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ELECTRIC VEHICLE BATTERY RESEARCH AND DEVELOPMENT

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PRICES SUBJECT TO CHANGE

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In the mid-1960's the United States rediscovered the electric car. Discovery was aided by a report from the Department of Commerce (Ref. 1) which showed that 60 percent of the air pollution in 1966 came from automobiles, a staggering 86 million tons per year. The man on the street found that he was being smothered by the sheer weight of the exhaust from his beloved automobile and the electric car was offered as his savior. Industry and the Federal Government moved to develop the necessary technology. The well known range and performance limitations of electric cars would be overcome with new high energy density batteries. This did not seem too far away since the Ford Motor Company had already announced the discovery of the solid electrolyte sodium beta alumina and described its use in a sodium-sulfur battery. Even more energetic high temperature lithium batteries were under development at Argonne National Laboratory and General Motors. A number of groups were investigating lithium batteries with organic electrolytes. An interesting interim solution was proposed (Refs. 1, 2) involving the development of hybrid heat engine-electric cars which could use conventional batteries. The Environmental Protection Agency began supporting battery projects for both electric and hybrid vehicles. A national electric car program was announced in Japan and substantial battery and vehicle development programs were underway in Europe. Clearly, electrics were on their way. Today some 30 companies are reported (Ref. 3) to have on-the-road electric vehicles in the prototype stage or limited production and yet electrics have had essentially no impact on the pollution problem. No Federal program exists to promote their development and there is little support of vehicle battery research. Much of the work on high energy batteries is being redirected to bulk energy storage systems for the electric utilities where the prospects of financial support appear better. It is reasonable to question then whether there is a real need for electric vehicles and if such a need can be established what course should battery development take to meet the need?

The Need For Electric Vehicles

While interest in electric cars rose on a cloud of exhaust fumes, the issue of energy conservation is rapidly becoming dominant in the transportation area. Figure 1 (Ref. 4) is familiar to most people today. It shows that the reserves of oil available worldwide are being rapidly consumed and that transportation is a major user of petroleum. Fifty-five percent of the petroleum consumed in the United States is used by transportation and the figure is expected to grow to 60 percent by the mid-1980's.

Since petroleum is the feed stock for a vast worldwide petrochemical industry which produces everything from plastics to pharmaceuticals, it is clear that the use of petroleum to move people and goods may have to stop in the not-too-distant future. One way to shift the transportation energy base away from petroleum would be to use electric cars. This opens up coal, oil shale, and nuclear energy as usable fuels. Assuming proper environmental safeguards can and are applied, Figure 2 shows that coal and oil shale could provide transportation energy well beyond the time when petroleum reserves would be exhausted. The same argument can be made for nuclear power, making electric cars a viable way for solving our transportation energy problem.

The issue of the air pollution also remains very much alive. Significant progress has been made by the auto manufacturers toward meeting the emission standards set by the Clean Air Act of 1970, though on a delayed basis. It appears that the 90 percent + reductions required by the Act will eventually be met at a stiff cost to the consumer. Emission controls will add several hundred dollars to sticker prices, cars already have poorer driving qualities, and fuel consumption will increase 20-30 percent. The Wankel rotary engine is promising but it too uses 25-30 percent more fuel than comparable sized piston engines. Perhaps the best solution will be the Honda CVCC engine which now meets 1975 emission standards with no emission control add-ons and no fuel penalty. Irrespective of the way the standards are met, it is now clear that many of our major urban areas will still be unable to meet the air quality standards required by the Clean Air Act. The EPA's plans to meet these requirements include reductions in vehicle weight to reduce the fuel required to move them and the reduction of vehicle miles traveled through gasoline rationing. This latter approach would require taking as many as 82 percent of the cars off the roads in Los Angeles during the May-October smog season. (Ref. 6), an approach which is probably unrealistic. Recently the EPA has been studying the possibility of a "two-car strategy", wherein families would own a zero pollution (electric) car for urban use and a conventional car for interurban driving. This is one aspect of EPA's Electric Car Impact Study being conducted by General Research Corporation.

Since energy consumption and air pollution are interrelated, it is logical to ask whether a change to electric cars will reduce or increase overall air pollution? The results of a study (Ref. 7) of this question are summarized in Figure 3. Despite the fact that the electric vehicle may use slightly more total energy, it is more attractive environmentally. Hydrocarbon and CO-emissions are substantially lower and NO_x is reduced by 30 percent based on the assumption that 42 percent of the power for the vehicles will come from fossil fuel burning plants. An analysis of particulates produced seems to heavily favor the GMV until the size and type are studied. Respirable (less than 5 micron) particulates are 30 percent lower with the EMV and suspected carcinogens are reduced 95 percent. Only in total SO_2 emissions is the GMV favored, but this advantage is lost if the comparison is made based on ground level emissions rather than total values. The problem of controlling a few thousand smokestacks also seems simpler than attempting to monitor tens of millions of cars. One can conclude then that electric cars offer a way to both shift our transportation energy base and improve the quality of the air we breath.

Batteries - The State of the Art

Perhaps the most obvious effect of interest in electric vehicles has been a proliferation of papers and reports dealing with the state-of-the-art of batteries which might be candidates for vehicular use. Among the more recent, the Federal Council on Science and Technology's Energy R&D Goals Study contains the recommendations of an electrochemical workshop (Ref. 4) which are in essence a consensus state-of-art survey compiled by fourteen electrochemical specialists drawn nationally from both government and industry. In addition, DOT had a state-of-art summary prepared independently by Arthur D. Little, Inc. (Ref. 8). The current state-of-the-art in batteries for electric vehicles is shown in Figure 4. The information in the figure may be summarized as follows:

a) Conventional Batteries

George points out (Ref. 8) that since 1968, "only the lead-acid and nickel-iron battery systems...have been developed further in directions relevant to electric highway vehicle applications."

Most of the lead-acid progress has been made in the intermediate size area, midway between SLI and industrial traction batteries. Goldman (Ref. 9) estimates that the batteries available today are 75% better than those available to him three years ago. At the present levels, a car which is compatible with modern city traffic is feasible. Modest improvements are still expected with an ultimate energy density of 18-25 WH/lb predicted for commercial batteries. Work on high rate lead-acid batteries for hybrid vehicles under EPA sponsorship has demonstrated that 100-150 watts/pound can be delivered at a sacrifice in energy density. Long cycle life in a pulsed mode (shallow discharge) was demonstrated by Tyco using a "quasi-bipolar plate". TRW and Gould have shown that a standard Group 22F SLI battery can deliver 100 watts/pound and could reach 170 watts/pound through plate and cell design changes.

The nickel-iron system has been proposed as a low cost replacement for the lead-acid battery, but this battery appears best suited for industrial applications. It offers little if any performance advantage over lead-acid.

The most likely candidate to replace lead-acid is now the nickel-zinc system. A realizable energy density of 30 watt-hours per pound seems possible. Life, presently 100-200 cycles, has been a drawback but work now underway may change the picture. The other major question is whether the cost can be reduced to where it is competitive with lead-acid.

b) Metal-Gas Batteries

These batteries tend to offer energy densities in the 30-60 watt-hour per pound range depending on the reactants selected. This is a substantial improvement over conventional batteries but is considered to be too low to allow development of a full-performance vehicle. The use of air is advantageous for obvious reasons, but requires the addition of scrubbers for CO_2 removal, an air blower, and a water makeup system which negate much of the gain. With either air or oxygen, an oxygen electrode catalyst is required. No catalysts exist which are cheap enough for car batteries. Reduced precious metal loadings or non-noble catalysts might be usable if hydrogen is used. However, the volume required for H_2 gaseous storage appears prohibitive and hydride storage systems are complex and/or expensive depending on the media chosen, and are heavy. In addition, the usual problems associated with zinc, cadmium and iron electrodes in conventional batteries appear in these cells as well. The zinc-air system has received the most development work to date. Prototype batteries have been built and tested by Gulf-General Atomics (circulating electrolyte), Sony (pulverized zinc fuel) and General Motors (mechanically rechargeable). The pumped systems are complex. GGA reported their system was unattractive economically and GM has declared the mechanical recharging approach to be impractical.

c) Alkali Metal - High Temperature Batteries

These systems are capable of meeting both the 100 WH/lb and 100 W/lb goals which have been established (Ref. 1) as necessary for full performance vehicles. High temperatures (300-700° C) allow use of relatively resistive solid ionic conductors and molten salts as electrolytes, as well as permitting rapid charging and discharging. In general the anticipated high power and energy densities have been demonstrated, although not always in the same cell. Life is found to be 500-1000 cycles in 1000-2000 hours for almost all systems. Life limitations are generally associated with materials problems.

The sodium-sulfur system, first announced by Ford Motor Company is receiving international attention. The concept uses beta-alumina as a solid electrolyte which conducts sodium ions at reasonable rates at the operating temperature of 350° C or slightly above. The major United States program on the sodium-sulfur battery is Ford's, although TRW, General Electric and others also have worked on this cell. Ford has tested single cells and a small (200 watt design, 400 watt peak) 24 cell battery. The latter reportedly ran for 2000 cycles and 7 months total hot life. This is the longest cycle life reported anywhere to date. The battery delivered 43 WH/lb and 93 W/lb exclusive of insulation. A little recognized fact is that in the Ford battery design power and energy density must be optimized separately. Thus a 500 watt battery optimized to deliver 135 WH/lb would produce 56 W/lb, while one designed for high power would put out 40 WH/lb but 150-250 W/lb (Ref. 10), again exclusive of insulation. Thus a vehicle powerplant could consist of a power battery and an energy battery, both sodium-sulfur but of different designs. The largest foreign programs are in the United Kingdom (British Railways Board, The Electricity Council), Japan (jointly between Yuasa and Toshiba), France (CGE), and Switzerland (Battelle-Geneva). British Rails has tested both tubular and flat-plate cells and has a 1 KW battery operational. The Electricity Council has developed a 960 cell, 50 KWH battery, the modules for which are shown on Figure 5. The battery was road tested in a Bedford van (Figure 6) in November 1972. The present battery is rated at 15.5 KW average output, 29 KW peak power, and weighs 800 Kg. The energy density is therefore 63 WH/Kg and the power density is 36 W/Kg. The energy density is expected to ultimately reach 200 WH/Kg, with a life in excess of 1000 cycles. The Japanese program is part of a government-sponsored electric vehicle program. The stated objective is to have a battery-powered vehicle in operation by 1975. Yuasa is testing single cells and seven cell units. Lifetimes in the order of 1000 hours (166 cycles) are common. The energy density delivered is about 110 WH/Kg. The French and Swiss efforts are also concentrating on operation of single cells and appear to be at a comparable technical state. All sodium-sulfur projects face the same key problem today, namely deterioration of the beta-alumina electrolyte after 1000-2000 hours at temperature. This deterioration is ascribed to a variety of causes and has lead to a number of proprietary "fixes", but no substantial increases in cycle life have been reported. Economic success will ultimately depend on finding inexpensive ways to produce the desired ceramic and to fabricate large batteries.

A different approach to the sodium-sulfur system is being pursued by Dow Chemical Company. Sodium ion conducting glass is used as the electrolyte in the form of hollow fibers with very thin walls (typically 85 micron O.D. x 35 micron I.D.). Thousands of these tubes are collected in bundles to form a cell using a glass header and aluminum for the container and current collector. Dow has a proprietary method of treating the current collector to prevent formation of a passivating film. Energy densities ranging from 176 WH/Kg for small cells to 297 WH/Kg for large cells are predicted. Dow has attempted to develop a 40 AH cell under a contract cosponsored by the Navy, Army, EPA, and DOT. This development effort was probably premature in view of the limited amount of life data and glass compatibility experience Dow has in hand. It did prove valuable however in that it served to focus attention on problem areas which will require work. This approach appears to have the best potential for low cost among the various high temperature batteries under development.

The lithium-sulfur system has been under development for a number of years at Argonne National Laboratories with a smaller effort at Atomics International. The system has the desired charge and discharge rate characteristics for a vehicle battery although the life is limited and sulfur utilization has been too low to allow high energy densities to be realized.

Unsealed cells have been cycled for 1500 cycles over 7000-8000 hours, but these were essentially tests of the positive electrode as the lithium electrode had to be replaced several times to correct internal shorting problems. Shorting arises due to a "dewetting" of the anode and subsequent formation of lithium globules between the electrodes. In sealed cells this results in failures in 500-800 hours and 130-250 cycles. High sulfur electrode capacity losses (as much as 75% in the first 60 cycles) may be correctable using a new "mixed cathode" construction but the required capacity densities (1 AH/cm^2) have not been sustained. The system is plagued with a variety of severe materials problems. Chromium appears to be virtually the only low cost material which might be corrosion resistant, assuming it can be plated and maintained void free on a lower cost base metal. Electrical insulators are also a problem. This system appears to have little chance for commercial success unless corrosion resistance low-cost materials can be found.

The lithium-chlorine system was first investigated by General Motors and later, in a modified form, by Sohio. The former showed high power densities but faces difficult corrosion problems at the 700° C operating temperature. The latter progressed to a 264 watt-hour, 12 cell battery which was tested for 100 cycles. This battery delivered 24 watt-hours/pound without insulation. Due to the particular method of storing lithium and chlorine used, the outlook for high energy densities is not promising.

d) Other Approaches

Organic electrolyte batteries offer the possibility for high energy densities at ordinary temperatures and are attractive for this reason. Existing literature shows that primary cells can deliver 100-200 watt-hours/pound at low (100 hours or more) rates. High rate cells have been built but have limited wet-stand capability due to solubility of the cathode materials used. To date no long cycle life rechargeable organic electrolyte cell has been built. Much basic research is necessary on electrode reactions in non-aqueous media and on electrolyte properties. Since the most promising approaches involve soluble cathodes, work on an ion-selective separator would improve the chances for success.

Zinc-halogen cells have been investigated in two laboratories. The Zito Company reports long cycle life for an aqueous zinc-bromine cell but the energy density is too low (20 WH/lb) to be of interest. A different concept has been demonstrated by Occidental Petroleum based on a zinc-chlorine battery in which chlorine is stored as a solid hydrate at 8° C or below. System development has progressed to where an 1800 pound battery has been installed in a Vega for testing. The energy density is 30 watt-hours/lb, but Occidental claims to be working on improvements which will increase this value to 75 WH/lb, giving the car a range of 200 miles. A joint venture between Occidental and Gulf and Western Industries was recently announced to develop the battery for vehicle and utility use.

Vehicle Battery R&D In The Future

Battery technology for electric vehicles is not advancing rapidly because of a general lack of support on the parts of both Government and private industry. The major reason for lack of support by the Government has been the absence of a clearly defined role for electric cars in our national transportation system. As a result EPA has chosen to apply its AAPS funds against the problem of developing an alternative to the conventional I.C. heat engine which can meet the existing Federal emissions standards. The recent electric vehicle impact study is expected to define for EPA the role which electrics can play in air pollution control. Unfortunately, the choice of Los Angeles as the area for study may lead to unfavorable conclusions since the driving patterns in that area may be unsuitable for electric cars. The Department of Transportation has as yet not identified a need within the present and future transportation systems of this country which can be uniquely met by electric vehicles. Despite this, the Department has begun to support high energy battery work in order to insure that necessary technology is ready if required at some future date. Within private industry, battery companies find little incentive for investing R and D money in new designs to meet a market which may only be thousands or a few tens of thousands of vehicles per year. The automobile industry likewise can see only the possibility of a long-range payoff on research and development money invested today, and at the same time it is under pressure to meet the emission standards with their present product line. Therefore they cannot be expected to put more than a minimum effort on batteries and electric cars. It appears then that the Government must take a more active role, if electric vehicles are to become part of our transportation system. In addition, I believe that the approach to vehicle development must be changed. To date, the standard approach has been to determine the specific power and specific energy which might be obtained from various batteries. Then the energy and power required to drive a full-size six passenger car are computed and the two sets of values co-plotted as in Figure 7. From figures like this one, the "magic numbers" of 100 WH/lb and 100 W/lb are extracted as the performance required to make electric cars feasible. The problem with this reasoning is that it fails to take into account the use patterns for vehicles that prevail. Statistics compiled by Automobile Manufacturers Association (Ref. 11) are plotted on Figure 8. These show that the largest percentage of the vehicle miles driven are on short trips. An electric car with a range of 20 miles will satisfy 50 percent of all automobile trips, and a range of 40 miles would handle 67 percent of all trips. Figure 9 (Ref. 12) shows the daily use patterns for cars in the Chicago area in terms of total miles driven each day. Here a car with a range of 20 miles would accommodate the range requirements of 60 percent of all of the cars in the area. An electric car with 40 mile range would meet the normal needs of 86 percent of the drivers in the area. Referring back to Figure 7, this means that the real gains are not in the upper right hand corner of the figure, but in the lower left! The battery technology needed for these kinds of cars exists already or can be brought into being soon, so we do not have to wait for the invention of new super batteries to reap the benefits of electric transportation.

The one thing an electric car lacks which will hinder its acceptance by the public is autonomy. The ICE car makes use of a fully developed support system of gasoline stations, garages and parts warehouses to assure that a car will continue to operate. The latter two will come as a natural result of a growing market, but the electrical equivalent of the corner service station must be developed since a driver who unexpectedly exceeds his vehicles range must be provided with a way to complete his trip. A number of schemes are possible. One simple approach will be to develop advanced high energy batteries to extend the vehicle range into the 100-200 mile class, increasing its usefulness and decreasing the possibility of a failure. Fast recharge schemes have been suggested, but average power levels in excess of 1 MW per vehicle would be required and it is unclear whether these power levels can be provided to a large network of stations. Battery exchange is feasible for fleet operations and could be used in emergencies by individuals. Another approach would be to install a small auxiliary engine in each car with a minimum performance and range capability to provide the driver with assurance that he can get home if his batteries run down.

Since we are talking about a gradual transition in our transportation system, intercity travel will continue to be done in conventional cars with the electric serving as an urban second car. Ideally as time goes on improved mass transit, which is inherently more energy efficient than personal automobiles, may reduce or eliminate the need for ICE powered vehicles entirely.

Introducing electrics on a large scale will be difficult since neither battery manufacturers or car manufacturers have an incentive to invest heavily in them at present. Semon E. Knudsen, former Ford Motor Company president and now board chairman of White Motor Company, recently stated that the Congress might have to pass a law requiring the development of new batteries and electric cars. Whatever the process it now appears that our transportation system must shift away from the petroleum base it now uses to a more abundant energy supply.

Battery-powered cars can greatly improve urban air quality, and can reduce the burden on our petroleum supply, but they will not find widespread public acceptance simply because we can build them today somewhat better than we could 50 years ago. Public acceptance will come when electrics are part of a total transportation system which meets the public's needs, and when they have sufficient autonomy to be used by the man on the street with confidence. Conversion to electric cars will be an evolutionary process. In order for them to be in use in time to conserve our petroleum supply, the planning and working for their appearance should begin now.

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OIL MARKET

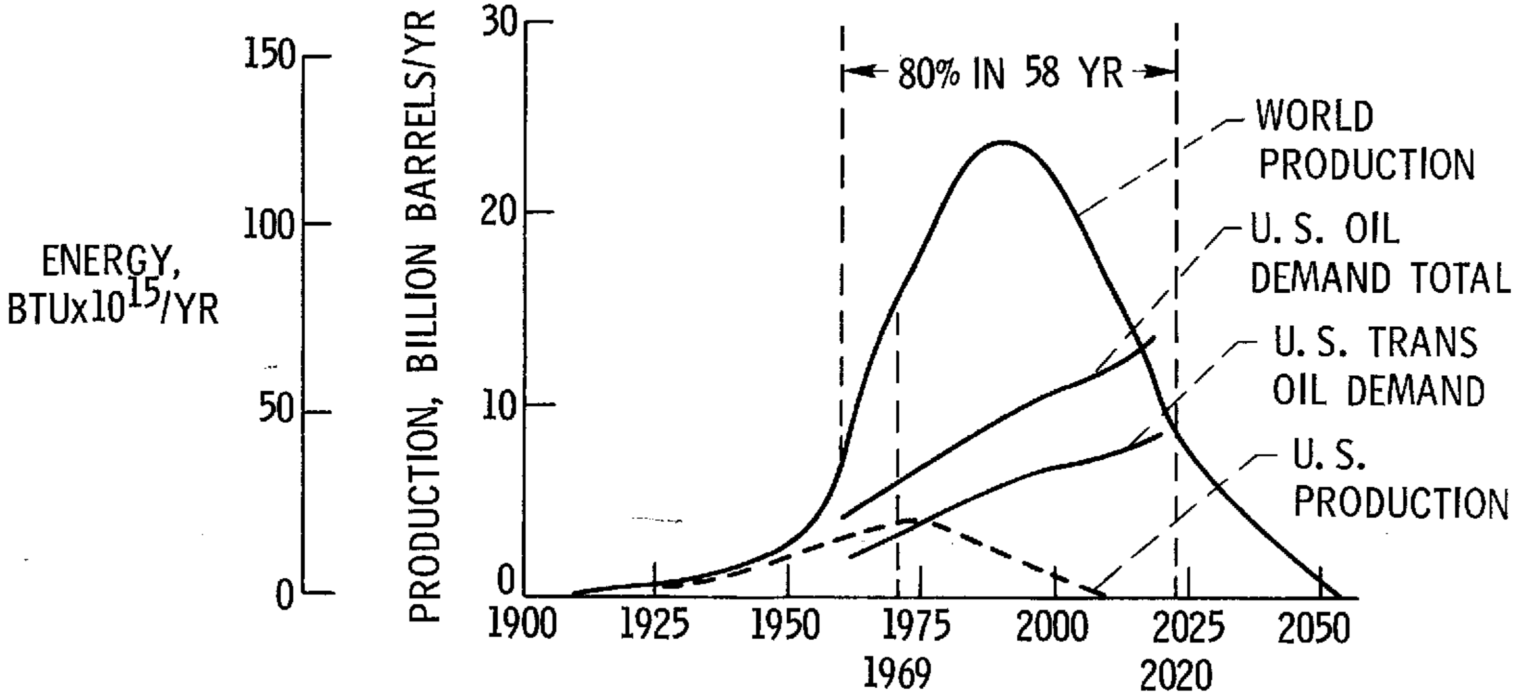

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Fig. 1

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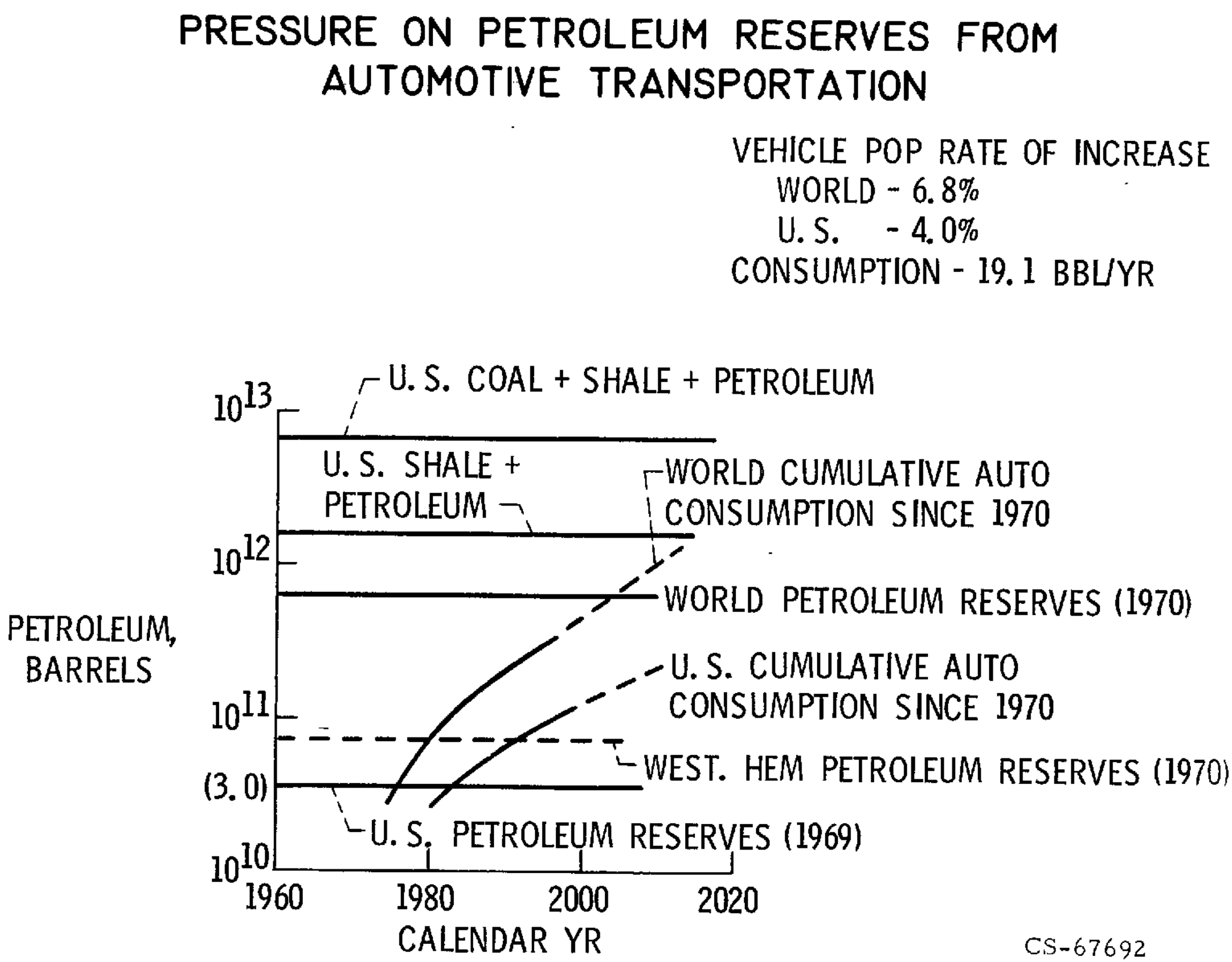

PRESSURE ON PETROLEUM RESERVES FROM AUTOMOTIVE TRANSPORTATION
VEHICLE POP RATE OF INCREASE
WORLD - 6.8%
U.S. - 4.0%
CONSUMPTION - 19.1 BBL/YR
U.S. COAL + SHALE + PETROLEUM
U.S. SHALE + PETROLEUM
WORLD CUMULATIVE AUTO CONSUMPTION SINCE 1970
WORLD PETROLEUM RESERVES (1970)
U.S. CUMULATIVE AUTO CONSUMPTION SINCE 1970
WEST. HEM PETROLEUM RESERVES (1970)
U.S. PETROLEUM RESERVES (1969)
PETROLEUM, BARRELS
10^{13}
10^{12}
10^{11}
(3.0)
10^{10}
1960
1980
2000
2020
CALENDAR YR
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Fig. 2

COMPARISON OF ELECTRIC MOTOR VEHICLES (EMV) AND GASOLINE MOTOR VEHICLES (GMV)

	EMV	GMV
ENERGY RELATIVE AMOUNT TYPE USED	1.1 NUCLEAR, COAL	1.0 OIL, COAL
EMISSIONS	HC LOWER BY 50:1 CO LOWER BY 200:1 NO_X LOWER BY 1.5:1 PARTICULATES RESPRIABLE - LOWER BY 1.5:1 CARCENOGENIC - LOWER BY 20:1	SO_2 LOWER BY 3:1 LESS RADIATION PARTICULATES TOTAL LOWER BY 2.5:1
LOCATION	LOCALIZED AT POWERPLANT SITES; SMOKESTACKS	DISTRIBUTED WITHIN CITY AT GROUND LEVEL
CONTROLS	FEW THOUSAND POWERPLANTS	MILLIONS OF AUTOMOBILES

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Fig. 3

12

BATTERIES FOR ELECTRIC VEHICLES

SYSTEM	PROJECTED MAX PERFORMANCE		PROBLEM AREAS
	WH/LB	W/LB	
CONVENTIONAL BATTERIES			
LEAD-ACID	18-25	20-30	LOW ENERGY DENSITY
LEAD-ACID (HIGH RATE)	5-10	150-200	LIFE UNDETERMINED
NICKEL-IRON	25	50?	GASSING, MAINTENANCE, EFF
NICKEL-ZINC	30	150	COST, LIFE
METAL-GAS			
IRON-AIR	40-50	10-20	CATHODE CORROSION, LIFE
ZINC-AIR	40-50	10-20	LIFE, COST, COMPLEXITY
NICKEL-HYDROGEN	30-40	?	VOLUME, LIFE
ZINC-OXYGEN	50-60	10-30	LIFE (Zn & AIR ELECTRODES), COST
CADMIUM-OXYGEN	30-40	?	LIFE (Cd & AIR ELECTRODES), COST
ALKALI METAL-HIGH TEMP			
SODIUM-SULFUR (BETA ALUMINA)	80-100	80-100	DETERIORATION OF ELECTROLYTE
SODIUM-SULFUR (GLASS)	80-150	80-400	LIFE, GLASS STABILITY
LITHIUM-SULFUR	100	>100	CORROSION, COST, MATERIALS
LITHIUM-CHLORINE	50	>100	CYCLE LIFE
OTHER SYSTEMS			
ZINC-BROMINE	20	?	LOW ENERGY DENSITY
ZINC-CHLORINE	75	50-60	?

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Fig. 4

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SODIUM-SULFUR BATTERY MODULES

Fig. 5

This [illegible] better detail.

Na-S BATTERY POWERED VAN

Fig. 6

VEHICLE REQUIREMENTS AND MOTIVE POWER SOURCE REQUIREMENTS

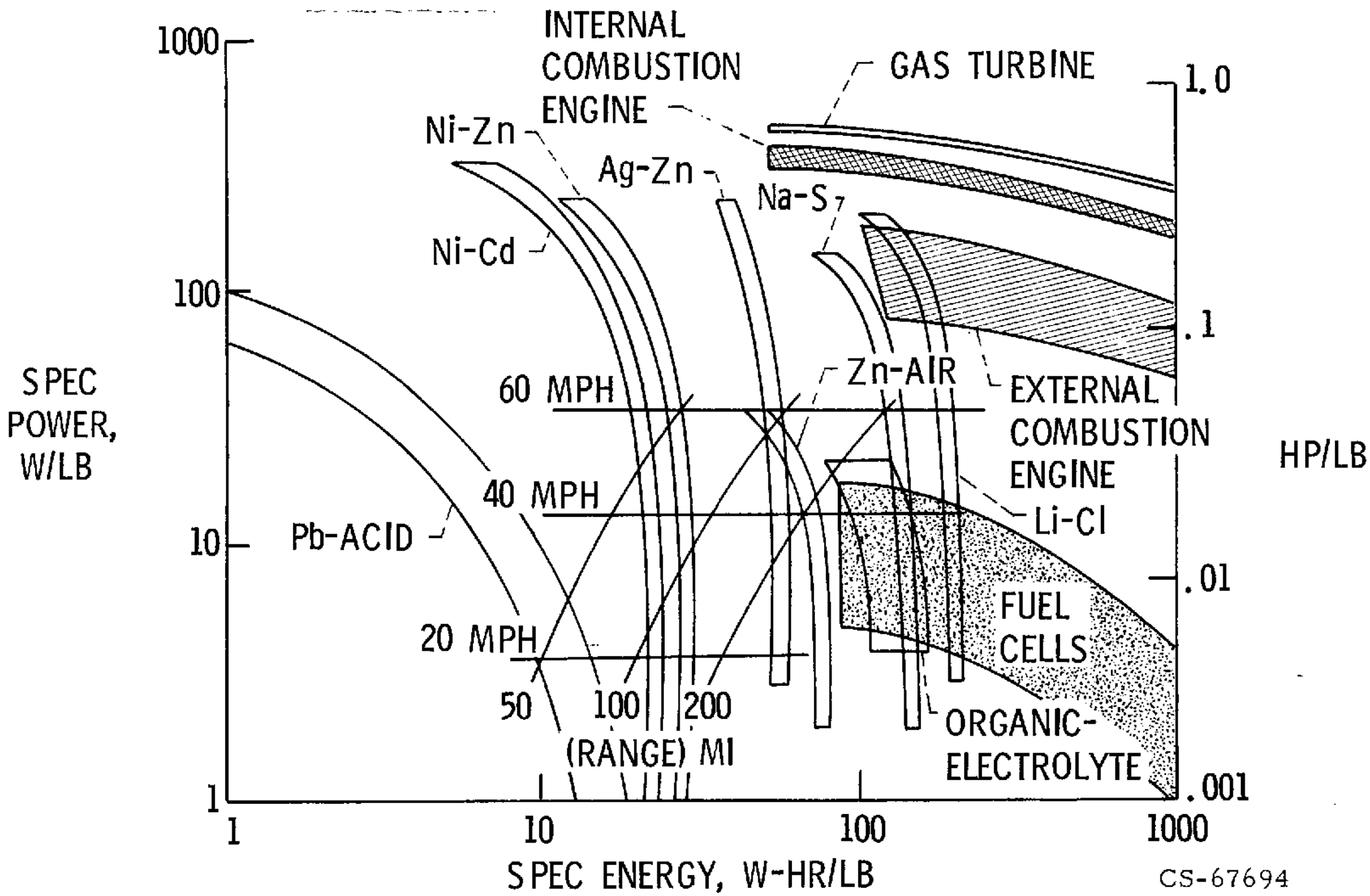

Fig. 7

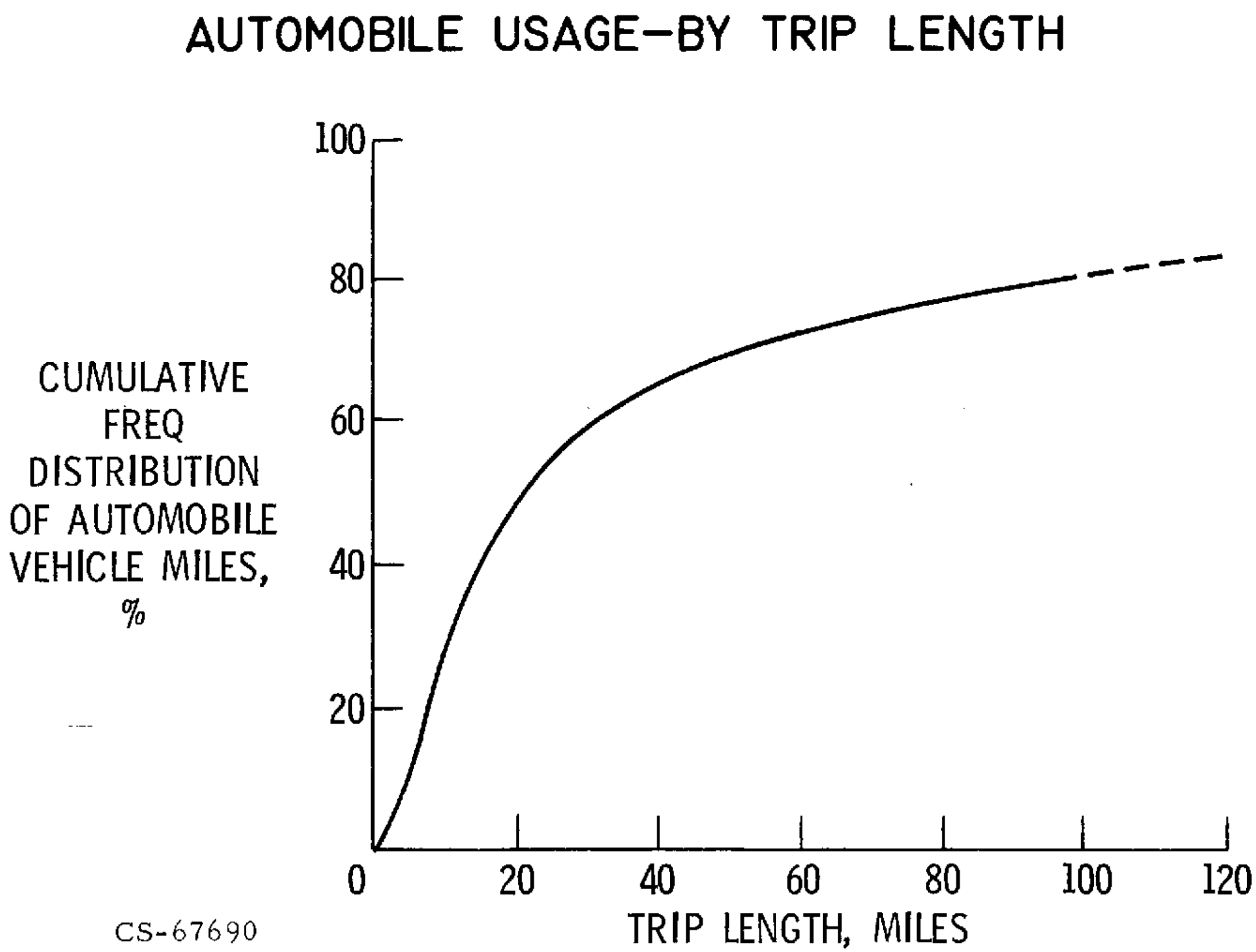

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Fig. 8

AUTO USAGE BY DAILY MILEAGE

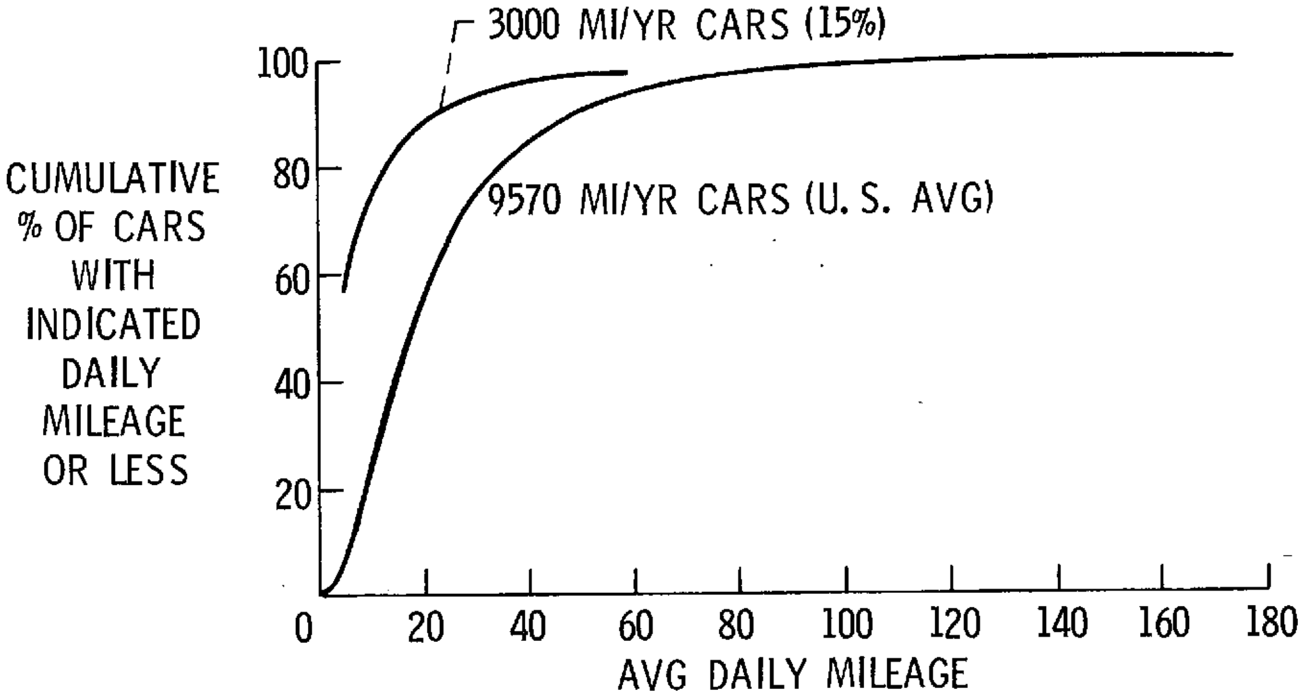

Fig. 9

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