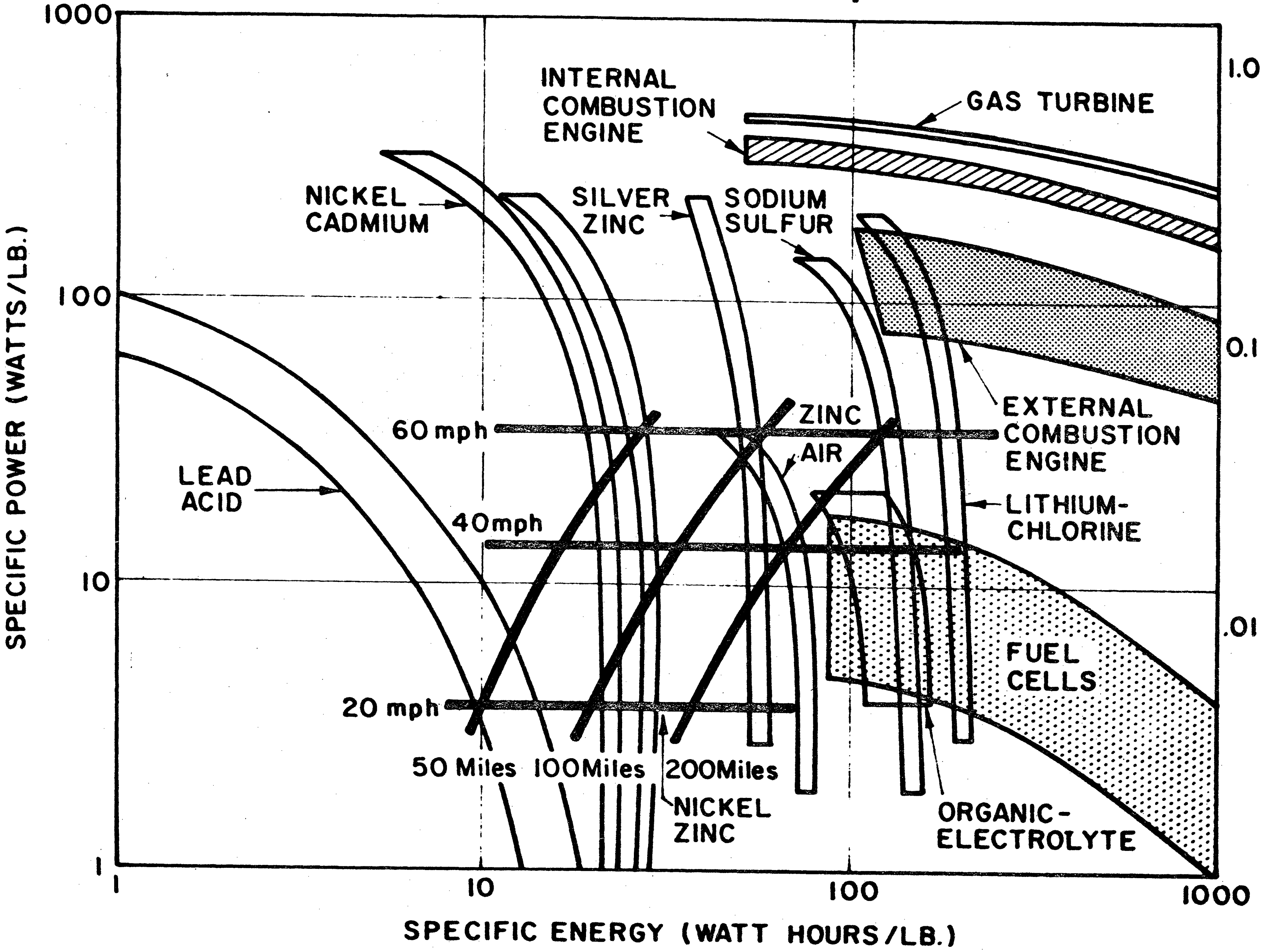

160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
10
0
1850
1875
1900
1925
1950
1975
2000
5
4.5
4
3.5
3
2.5
2
1.5
1
.5
0
U.S. ENERGY CONSUMPTION (10' WATT-YEARS)
NUCLEAR
GAS
OIL
COAL
HYDRO
WOOD


TRILLIONS OF METRIC TONS
8
6
4
2
0
COAL
TRILLIONS OF BARRELS
2.000
1.000
0
OIL
QUADRILLIONS OF CUBIC FEET
10
8
6
4
2
0
NATURAL GAS


300
200
100
0
1960
1970
1980
1990
Year
Annual petroleum consumption — billions of gallons
Estimated effect of 747's instead of SST's
Air
Pipelines, waterways
Rail, bus
Truck
Auto
Intercity
Urban
Other urban (institutional vehicles, delivery vans, etc.)


Cumulative oil consumption
(10⁹ bbl)
108
210
Total demand
Imports
Domestic supply
Electric utilities
Industrial
Residential/
commercial
Transportation
Cumulative
transportation
(60 × 10⁹ bbl)
Annual oil consumption — billions of barrels
0
1
2
3
4
5
6
7
8
9
10
1950
1960
1970
1980
1990
Year

Vehicle Requirements (2000 Lb. Vehicle) and Motive Power Source Requirements



CLOSED HYDROGEN FUEL CYCLE