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STUDY OF HYDROGEN-POWERED VERSUS
BATTERY-POWERED AUTOMOBILES

Volume 3

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MASTER

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PREFACE

This report, prepared by The Aerospace Corporation for the Department of Energy, Office of Transportation Programs, documents the study conducted to compare the technological status and the resultant potential vehicle characteristics for hydrogen- and battery-powered automobiles that could be produced from 1985 to 2000. The primary objectives of the study were: (1) the assessments of applicable energy storage and propulsion technology for the two basic vehicle types (applied to four-passenger cars), (2) a rigorous comparison of vehicle weight, size, and usefulness versus design range, and (3) an investigation of the relative efficiencies of expending energy from various primary sources to power the subject vehicles. Another important objective, unique to hydrogen-powered vehicles, was the assessment of the technology, logistics, and cost implications of a hydrogen production and delivery capability.

The information contained in the technology assessments was obtained by a review of the literature available up to mid-1977 and by personal contacts with government, university, and industry researchers.

This report is organized in three volumes. Volume I provides a summary of study scope, methodology, results, and conclusions relative to principal propulsion options considered for the 1985, 1990, and 2000 model years.

Volume II provides an introduction to the study and two major sections applicable to hydrogen-powered vehicles - the study of hydrogen production and delivery alternatives before the year 2000 and the assessment of automotive technology for hydrogen storage and use in internal combustion engines.

This volume, Volume III, contains three major sections: the assessment of battery electric vehicle technology for energy storage and the drivetrain system; the technical and economic comparison of

hydrogen- and battery-powered vehicles derived primarily from data in the previous vehicle technology assessments, with consideration of alternative energy sources; and a series of appendices that support the vehicle definitions and comparisons.

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SECTION 4

ELECTRIC VEHICLE ASSESSMENT

The objective of this portion of the study is to assess the design, performance, and economic characteristics of battery-powered vehicles. The ultimate purpose of the study is to compare the present and future potential of the electrically powered vehicle to the potential for a vehicle powered by a hydrogen internal combustion engine (ICE). Each of these vehicles is actually competing with the present conventional internal combustion vehicle (ICV) for the future automobile market, and it is through a comparison of each of these concepts of a conventional vehicle that the electric vehicle (EV) will initially be compared to the hydrogen-powered vehicle (HV). In Section 5, a direct comparison of battery-powered and hydrogen-powered vehicles is made.

The EV is competing with conventional vehicles and "therefore, EV's must perform like conventional vehicles if they are to be commercially successful and if they are not to pose road hazards when mingling with gasoline-powered cars." (Ref. 4-1). This assumes that EV's replace ICV's through an evolutionary process, reflecting greater freedom of choice. Near-term EV's cannot be expected to achieve the acceleration and range capabilities of conventional cars, but advanced EV's will be much more competitive. In a period of rising fuel costs and possible uncertain fuel availability, they do, however, offer a convenient, relatively secure energy supply with the cost advantages typically associated with off-peak energy use. Unlike all other alternatives, air polluting emissions from EV's are negligible.

The type of EV which evolves will depend upon the details of competing systems from performance, safety, and economic standpoints. In this study, only battery-powered EV's are considered. Clearly, there are potential improvements in acceleration, by the use of flywheels, and range,

by the addition of a small heat engine. Inclusion of such provisions increases the complexity and cost of the vehicle and clouds the weight, range, size, cost, and energy comparison of vehicles of different battery types and their comparison with HV's. For the more attractive battery EV alternatives, future analyses could more fully evaluate the benefits and costs of various hybrid versions for several driving cycles.

In order to define the characteristics of practical EV's, several comparisons with conventional petroleum-fueled vehicles are presented. The ICV is not only the principal competitor impeding the major introduction of EV's, but it is also the only well-defined vehicle for which preliminary comparisons can be made. Despite weight and cost penalties, the EV must meet certain minimum requirements in range, acceleration, maximum speed, roominess, safety, comfort, and styling if it is to be safely operated in a mix with conventional vehicles and other advanced vehicles and if it is to achieve the consumer acceptance which has eluded it to date. These and other characteristics need not be matched point-by-point but must be recognized as what the public has come to expect from its increasingly more expensive personal vehicles. Comparisons with conventional automobiles are helpful in evolving compromise EV characteristics permitting the direct comparison with hydrogen-powered automobiles in Section 5.

This section of the report is concerned with both battery systems and the remainder of the powertrain. It includes current and projected characteristics and development problems for each, vehicle integration considerations, availability dates for different levels of technology, and estimated costs of propulsion components.

4.1 ELECTRIC VEHICLE TECHNOLOGY

The widespread utilization of battery electric automobiles is primarily dependent upon the availability of practical battery subsystems and drivetrain subsystems. These subsystem technologies are assessed separately in the following sections prior to specifying vehicle characteristics projected for 1985, 1990, and 2000.

4.1.1

Battery Technology

Any discussion of EV's must start with batteries. The availability of batteries of sufficient power output and storage energy density per unit weight, at a reasonable price, will permit the EV to compete with the current ICV on energy economy, environmental, cost, reliability, and performance attributes. Relative safety will depend upon the type of battery, the system voltage, and the safety devices that can be built into the vehicle relative to the inherent safety hazard of the gasoline-fueled vehicle.

Approximately 70 battery types can be considered as candidates for EV propulsion (Ref. 4-2). Many of these have variations in alloys, chemistry, electrolyte, operating temperatures, separator materials, and use of plastics, special dopes, pastes, and other proprietary materials, which make it impossible to catalogue all the options available at any point in time. Numerous tradeoffs are possible, leading to designs which emphasize one or more criteria at the expense of others. The important point is that a substantial number of systems is available for development. In view of "the good technical progress demonstrated with vehicles using conventional lead/acid batteries having energy densities less than 18 Wh/lb" (Ref. 4-2), any battery system with achievable energy density greater than the conventional battery will advance the potential for EV's. Several high-performance commercial vehicles are in operation in England utilizing lead/acid batteries with energy densities from 14 to 16.5 Wh/lb (Ref. 4-3). Reference 4-2 lists secondary battery systems, some of which show promise of achieving many of the attributes of cost, size, energy density, power density, efficiency, life, safety, reliability, and charge-discharge characteristics necessary for a viable vehicle battery system. This list is shown in Table 4-1. It includes qualitative comments and major factors affecting possible use. These are judgments made in 1974. Other references include descriptions, development problems, and status and express opinions on prospects for automotive application. New data available since 1974 may also have brightened the prospects for some of

TABLE 4-1. SELECTED CANDIDATE SECONDARY BATTERIES (Ref. 4-2)

Battery	Major Factors Affecting Possible Use	Near-Term Prospects (0-5 Years)	Long-Term Prospects (5-15 Years)	Other References
Lead/Acid	Low cost, better energy density and life needed	Excellent	Good	4-3 through 4-15
Nickel/Zinc	Need improved cycle life	Fair	Good	4-5, 4-6, 4-9, 4-10, 4-12, 4-13, 4-15, 4-16, 4-17
Zinc/Bromine	Need separator for long activated stand	Poor	Fair	4-18, 4-19
Nickel/Iron	Uncertain cost	Good	Good	4-7, 4-9, 4-10, 4-12, 4-13, 4-15
Nickel/Cadmium	High cost, limited cadmium supply	Poor	Very poor	4-6, 4-7, 4-20
Nickel/Hydrogen	Cost and hydrogen tank weight	Good	Good	4-13
Zinc/Chlorine Hydrate	Weight, cost, and reliability	Poor	Fair	4-4, 4-6, 4-10, 4-12, 4-13, 4-19, 4-21 through 4-28
Zinc/Air	Weight, cost, and life	Poor	Poor	4-4, 4-6, 4-8, 4-28
Aluminum/Air	Rechargeable aluminum electrode	Poor	Fair	
Iron/Air	System complexity, cost, life	Fair	Good	4-8
Lead/Air	Weight and life	Very poor	Very poor	
Sodium/Sulfur	Solid separator, life, cost	Fair	Good	4-4, 4-6, 4-8, 4-11, 4-13, 4-29 through 4-35
Sodium-Phosphorus/Sulfur	Solid separator, life, cost	Poor	Fair	
Sodium/Selenium	Limited selenium supply, cost, improved energy density	Very poor	Poor	
Lithium/Sulfur	Improved sulfur electrode, life	Poor	Good	4-4, 4-9, 4-12, 4-13, 4-15, 4-28, 4-36 through 4-42
Lithium/Chlorine	Improved energy density	Poor	Good	4-4, 4-6, 4-20
Lithium/Tellurium Tetrachloride	Improved energy density	Poor	Good	
Lithium/Selenium	Limited selenium supply, cost, improved energy density	Poor	Fair	
Aluminum/Chlorine	Improved aluminum electrode	Poor	Good	4-4
Lithium-Phosphorus/Sulfur	Improved sulfur electrode, life	Poor	Good	
Magnesium/Chlorine	Requires more basic research	Very poor	Poor	
Calcium/Barium-Chlorine	Requires more basic research	Very poor	Poor	
Calcium/Nickel Fluoride	Improved solid electrolyte doping, better electrode geometry	Very poor	Fair	
Lithium/Sulfur Dioxide	Cost, high rate capability	Poor	Poor	
Lithium/Lamellar Structure	Cost, high rate capability	Poor	Poor	
Antimony Redox	Requires more research and development	Poor	Fair	

these systems. The major point of the table is to show that there are many candidate systems, and 18 out of the 26 listed rated fair or better as long-term prospects. Certainly, with the increased interest and the funding available since 1974, the prospects should be better than this table depicts.

Some description and discussion of the chemistry, configuration, and problems associated with each of these battery candidates is contained in Reference 4-2. Additional references for a number of these candidates have been provided in Table 4-1 to assist those who desire more detailed information on each battery type. This table, of course, does not describe the battery combinations listed or indicate the level of effort being devoted to further research and development. An important aspect of many battery systems not highlighted by Table 4-1 is the substantial departure in design (and associated operating characteristics) from the familiar lead/acid battery. The newer systems may involve one or more of the following: external electrolyte reservoirs or reactant storage units, air cooling provisions, pumps, heat exchangers, refrigeration provisions, molten electrodes with solid electrolyte, insulation, or individual cell charging requirements. Thus, there is a great variation in battery complexity, operating temperature, safety, volume, and charging complexity in addition to the most commonly considered factors of energy and power levels achievable, for a given weight, cycle life, and cost. This report does not detail the features of even the principal battery alternatives but does illustrate the range of characteristics by describing several alternatives to the lead/acid battery.

The full evolution of EV's, which began about the same time as the development of ICV's, has been severely retarded by several battery performance limitations. The foremost restriction has been stored energy per unit weight or energy density. This has a direct effect on achievable range for a given vehicle weight and operating speed. Almost as important, and directly affecting the energy density, is the battery output power per unit weight or the power density. This imposes a limitation on the achievable acceleration and maximum speed of a vehicle. The third vital factor is battery cycle life or

the total number of charge-discharge cycles which can be imposed before the battery fails to provide the adequate energy or power densities required to meet vehicle driveability requirements. It has a strong effect on the vehicle operating cost associated with battery replacement. Improvement in these parameters in recent years for the lead/acid battery and for newer systems has enabled EV's to find application primarily as commercial delivery vehicles and transit buses. The low-speed, short-range, repetitive operating cycles maintained by such vehicles are quite compatible with the moderate capabilities of current batteries. The principal benefits are reduced urban pollution, reduced energy waste in the idle mode and simpler, less extensive maintenance. Battery developments in the last few years have broadened the field of potential candidates, and the prospect is good that one or more of these will be developed into a battery system suitable for an electric automobile propulsion system in the 1980 to 2000 time frame. Many factors are discussed in this section of the report which relate to current and projected battery characteristics, special development problems, cost, reliability, production, and safety. These factors provide a qualitative feel for the relative probability of success for some of the candidate systems. The ultimate purposes of this section are to indicate the projected energy and cost characteristics of these batteries and their production availability dates. In Section 5, the physical, performance, and cost characteristics of EV's using these batteries are estimated.

4.1.1.1 Battery Programs and Prospects

From a long-term standpoint, some progress in battery capability has been made. In the 1920's the lead/acid battery yielded 4 to 6 watt hours per pound (Wh/lb) and the nickel/iron battery yielded 14 Wh/lb (Ref. 4-15). Today, typical values for lead/acid batteries are 14 to 16 Wh/lb (Ref. 4-3), and the nickel/iron system provides 20 Wh/lb (Ref. 4-15). The lead/acid battery has been used extensively as a starting, lighting, and ignition (SLI) battery for automotive applications during this interval. The nickel/iron battery has also found application but "after Thomas Edison discontinued efforts

to perfect the nickel/iron system for automobile engine starting, development on the system stopped, and the batteries marketed today are essentially the same design established by Edison many years ago" (Ref. 4-2). The point of the above is that through an evolutionary process over approximately 50 years, the SLI and Edison batteries have improved by 50 to 100 percent without the expenditure of vast sums of money for development and without the incentive of a looming energy crisis. Because of this energy crisis and the increasing concern for clean air, the U.S. Congress enacted PL 94-413, the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976. As a consequence, several of the battery developments are being pursued more vigorously today under the sponsorship of the Department of Energy (DOE), the Electric Power Research Institute (EPRI), and several private corporations.

Table 4-2 (Ref. 4) summarizes the activities for various battery systems in 1974. Table 4-3 (Ref. 15) shows the total estimated research and development (R&D) funding in the United States by both industry and government for the years 1972 and 1975. The distribution of R&D expenditures in the United States in 1976 between industry and government is presented in Table 4-4. These tables clearly indicate the involvement of many organizations in the various battery technologies and a considerable increase in the funding available in the United States for battery development. This increase in activity occurred prior to the enactment of PL 94-413. This law mandated the expenditure of \$10 million on battery R&D in fiscal year 1977. From this standpoint then, it appears that increasing emphasis will continue to be placed upon battery development. This concentrated effort, backed by adequate funding, is replacing the laissez-faire attitude of the past 50 years. It seems reasonable, therefore, that accelerated progress should be realized. As previously noted, the nondevelopment program of the past 50 years produced a 50- to 100-percent improvement in the energy density of two battery systems. These two systems will continue to develop as they are prime candidates for the early generation of EV's. Other systems receiving major attention are also listed in Tables 4-3 and 4-4.

TABLE 4-2. 1974 BATTERY RESEARCH AND DEVELOPMENT PROGRAMS (Ref. 4-4)

Type of Cell	Organization	Estimated Level of Effort (Staff Level) ⁽¹⁾	Goal ⁽¹⁾
Lithium/Sulfur	Argonne National Lab.	25	U, T
	Atomics International Div.,	4	U
	Rockwell International		
	General Motors Corp.	5 to 10	T
	Institute of Power Sources (Moscow)	NA	NA
Sodium/Sulfur	Electrical Engineering Lab. (Prague)	NA	NA
	Ford Motor Co.	13	U, T
	TRW, Inc.	5	T
	General Electric Co.	5	U, T
	Dow Chemical Co.	5	
	ESB, Inc.	NA	U
	British Railways Board (UK)	12	T
	Electricity Council Research	15	U, T
	Compagnie GE (France)	12	U, T
	Yuasa, Battery Co.	30	U, T
	(Toshiba) (Japan)		
	Japan Storage Battery	NA	U, T
	Toyota Motor Co.	NA	T
	Brown Boveri and Co. (Switzerland)	NA	U
Zinc/Chlorine	Udylite	35	U, T
Lithium/Chlorine	Standard Oil Co. of Ohio	NA	T
	General Motors Corp.	NA	T
	Oak Ridge National Lab.	1	E
	Westinghouse Electric Corp.	NA	E
Aluminum/Chlorine	ESB, Inc.	NA	U
Advanced Lead/Acid	Gould, Inc.	NA	T
	Japan Storage Battery	NA	T
	Yuasa Battery Co. (Toshiba) (Japan)	NA	T
	ESB, Inc.	NA	T
Lithium/Organic	Electrochimica Corp.	NA	E
	Globe Union Corp.	NA	E
	Union Carbide Corp., Ohio	NA	E
	Tyco Laboratories, Inc.	NA	E
	SAFT (France)	NA	E
	Matsushita Electric Industries (Japan)	NA	E
Zinc/Air	All major battery companies listed above	Variable	T

⁽¹⁾U, utility applications; T, transportation uses; E, exploratory, and NA, not available.

TABLE 4-3. BATTERY RESEARCH AND DEVELOPMENT FUNDING
IN THE UNITED STATES (Ref. 4-15)

Battery System	Millions of Dollars	
	1972	1975
Lead/Acid	1.0 to 1.5	2.3
Nickel/Iron		0.5
Nickel/Zinc	1.5 to 2.0	1.3
Metal/Air		2.15
Zinc/Chlorine		0.5
Lithium-Aluminum/ Metal Sulfide	1.5 to 2.5	5.0
Sodium/Sulfur		3.2
Total	4.0 to 6.0	15.0

TABLE 4-4. ESTIMATED BATTERY RESEARCH AND DEVELOPMENT EX-
PENDITURES IN THE UNITED STATES IN 1976 (Ref. 4-43)

Battery System	Estimated R&D, millions of dollars	
	Industry	Government and Others
Lead/Acid	2.5	0.3
Iron/Nickel Oxide	0.3	0.4
Zinc/Nickel Oxide	1.6	0.4
Zinc-Air/Iron-Air	0.7	0.1
Zinc-Chlorine/Zinc-Bromine	2.5	1.0
Lithium/Iron Sulfide	0.4	4.5
Sodium-Sulfur/Sodium-Antimony Chloride	1.4	2.3
Redox	0.1	0.5
Others	0.2	1.3
Total	9.7	10.8

In anticipation of the increasing need for EV's to minimize petroleum consumption and aid in controlling pollution, DOE has been active in the development and funding of existing and new battery systems. The concerns encompass energy storage for load-leveling of electric utilities, to make best use of the capacity of generating equipment, and vehicle storage batteries primarily for automobiles, which are the principal petroleum consumer and a major atmosphere pollution source. DOE is also sponsoring the design and development of EV's of increasing performance sophistication to demonstrate the maturing of vehicle characteristics with successful development and production of better batteries and drivetrain systems including fly-wheel energy storage units.

In addition to this DOE program, PL 94-413, the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976, provides for a substantially expanded program under DOE's direction. Specific provisions were included for funding of battery R&D and the government's procurement of 2500 near-term and 5000 more advanced EV's and HV's for major public demonstrations of vehicle characteristics. Procurement plans have been altered significantly but similarly large numbers of vehicles are to be utilized by commercial, industrial, governmental, and private users to obtain operational experience.

DOE has delegated to Argonne National Laboratories (ANL) the responsibility for battery development and evaluation for the existing and PL 94-413 programs. Among its activities in support of DOE, ANL has initiated several contracts for the development of lead/acid, nickel/iron, and nickel/zinc batteries in accordance with the goals specified in Table 4-5. These battery systems represent the best prospects for near-term vehicle application. ANL is confident that the goals are achievable and points out that there never has been a concerted effort to develop battery technology in this country. Much can be done just by optimizing packaging, using larger cells with fewer walls, reducing cell connector lengths, reducing excess material in the plates, and eliminating excess electrolyte. These factors also tend to

TABLE 4-5. DEVELOPMENT GOALS FOR NEAR- AND INTERMEDIATE-TERM
ELECTRIC VEHICLE BATTERIES (Refs. 4-44 and 4-45)

Battery Characteristics ⁽¹⁾	Lead/Acid			Nickel/Iron			Nickel/Zinc		
	Present	1979	1981	Present	1979	1981	Present	1979	1981
Specific Energy (100% DOD), Wh/kg	30	40	50	44	50	60	70	70	90
Specific Power, W/kg									
Sustained	15	20	25	20	40	50	20	40	50
Peak (50% Charge)	50	100	150	130	150	200	130	150	200
Energy Efficiency, %	65	>60 ⁽²⁾	>60 ⁽²⁾	70	70	70	>60	>60	>60
Cycle Life (80% DOD)	700	800	1000	1500	1500	2000	200	500	700
Initial Installed Cost, \$/kWh									
<10 ⁴ Batteries	100	80-100	80-100	--	100-120	100-120	--	100-120	100-120
>10 ⁴ Batteries	50	50	40	120	70-80	50-60	--	70-80	50-60

(1) Battery Duty Cycle: 2-4 hr discharge, 70-80% DOD, 1-6 hr charge.

(2) Typical charge-discharge conditions yield 70% efficiency.

reduce cost. Many other well-known methods are being pursued that require development. None of these methods is free of technical problems, but there appears to be little doubt that significant improvement can be made in these batteries.

ANL is also establishing a pilot facility through its battery contractors for the production of 100 to 500 nickel/zinc batteries per year. This facility will yield batteries for early evaluation in the EV program and will provide data on manufacturing processes, product yield, percentage of waste, and battery cost. Table 4-5 specifies that nickel/zinc batteries currently possess twice the energy density of the lead/acid battery, and if the goals can be achieved most of that advantage will be maintained. The nickel/iron battery system of Table 4-5 does not possess the energy potential of the nickel/zinc system, but these batteries are attractive because of their proven ability to obtain long life under deep discharge cycles. One manufacturer gives a 5-year guarantee on his nickel/iron batteries on the basis of one 100-percent discharge each day (Ref. 4-2). Some batteries have been in continuous service for 20 years. If these features of long life and reliability can be coupled with improved power and energy density at a low initial cost, this battery could be a strong contender for the EV market.

Table 4-5 is a typical method of presenting battery characteristics, but care must be used in drawing conclusions from such a table since many of the terms are interrelated. The total energy in watt hours per kilogram (Wh/kg) that may be drawn from a fully charged battery is a function of the power draw in W/kg. For the table presented, the goal is that the battery will deliver the specific energy stated at the specific sustaining power level indicated. This is one point on the curve of energy density versus power density, and it nominally represents a vehicle cruise condition. The goals presented here are for 100-percent discharge to a predetermined cutoff voltage. To attain the cycle life tabulated, the conditions of the battery duty cycle must be satisfied. This limits usable depth of discharge (DOD) to 80 percent. Unfortunately, the discharge times presented in Table 4-5 are not uniform,

varying from 1.2 to 3.5 hr (as obtained by dividing specific energy by sustaining specific power). An EV designed for a 200-mi range would require battery characteristic evaluation for a 4 to 6 hr discharge depending upon the assumed driving cycle.

The peak power shown is the maximum power that can be drawn from the battery system at 50-percent state of charge. It can be sustained for only 15 to 20 sec at a time because of battery heating and other factors. The battery does not deliver the specific energy shown when many peak power demands are required during the duty cycle or the total discharge time is significantly less than the 1 to 3 hr implied in the table. The curves showing the interrelationship of power and energy densities are presented later in this section.

The other parameters shown in Table 4-5 are linked together in a similar fashion. Cycle life is a function of DOD. The cycle life goals shown are for the 70- to 80-percent DOD indicated. How cycle life varies with DOD is discussed later for several battery systems.

Table 4-5 also quotes energy efficiency values. The battery efficiency quoted is the overall charge-discharge energy efficiency of the battery system measured at the battery terminals. It is dependent both upon the conditions of charge and discharge as well as upon battery type. The values presented correspond nominally to the quoted range of battery duty cycle conditions. Considerably higher efficiencies might be attained if full or equalizing charges were not administered every day (Ref. 4-15). The final parameter presented in the table is the installed cost per unit of output energy. The candidates show a fair degree of uniformity at \$40 to \$60/kWh. Clearly, battery cost, as well as energy density, tends to limit vehicle design range.

An important factor not evident from Table 4-5 is the increased complexity of many alternatives to the lead/acid battery as the public knows it (from SLI experience), even for near-term use. Figure 4-1 is a schematic of one type of nickel/iron battery showing that the battery cell module is

FIGURE 4-1. NICKEL/IRON BATTERY SCHEMATIC
(Ref. 4-7)

complemented by an electrically driven electrolyte pump, an electrolyte reservoir, flexible hose, module manifolds, a gas vent, and a heat exchange coil to utilize externally supplied coolant. The latter implies a cooling circuit requiring a radiator, circulation pump, and possibly a fan. Although these elements are not major engineering challenges, they present new battery system failure modes and hazards affecting development, integration, safety, and maintenance.

A battery system significantly different from the ambient temperature systems identified in Table 4-5 is the zinc/chlorine hydrate battery. Energy Development Associates (EDA) is a corporation specially set up as a joint venture between Gulf and Western Company and Hooker Chemical Company to develop the zinc/chlorine hydrate battery system for EV and

load-leveling applications (Ref. 4-22). The feasibility of such a battery had been demonstrated in an actual automobile test (Ref. 4-21). During the automobile test run, the battery used was not rechargeable, but subsequent systems have incorporated this feature. A schematic of a rechargeable battery is shown in Figure 4-2. EDA is building a battery under DOE sponsorship for an EV in accordance with the goals of Table 4-6. EDA is also working on load-leveling applications for EPRI (Ref. 4-23). EDA has built many 1-kWh battery systems but current EPRI and DOE efforts are on batteries in the 40- to 50-kWh class. As Table 4-6 illustrates, these batteries are envisioned for the intermediate term (1980 to 1983) and represent, if the goals can be met, more than a 200-percent improvement in energy and power densities over the improved lead/acid system for the same discharge time.

The zinc/chlorine system represents a significant departure from the three batteries of Table 4-5. As depicted in Figure 4-2, the battery system consists of a plate area, a hydrate store, electrolyte and hydrate circulation pumps, a heat exchanger, and a chlorine hydrate chilling provision. The latter is required to transfer heat to freeze the hydrate during battery charging and melt it during discharging. The freezing and melting take place at 50°F (1 atm) to 70°F (3 atm). A cooling capability of 80 cal/gm

FIGURE 4-2. ZINC/CHLORINE HYDRATE BATTERY SCHEMATIC (Ref. 4-21)

TABLE 4-6. DEVELOPMENT GOALS FOR ZINC/CHLORINE BATTERY
(Ref. 4-12)

Battery	Present, 1975	Module Demo(I), 1978	Module Demo(II), 1980	In-Vehicle Demo, 1983
Specific Energy (100% DOD), Wh/kg	<66	90	120	150 ⁽¹⁾
Specific Power, W/kg				
Sustained	30	50	80	100
Peak (50% Charge)	60	120	150	150
Cycle Life	~100 (kWh size)	>500	>1000	>1000
Cost, \$/kWh	>2000	<1000 ⁽²⁾	<250 ⁽²⁾	50

(1) Reference 4-43 indicates 120 Wh/kg.

(2) Preproduction.

of hydrate must be available during charging, and an equivalent quantity of heat must be provided by the vehicle during discharging. This is equivalent to 15 percent of the battery output. It is conceivable that this heat sink could accommodate a simple compartment air conditioning system.

Details on how this system works can be obtained from many of the references listed in Table 4-1. The main point to be noted here is that the battery is a complex of tanks, pumps, tubing, and flowing electrolyte and, therefore, more complex than the familiar SLI battery. Like the nickel/iron battery, these differences pose some design and safety problems. They also add a unique potential for a simple air conditioning system which consumes almost no power. No efficiency goal was indicated by DOE, but EDA states that the goal is 65-percent overall energy efficiency.

For the longer term, other batteries are being developed such as the sodium/sulfur and the lithium/sulfur high-temperature systems.

Primary attention by DOE is focused on the lithium/sulfur battery and Table 4-7 provides the ANL goals in 1977 for the vehicle battery development program as it stood in September 1977. ANL's efforts are currently concentrated in developing cells featuring porous lithium-aluminum alloy (negative) and ferrous sulfide (positive) electrodes which contain molten salt electrolyte (Li Cl-KCl eutectic). A typical cell is depicted in Figure 4-3. The Mark IA battery, which superseded the Mark I battery of Table 4-7, is a 40-kWh battery (144-V Output) scheduled for in-vehicle tests in April 1979. It consists of 120 cells assembled in two rectangular modules, each of 20-kWh capacity. Each module has dimensions of $152 \times 46 \times 33$ cm. The modules utilize a double wall container with thermal insulation between the inner and outer walls. The inner shell contains argon at 1 atm, primarily to prevent corrosion of the steel cell case and copper bus. The battery operating temperature of 425 to 450°C is maintained by intermittent air coolant flow. The Mark IA battery thermal loss is less than 400 W using 1 cm of Multifoil* insulation in a vacuum space between inner and outer walls. The design goal for future batteries is 75 to 125 W loss. ANL projects a temperature decay of 1°C/hr for an idle Mark II or Mark III battery. Subsequent operation returns the battery to optimum temperatures by normal ohmic heating losses.

Charging of the lithium-aluminum/iron sulfide battery requires a bulk charger and a trickle charger or cell equalizer. Individual 7-amp charging wires are provided to the 120 cells to assure that they can each be charged to the same voltage. Figure 4-4 provides longitudinal and transverse sectional views of an early conceptual design using a cylindrical configuration. The present Mark IA design utilizes a rectangular case.

Three contractors are working with ANL to the goals established by Table 4-7.

A comparison of Tables 4-6 and 4-7 indicates that the lithium-aluminum/iron sulfide battery is not expected to have an advantage in any performance parameter relative to the zinc/chlorine hydrate battery until at least

*Multifoil is a registered trademark of the Thermo Electron Corporation, Waltham, Mass.

TABLE 4-7. GOALS FOR ELECTRIC VEHICLE LITHIUM-ALUMINUM/IRON
SULFIDE CELLS AND BATTERIES (Refs. 4-44 and 4-45)

Battery Characteristics	Present Performance		Mark I, 1979 ⁽²⁾	Mark II, 1980	Mark III, 1981	1985 ⁽²⁾
	ANL ⁽¹⁾	Industrially Fabricated				
Specific Energy (100% Depth of Discharge), Wh/kg						
Cell	130	75	110	130	160	180-200
Battery	--	--	75	100	130	145-160
Specific Power, W/kg ⁽³⁾						
Cell (peak)	120	75	110	150	200	240
Battery (peak) ⁽⁴⁾	--		75	120	160	200
Energy Efficiency, %			70	75	75	75
Battery Cycle Life						
Full Discharge Equivalent ⁽⁵⁾	400	200	300	500	700	1,000
Installed Cost, \$/kWh ⁽⁴⁾						50

(1) Data from selected experimental cells.

(2) Updated battery performance goals received from ANL subsequent to completion of the study indicate 1979 Mark IA goals are 60 to 80 percent of the values tabulated for Mark I, but long-range goals (beyond 1986) are virtually identical to the tabulated 1985 goals.

(3) Power capability for 15 sec with battery at 50-percent DOD.

(4) For mature battery plant producing 2000 MW-h of battery capacity per year.

(5) Cell voltage cutoff at 1.0 V/cell (equivalent to 65 to 75 percent utilization of active materials).

FIGURE 4-3. DESIGN OF PRISMATIC LITHIUM-ALUMINUM/IRON SULFIDE CELL (Ref. 4-40)

FIGURE 4-4. SECTIONAL VIEW OF AN EARLY CONCEPT OF A LITHIUM-ALUMINUM/IRON SULFIDE VEHICLE BATTERY (Ref. 4-40)

1985. However, the ultimate attainable specific energy and projected charge-discharge efficiency are higher, and the cost per kWh is expected to be lower for the lithium-aluminum/iron sulfide system. The 800°F operating temperature of the latter is its strongest drawback and necessitates a good insulation system for safety, minimization of energy loss, and avoidance of solidification of molten electrolyte during protracted periods of inactivity.

One study (Ref. 4-15) compares the goals established in the 1973 to 1974 time frame with the recent goals for several of these battery systems. Figure 4-5 illustrates this comparison. No new goals are shown for the zinc/chlorine battery, but the goals for the nickel/zinc and lithium/sulfur systems have moved down while the projection for lead/acid batteries in 1980 has improved. The nickel/zinc performance reduction is a moderate one (about 17 percent), but the change from lithium/sulfur to lithium-aluminum alloy/iron sulfide reduced the projected energy density about 60 percent. This indicates that as an appreciation is gained of the problems associated with these new systems, compromises must be made that reduce their potential. However, the history of the lead/acid and nickel/iron batteries discussed

FIGURE 4-5. COMPARISON OF BATTERY PERFORMANCE PROJECTIONS (Ref. 4-15)

earlier shows that some simple batteries may improve with time even without strenuous effort.

4.1.1.2 Energy and Power Densities

In the previous section the DOE and ANL goals for the various battery systems were discussed. Figure 4-5 illustrates how battery energy and power density projections have changed within the past few years. How do these projections compare with the goals of Section 4.1.1.1?

Figure 4-6 shows a comparison of the ANL goals with the recent projections for the lead/acid, nickel/zinc, and lithium-aluminum/iron sulfide batteries from Reference 4-15. The ANL goals for lead/acid and nickel/zinc batteries are slightly more ambitious than the projections (8 and 14 percent, respectively). When one considers the familiarity of these battery types and the increased R&D funds available, the ANL goals appear reasonable.

FIGURE 4-6. POWER AND ENERGY DENSITIES OF REPRESENTATIVE BATTERIES (Refs. 4-15, 4-44, 4-45, 4-46)

For the nickel/iron battery, Reference 4-15 presents only a tabulation of properties projected for approximately 1978 according to Reference 4-47. The latter indicates an even higher specific energy, 60 Wh/kg; the same peak power, 150 W/kg; a lifetime of >1000 cycles; and a specific cost of \$120/kWh, which is 50 percent higher than ANL's goal. However, projections in Reference 4-48 for 1977 to 1982 are significantly less hopeful, assuming 30 to 50 Wh/kg (versus 60), 80-W/kg peak power (versus 200), and 17-W/kg (versus 50 for 1.2 hr) sustained power level. The forecasts for other parameters are also less optimistic than ANL goals, including a life of 1000 cycles (versus 2000), a cost of \$500/kWh (versus \$50 to \$60), and an energy efficiency of 55 percent (versus 70 percent). Projections for 1982 to 1990 still have large differences in specific power and in cost (\$100/kWh versus ANL's \$50 to \$60/kWh). In summary, ANL's goals for the 1981 nickel/iron battery are optimistic compared to other available forecasts.

The lithium-aluminum/iron sulfide battery is also somewhat beyond the 1985 projection of Reference 4-15. ANL's goals of 145 to 160 Wh/kg, apparently for a 4-hr discharge, are 13 to 25 percent higher than the curve at this discharge time. ANL's peak power goal of 200 W/kg, for a 15-sec duration, is one third higher than the projection of Reference 4-15. The 1985 battery performance goals are nominally twice as high as current capability.

Figure 4-7 duplicates the 1973 to 1974 projection (from Figure 4-5) for the zinc/chlorine battery and presents a recent ANL projection for 1978 zinc/chlorine hydrate battery performance. DOE performance goals for 1980 and 1983 are also presented (Ref. 4-12). These 1.5-hr discharge values are seen to represent a 33- and 67-percent improvement in performance over that projected for 1978. The 1983 goals are about 2.5 times as high as the 1975 system performance capabilities for the same discharge time. This will be a significant accomplishment if the 1983 goals are met

FIGURE 4-7. ZINC/CHLORINE BATTERY PERFORMANCE

(150 Wh/kg, 100 W/kg), since this low-temperature battery system would exceed ANL's 1985 goals for the high-temperature lithium-aluminum/iron sulfide battery system at equivalent discharge times.

A factor of considerable importance in vehicle design, which is often disregarded, is the mass density of the battery. The weight of an automotive propulsion battery and the secondary weight changes induced in the vehicle for structure, suspension, brakes, motor power, etc., are of primary importance. The battery space requirement and its cost in vehicle weight must also be considered, especially as vehicle range increases beyond current modest capabilities and new classes of batteries are introduced. Table 4-8 presents typical mass densities for near-term and advanced batteries and the associated battery energy densities in kWh/m³. The near-term batteries are uniformly dense, whereas the advanced systems have significantly lower densities, which partially offset their energy advantages. However, the specified advanced batteries in the year 2000 will have 1.6 to 2.1 times the volumetric energy density of the 1981 lead/acid battery, even without improving their packaging designs.

TABLE 4-8. BATTERY DENSITY

Battery	Density		Specific Energy, Wh/kg	Energy Density, kWh/m ³
	lb/ft ³	kg/m ³		
Lead/Acid (1981)	125	2002	50	100.1
Nickel/Iron (1981)	93	1489	60	89.3
Nickel/Zinc (1981)	100	1602	90	144
Zinc/Chlorine Hydrate				
1985	57	913	150	137
2000	57	913	180	164
Lithium-Aluminum/ Iron Sulfide				
1985	75	1201	145	174
2000	75	1201	175	210

4.1.1.3 Cycle Life

Two factors of critical performance to the acceptability of a battery system for vehicle propulsion are initial cost per unit of storage energy and cycle life. Ideally, a battery would be low in cost and last the life of the vehicle, perhaps 100,000 mi or more. Since normal automobile usage is nominally 10,000 mi/year (27.4 mi/day), an ideal battery should last about 10 years. Nightly charging would correspond to over 3000 charge-discharge cycles. No batteries are currently projected to last this many full cycles. The three basic alternatives are (1) to use the smallest practical battery capacity and replace the original car battery one or more times during the vehicle lifetime, (2) to use a large battery permitting full recharging to be done every third day of vehicle use (assuming a nominal life of 1000 cycles), and (3) to use a large battery and partially recharge it nightly to replace the nominal one third of its capacity discharged during a typical day's usage. Selection of the most advantageous procedure is dependent upon (1) detailed

knowledge of battery behavior (deterioration, efficiency, and time-dependent failure mechanisms) under representative charge-discharge cycling conditions; (2) the tradeoffs between performance, cycle life, and cost; and (3) the predictability of vehicle mission or usage, i.e., the acceptability of starting a day's driving pattern with a one-third charge on the battery. Life cycle prediction, based on fixed periods of time for charging (1 to 6 hr or more) and fixed periods of time for discharging (2 to 4 hr or more) to a given depth of discharge, is, at best, a crude approximation to the operational life in a vehicle. It is most useful for evaluating vehicles used in steady-speed, level highway cruise conditions. Life cycle prediction is least reliable for the variable speed and variable load conditions implicit in the urban and commuter EV usage considered in this study.

Data on cycle life versus DOD is limited. That which is generally available is for lead/acid batteries. Figure 4-8 (Ref. 4-15) presents best and worst case projections made in 1973 to 1974 for 1980 lead/acid batteries, assuming daily charging. Obviously, the variation from best to worst is very large for DOD's from roughly 20- to 85-percent DOD. These curves are replotted in Figure 4-9 in terms of relative total delivered energy or total lifetime vehicle range versus DOD. This mode of presentation indicates that, for lead/acid batteries of a given size, dramatic effects on the total attainable EV mileage can be achieved by selection of an optimum energy expenditure before recharging. Maximum integrated battery output is achieved at DOD's between about 40 and 70 percent. A more recent treatment contained in Reference 4-15 is presented in Figure 4-10. The dashed curve (a hyperbola) is the typical assumption made in the absence of data on cycle life versus DOD. It assumes that there is a constant total energy output from a battery during its life, independent of cycle depth. This is known to be unrealistic for lead/acid batteries since deep cycling is especially detrimental to battery life and lifetime cannot be continuously extended by reducing cycle depth as other progressive failure mechanisms, such as corrosion, become life-limiting. The straight-line

FIGURE 4-8. 1973 TO 1974 PROJECTED LIFE OF 1980 LEAD/ACID ELECTRIC VEHICLE BATTERIES (Ref. 4-15)

FIGURE 4-9. RELATIVE TOTAL ENERGY FOR LEAD/ACID BATTERIES VERSUS DEPTH OF DISCHARGE (from Figure 4-8)

FIGURE 4-10. ASSUMED LIFE OF REPRESENTATIVE 1980 LEAD/ACID BATTERY IN AUTOMOTIVE SERVICE (Ref. 4-15)

relationship shown in Figure 4-10 is simply a first-order relationship between the parameters for lifetimes, up to about 8 years. When the straight-line relationship is translated into relative total energy or attainable vehicle mileage, the result shown in Figure 4-11 is obtained. It indicates that more total mileage can be achieved at a DOD of between 100 percent and 42 percent than one at 100 percent. The maximum gain calculated is about 20 percent at 65-percent DOD. It is also apparent that if a vehicle's daily mileage is about one third its design range, say 27 versus 82 mi, it would be advantageous to charge the battery every second or third night, rather than nightly. However, little significance should be ascribed to such observations without reliable data to establish the DOD versus life relationship. Such data should be sought to permit most economical battery system design and to identify an optimum charging strategy. For systems other than lead/acid, a constant total energy output

FIGURE 4-11. TOTAL MILEAGE FOR LINEAR DEPTH OF DISCHARGE VERSUS LIFE RELATIONSHIP FOR LEAD/ACID BATTERY

is assumed in the absence of data to the contrary. Apparently, the nickel/iron battery does not experience the same level of degradation with time that is found in the lead/acid battery. Nickel/iron batteries have been in continuous service for more than 20 years (Ref. 4-2) and so tend to support the constant total output assumption.

If battery lifetime is significantly less than vehicle lifetime, battery replacement will be necessary. Such a replacement would be made with a high-cost, original equipment battery, a rebuilt or refurbished battery of equivalent rating (but shorter guaranteed life), or an aftermarket battery of equivalent energy and power density but reduced life capability. A source of second-hand batteries would gradually develop from wrecked or retired EV's. The car owner, therefore, could either extend the life of the car to its practical design limit by purchase of a costly replacement battery or economize by purchasing battery capacity for the period of time he wishes to retain the car. Battery leasing may prove an attractive alternative to some EV owners.

4.1.1.4

Batteries for Near-Term Vehicles -- 1985Model Year

It will be assumed that the ANL battery development goals for 1981 (Table 4-4) will be met for the lead/acid, nickel/iron, and nickel/zinc systems. One or more of these battery types would be expected to undergo extensive field evaluation, production engineering, and buildup to large-scale production capacity for use in production passenger cars by the 1985 model year. Table 4-9 summarizes battery characteristics available for the 1985 EV, neglecting differences in the assumed discharge times. Figure 4-12 depicts the battery life assumptions as functions of DOD.

TABLE 4-9. ASSUMED BATTERY CHARACTERISTICS --
1985 MODEL YEAR CARS

Battery Characteristics	Lead/Acid	Nickel/Iron	Nickel/Zinc
Specific Energy (100% DOD), Wh/kg	50	60	90
Specific Power, W/kg			
Sustained	25	50	50
Peak (≤ 15 sec, 50% DOD)	150	200	200
Energy Efficiency, % ⁽¹⁾	70	70	70
Cycle Life (80% DOD)	1000	2000	700
Cost, \$/kWh	40	50-60	50-60

(1) Overall charge-discharge efficiency of the battery excluding charger and power controller losses.

4.1.1.5

Batteries for Midterm Vehicles -- 1990 Model Year

The development goals for the 1983 zinc/chlorine hydrate battery (from Table 4-6) and the 1985 lithium-aluminum/iron sulfide battery (from Table 4-7) will be assumed to be met by 1985. Either of these batteries should be available in large-scale production quantities on or before the 1990 model

FIGURE 4-12. ASSUMED LIFE OF REPRESENTATIVE 1985 NICKEL/ZINC, LEAD/ACID, AND NICKEL/IRON BATTERIES IN AUTOMOTIVE SERVICE

year. Table 4-10 summarizes the midterm battery characteristics, neglecting the differences in the assumed discharge time (1.5 hr for zinc/chlorine hydrate and 4 hr for lithium-aluminum/iron sulfide).

4.1.1.6 Batteries for Far-Term Vehicles -- 2000 Model Year

Meaningful projection of battery characteristics over 20 years into the future in the current environment of high development funding and accelerating development is virtually impossible. No credible projections to the year 2000 were found. Rather than assume that battery characteristics at the turn of the century will be no different from what can be projected for from 1985 to 1990, it was decided to assume an arbitrary, but reasonable, improvement in all major characteristics for the two representative batteries identified for 1990. Table 4-11 assumes a nominal 20-percent improvement over the Table 4-10 values for specific energy, specific power, efficiency, cycle life, and cost for the capability of the far-term zinc/chlorine hydrate battery and the lithium-aluminum/iron sulfide battery by the year 2000.

TABLE 4-10. ASSUMED BATTERY CHARACTERISTICS --
1990 MODEL YEAR CARS

Battery Characteristics	Zinc/ Chlorine Hydrate	Lithium- Aluminum/ Iron Sulfide
Specific Energy (100% DOD), Wh/kg	150	145
Specific Power, W/kg		
Sustained	100	
Peak (≤ 15 sec, 50% DOD)	150	200
Energy Efficiency, % ⁽¹⁾	65 ⁽²⁾	75 (Ref. 4-46)
Cycle Life (80% DOD)	1000	1000
Cost, \$/kWh	50	50 (Ref. 4-46)

(1) Overall charge-discharge efficiency of the battery,
excluding charger and power controller losses.

(2) Estimated.

TABLE 4-11. ASSUMED BATTERY CHARACTERISTICS --
2000 MODEL YEAR CARS (20% IMPROVE-
MENT OVER TABLE 4-10 VALUES)

Battery Characteristics	Zinc/ Chlorine Hydrate	Lithium- Aluminum/ Iron Sulfide
Specific Energy (100% DOD), Wh/kg	180	175
Specific Power, W/kg		
Sustained	120	
Peak (≤ 15 sec, 50% DOD)	180	240
Energy Efficiency, %	78	90
Cycle Life (80% DOD)	1200	1200
Cost, \$/kWh	40	40

4.1.1.7 Material Availability

Table 4-12 from Reference 4-9 shows the material consumption for four battery types, assuming a buildup to 30 million EV's over a 20-year period with all 30 million vehicles powered by a single battery type. The peak consumption values would occur at about 10 years, and, assuming 90-percent recycle of material, this value would reduce to about 10 percent of the peak value after 20 years. The 1500-lb lead/acid and 1090-lb nickel/zinc batteries, calculated in Reference 4-9, involve large increases in the consumption of imported lead and antimony for the former and nickel for the latter. These requirements may impose a restriction on the use of these battery types (Ref. 4-9).

The zinc/chlorine and lithium/sulfur systems also show large increases in consumption of titanium and lithium, respectively, but there has been little demand for these resources. World reserves appear adequate, but production would have to be increased appreciably to meet the increased demand.

The Bureau of Mines (BOM) has also made forecasts of prices of mineral resources to the year 2000 (Ref. 4-49). Table 4-13 provides BOM estimates in constant 1968 dollars for many of the materials required for EV technology. Also included is a column of commodity prices for May 1977. The energy crisis and inflation since 1968 have caused most commodities to exceed the BOM estimate, which is in 1968 dollars. Some of these materials have price histories which are quite volatile, and therefore the spot prices may not represent a true trend. As prices rise there will also be more incentive to use recycled materials, which will help to control the price rise. Lead and antimony are already highly recycled so that recycling can have little additional effect on these prices.

4.1.1.8 Battery Chargers

The technology for highly efficient battery chargers exists. Reference 4-15 states:

TABLE 4-12. MATERIALS CONSUMPTION INCREASE (%) FOR 20-YEAR CONVERSION TO A 30-MILLION ELECTRIC VEHICLE POPULATION (Ref. 4-9)

Quantity	Material									
	Al	Cl	Cu	Li	Ni	Pb	S	Sb	Ti	Zn
Estimated World Reserves, 10 ⁶ ton	1168	Unlimited	308	6	75	100	2500	4	140	123
1968 U.S. Annual Consumption, 10 ⁶ ton	4.7	8.4	2.8	0.003	0.187	1.45	9.0	0.044	0.025	1.4
Import Fraction (1968), %	94	0	33	0	91	60	0	84	100	60
<u>1500-lb Lead/Acid Battery</u>										
lb/Vehicle						970		24		
Peak % 1968 U.S. Consumption						100		82		
% Annual Growth Rate						7.2		6.2		
<u>1090-lb Nickel/ Zinc Battery</u>										
lb/Vehicle			11		362					328
Peak % 1968 U.S. Consumption			0.6		290					35
% Annual Growth Rate			0.006		14.6					3.0
<u>570-lb Zinc/Chlorine Battery</u>										
lb/Vehicle		69							40	64
Peak % 1968 U.S. Consumption		1.2							240	7.0
% Annual Growth Rate		0.12							13	0.7
<u>300-lb Lithium/Sulfur Battery</u>										
lb/Vehicle				17			66			
Peak % 1968 U.S. Consumption				850			1.1			
% Annual Growth Rate				25			0.11			
<u>Motor Controller</u>										
lb/Vehicle	53		56							
Peak % 1968 U.S. Consumption	1.7		3.0							
% Annual Growth Rate	0.2		0.3							

TABLE 4-13. PRICE TRENDS OF MATERIALS IMPORTANT TO ELECTRIC VEHICLES (Refs. 4-49, 4-50 through 4-52)

Materials	BOM Estimate, 1968 ¢/lb		Spot Prices, May 1977 ¢/lb
	1968	2000	
Lead	13.5	11.5	25
Antimony	45.75	60	135 to 140
Lithium (Metallic)	750 to 1100	750 to 1100	1160 to 1500
Graphite (Crystalline)	7.2	7.2	
Sulfur	2.1	1.9 2.0	2.7
Copper	42.2	75	65 to 73
Nickel	94	200	231 to 241
Titanium (Metal)	132	132	500 (est.)
Zinc	13.5	27	37 to 39

...a major manufacturer of batteries and chargers states that, in practice, well-designed charging equipment of either the motor-generator or phase-controlled rectifier type gives overall energy efficiencies of 65-75%. Actual fleet testing of electric vehicles in France recorded efficiencies of 60-70% for two different types of charging systems. Nevertheless, proper application of efficient solid-state electronics should allow much lower charger losses. Engineers at General Motors have estimated 90% as a reasonable figure for future battery charger efficiency. A specially designed charger now operating in an experimental electric car is reported to exceed 98% efficiency.

ANL is supporting charger development with a goal of 90-percent efficiency. It will be assumed, therefore, that onboard or separate battery chargers for 1985, 1990, and 2000 will obtain 90-percent efficiency. This applies to solid-state chargers tailored to the battery type and size and a selected charging cycle.

4.1.2 Drivetrain and Control Technology

4.1.2.1 General

In the operation of a vehicle, the conversion of stored energy into useful linear motion entails losses within the vehicle and in its interaction with the environment. An automobile operated between two points at the same elevation actually does no useful work, in a technical sense, and hence has zero efficiency. Instead, the propulsion system is used to overcome a long list of losses to enable the vehicle to traverse the trip distance over a period of time. Internal losses of energy can be measured from the efficiencies of the principal components in delivering power to the drive wheels. From that point on, there is no measure of efficiency for steady, level running since all power is dissipated in tire friction and aerodynamic losses. An increase in travel speed invariably leads to increases in road-load horsepower and energy output from the battery. However, the increase in battery output may be less than proportional to the road-load increase, depending upon the efficiency versus speed characteristics of certain equipment like the drive motor or transmission. As the vehicle accelerates or climbs hills, there are temporary kinetic and potential storage energy accumulations for the vehicle as a whole or for parts of the vehicle. Examples of the latter are the rotational kinetic energy increases in the motor, transmission, driveshaft, and wheels whenever the vehicle is accelerated. It is the reductions in the linear speed of the vehicle, the rotational speed of its internal and external components, and the reduction of vehicle altitude which allow some recapture of expended battery energy. This is called regenerative braking. The driving cycle or speed versus time relationship determines the road-load horsepower and energy requirements for a vehicle having a given set of weight, size, aerodynamic design, and tire friction characteristics. The variable efficiency of the powertrain, from the battery through the controller, drive motor, transmission, drive shaft, differential, and rear axle assembly establishes the amount of energy needed in the battery. The energy stored in the battery is

the total of that delivered to the controller and that lost internally in discharge losses divided by the corresponding DOD (perhaps 70 to 80 percent). To have this amount of energy in store, additional energy had to be supplied from a charger to allow some dissipation within the battery, depending upon the rate of charging. The battery charger itself has an overall efficiency in converting electric grid power to a charging energy stream, previously noted at about 70 percent currently but likely to be 90 percent by 1985.

The level highway road-load power which must be supplied to the drive wheels consists of power to overcome the following:

1. Rolling resistance of the tires, which depends primarily upon vehicle weight and speed, tire type, size and pressure, and road surface conditions.
2. Aerodynamic drag of the body, chassis, and wheels, which depend primarily upon vehicle cross sectional area and vehicle aerodynamic drag coefficient. Wind conditions, even lateral winds, can strongly increase drag horsepower, which is basically proportional to the cube of velocity.
3. Inertia, if the vehicle is being accelerated. This consists of linear kinetic energy of the entire vehicle and rotational kinetic energy of the wheels and the drivetrain. The angular kinetic energy of the motor, transmission, etc., may, for convenience, be added to that of the wheels although they operate at different speeds. These energies are often referred to as inertia losses but, of course, can have negative values.

The primary internal losses in the powertrain are related to inefficiencies in transmitting power to the wheels:

1. Battery discharge, the efficiency of which is dependent upon battery type and discharge rate, state of charge, and controller type. A controller which "chops" armature current can significantly increase battery power loss.
2. Motor controller, the efficiency of which is dependent upon controller type, battery discharge rate, and electric motor characteristics.
3. Electric motor efficiency, which depends upon motor type, current, speed, and controller type. A controller which chops armature current can adversely affect motor efficiency.

4. Transmission, if used, will have an efficiency which decreases with increases in speed ratio.
5. Driveshaft, differential, and drive axle assembly.

There are other vehicle uses to which battery energy or heat losses may be put including compartment heating and recharging of SLI batteries. These may be unrelated to propulsive energy consumption but must be considered when sizing a battery. In a study of this kind, which does not contemplate detailed simulations of many vehicles and driving conditions, it will be necessary and probably sufficient, in light of the accuracy of energy projections, to estimate average efficiencies for operation of much of the equipment over the driving cycle. Technology data, efficiencies, and costs for the major drivetrain components will be presented in the following paragraphs of this section. Road-load losses must be treated parametrically and will be related to the driving cycle in Section 5 of this report.

4.1.2.2 Driving Cycles

Standard driving cycles have been defined by various organizations and government agencies to accommodate design and comparison of vehicles in performance, range, exhaust emissions, and fuel economy. These characteristics vary widely with the cycle; therefore, a choice should be made carefully to assure reasonable study results. An exaggerated example of a poor choice for application to a commuter automobile would be the U.S. Postal Service driving cycle. This cycle, with its low speeds and many stops per mile, would indicate unreasonably short range, excessive exhaust emissions, and high benefits from regenerative braking. For this study, the Society of Automotive Engineers Electric Vehicle Test Procedure--SAE J227a Schedule D Driving Cycle will be used (Ref. 4-53). This cycle and the SAE J227 Metropolitan Area Driving Cycle, which it replaced, are presented in Figure 4-13. Since the top speed of 45 mph is not considered adequate for general metropolitan area use, the cycle requirements will be supplemented by a required maximum cruise speed capability of 60 mph. Operation at a constant cruise

FIGURE 4-13. SAE J227 DRIVING CYCLES

speed is expected to result in several times the vehicle operating range compared to operation on an urban driving cycle because of the higher values of battery specific energy and average efficiencies of EV drivetrain components. In Section 5 of this report, the implications of the driveability requirements for battery-powered and hydrogen-powered vehicles are assessed and comparisons are made.

4.1.2.3 Overall Drivetrain Efficiency

Efficiency of the drivetrain has been estimated from the efficiencies of the major components and the nominal requirements of the driving cycle. Component data are provided in following subsections. As an indication of current drivetrain capability (neglecting battery discharge efficiency), a van designed by DAUG in Germany has achieved a battery-to-wheel efficiency of approximately 70 percent for most of a driving cycle, but lower values at low speeds (Ref. 4-23). The 70-percent efficiency is a result of the use of an 85-percent efficient motor, a controller which employs starting resistance in the motor armature circuit and a chopper in the motor field circuit, a torque converter, and a conventional gearbox using the second gear for forward motion. Details of the driving cycle and drivetrain are not available but the energy losses consist of the electrical losses in the control system and motor; the mechanical slippage loss in the converter; and the mechanical friction losses in the motor, gear box, drive shaft, reduction gear, differential, and wheel bearings. Over a complete driving cycle, something less than 70 percent of the energy removed from the battery is available (in this instance) for overcoming aerodynamic drag, tire rolling resistance, and inertia loads. The latter include linear and rotational (drivetrain plus wheels) kinetic energy changes and potential energy changes (elevation).

4.1.2.4 Motor Controller

The direct current motor has been used in most EV's designed to date. The most common controller for this drive system over the years

has been a resistor step controller (Ref. 4-54). In this type of device, as applied to a series wound dc motor (field and armature in series), resistance in the circuit is reduced in several steps as the vehicle accelerates from rest, resulting in successively higher levels of motor current and torque. Consequently, at all speeds up to the cutout of the last resistor, energy is dissipated in the control resistors, and potential vehicle travel range is lost. At low speed, as much as 90 percent of the energy from the battery can be wasted (Ref. 4-55).

Solid-state controllers called choppers have recently been introduced to reduce resistance heat loss in the controller. These chopper controllers usually modulate motor armature current and typically have efficiencies of 97 percent (Ref. 4-55). However, propulsion systems using chopper control do not always realize high efficiency. Most vehicles use dc motors which have not been designed to use the high-frequency component of the energy delivered by choppers. This results in controller and motor losses which rival the system losses associated with the simpler step controllers. Motors can be designed to utilize this high-frequency component and reduce these losses, but the energy saving incentive has been insufficient for the low-volume, high-cost EV market.

Most solid-state controllers have been applied to control the armature current of the motors (Ref. 4-55). Some studies indicate that better results will be achieved by using the silicon-controlled rectifiers (SCR's) or choppers to control field current in future designs (Ref. 4-56). This was done in the case of the relatively efficient DAUG van.

Controller characteristics and associated weight and cost are strongly dependent upon the types and capacities of the motors they control. Ford Motor Company performed a study of EV's in 1973 and gave detailed attention to the motor and controller interaction. Table 4-14 summarizes the functional, physical, and maintenance characteristics of four combinations. There is little efficiency difference at full output, but substantial differences are seen at reduced output. This same study also detailed equipment requirements and original equipment manufacturer (OEM) costs for controllers

TABLE 4-14. SUMMARY OF MOTOR AND CONTROLLER CHARACTERISTICS
(Ref. 4-57)

Characteristics	Commutator Motor and Contactor	Commutator Motor and SCR Chopper	Disc Motor and SCR Chopper	Induction Motor and Inverter
Torque and speed characteristics for motor-controller combination	Suitable for traction application with some low-speed jerkiness	Inherently suitable for traction application	Well-suited for traction application	Suitable for traction application when operated in controlled slip mode
Efficiency of (%) motor-controller combination	High-speed and load, 85% Reduced speed and load, 50%	High-speed and load, 85% Reduced speed load, 40%	High-speed and power, 84% Low-speed, reduced power, 50%	High-speed and load, 85% Reduced speed and load, 30%
Packaging space and locating requirements for motor-controller combination	Motor location flexible. Controller must be located near battery.	Motor controller location flexible	Motor controller location, very flexible	Motor controller location is flexible. Limited by volume of inverter
Cooling requirements for motor-controller combination	Forced air cooling on motor, no controller cooling	Forced air cooling for motor and controller	Readily adaptable to either liquid or forced air cooling	Oil cooling of motor and controller
Operation at reduced battery voltage	Capable of operation at reduced battery voltage	Can be operated at reduced voltage	Very well-suited to reduce voltage operation	Can be operated at reduced voltage
Weight for motor-controller combination	Motor, 250 lb at 40 hp Controller, 50 lb	Motor, 250 lb at Controller, 90 lb 40 hp	Motor, 98 lb at Controller, 150 lb 40 hp	Motor, 60 lb at Controller, 180 lb 40 hp
Relative cost of motor and controller; 1 = least expensive; 10 = most expensive	Motor: high, 10 Controller: low, 2	Motor: high, 10 Controller: low, 4	Motor: low, 3 Controller: medium, 5	Motor: medium, 5 Controller: very high, 10
Maintenance and repair considerations	Periodic: brushes; commutator Other: bearings	Periodic: brushes, commutator Other: bearings	Periodic: none Other: bearings	Periodic: none Other: bearings

designed for different motors in series and parallel arrangements, with and without regenerative braking capability. These data are presented in Table 4-15. A controller for a 115-hp induction motor is shown to be substantially more complex and expensive (without regenerative braking capability) than units for dc motors with regeneration capability, even when not a feature of the basic controller design.

It is expected that controller cost will be reduced significantly in the future as the technology is relatively new and future applications will involve large production quantities.

4.1.2.5 Electric Motors

Many motor types have been used in the EV (Refs. 4-1, 4-54 and 4-58). Table 4-16 from Reference 4-57 provides data for four basic motor types. The efficiencies range from 33 to 92 percent depending upon the motor type, torque level, and speed. The Ford disc motor is reported to have a more uniform efficiency characteristic than other motors, varying from 82 to 90 percent over the torque and speed ranges from 35 percent to maximum. As speed is reduced to zero, all motors go to zero efficiency for all loads.

Table 4-16 presents other data on maximum armature speed, specific weight, and specific cost. The synchronous induction motor has the highest speed capability and hence lightest weight but requires the heaviest and most costly controller according to Table 4-14. The low speed capability and heavy weight of the commutated dc motor affect its cost adversely, but its controller alternatives are lighter and cheaper than others. The simple configuration of the Ford disc motor leads to an estimate of its cost being lowest.

Selection of an electric motor cannot be made without consideration of the associated controller, which has comparable weight and cost features. Definitive vehicle performance requirements and updated motor and controller performance, size, and cost characteristics are necessary to make such selections at different points in time.

TABLE 4-15. SUMMARY OF ORIGINAL EQUIPMENT MANUFACTURER COSTS OF MAJOR COMPONENTS AND SUBSYSTEMS OF VARIOUS POWER CONTROLLERS (Ref. 4-57)

Type of Controller	Required Components	OEM Cost	
		1975 Price/ 10,000 Units	1975 Price/ 1 Million Units
DC Chopper for 40-hp dc Motor Without Regeneration	SCR's: 2 ea C 394 1 ea C 398 1 ea C 385 Diodes: 2 ea A 396 Commutating Capacitor: 1 ea 500μfd at 200 VDC Logic and peripheral system	2 × \$ 33 = \$ 66 1 × \$ 36 = \$ 36 1 × \$ 17 = \$ 17 2 × \$ 10 = \$ 20 1 × \$ 36 = \$ 36 \$ 29 Total \$204	2 × \$ 17 = \$ 34 1 × \$ 18 = \$ 18 1 × \$ 9 = \$ 9 2 × \$ 4 = \$ 8 2 × \$ 15 = \$ 15 \$ 20 Total \$104
Modulating Inverter for 115-hp Induction Motor Without Regeneration	SCR's: 6 ea C 398 12 ea C 380 Diodes: 6 ea A 396 Commutating Capacitor 1 ea 100μfd Logic and peripheral system	6 × \$ 41 = \$246 12 × \$ 24 = \$288 6 × \$ 12 = \$ 72 1 × \$ 60 = \$ 60 \$100 Total \$776	6 × \$ 20 = \$120 12 × \$ 12 = \$144 6 × \$ 6 = \$ 36 1 × \$ 30 = \$ 30 \$ 69 Total \$399
Parallel Controller for 40-hp Disc Motor (3 Phase, Includes Regeneration)	SCR's: 6 ea C 394 6 ea C 385 Diodes: 3 ea A 396 Commutating Capacitor: 3 ea 40μfd at 600 VDC Logic and peripheral system	6 × \$ 33 = \$198 6 × \$ 17 = \$102 3 × \$ 10 = \$ 30 3 × \$ 18 = \$ 54 \$ 75 Total \$459	6 × \$ 17 = \$102 6 × \$ 9 = \$ 54 3 × \$ 4 = \$ 12 3 × \$ 8 = \$ 24 \$ 46 Total \$238
Series Controller for 40-hp Disc Motor (3-Phase, Includes Regeneration)	SCR's: 6 ea C 508 6 ea C 385 Series Capacitor: 3 ea 135μfd at 600 VDC Logic and peripheral system	6 × \$ 30 = \$180 6 × \$ 17 = \$102 3 × \$ 28 = \$ 84 \$ 75 Total \$441	6 × \$ 16 = \$ 96 6 × \$ 9 = \$ 54 3 × \$ 12 = \$ 36 \$ 46 Total \$232
Additional Requirements To Provide Regeneration in dc Chopper for 40-hp dc Motor	SCR's: 4 ea C 501 Diodes: 4 ea A 390 Additional logic	4 × \$ 26 = \$104 4 × \$ 9 = \$ 36 \$ 25 Subtotal \$165 Basic Chopper Cost \$204 Total \$369	4 × \$ 15 = \$ 60 4 × \$ 4 = \$ 16 \$ 15 Subtotal \$ 91 Basic Chopper Cost \$104 Total \$195

TABLE 4-16. ELECTRIC MOTOR CHARACTERISTICS (Ref. 4-57)

Parameter	DC Commutator	Cage Induction	Synchronous Inductor	Ford Disc Motor
Specific weight, lb/hp (speed, rpm)	6.1 (8,000)	1.5 (12,000)	1.0 (24,000)	2.4 (6,000)
Specific cost, \$/hp	5.00	3.00	2.75	2.50
Maximum speed, rpm, based on stress limitations of a 4.5-in.-diam rotor	12,000	30,000	92,000	40,000
Relative complexity and cost of required control (dc = 1.0)	1.0	2.0	2.0	1.2
Efficiencies, %				
Maximum torque, rated speed	92	90	86	90
35% torque, 35% rated speed	77	65	75	82
Maximum torque, 5% rated speed	55	33	50	60

The efficiency characteristics of a modern dc traction motor are depicted in Figure 4-14. The maximum torque, design-speed efficiency is comparable to that in Table 4-16 but part-load efficiencies below 30-percent speed are higher. However, the maximum torque condition at 5-percent speed shows only about 27-percent efficiency versus more than twice this level predicted by the table.

4.1.2.6 Drivetrain Mechanical Components

The shaft power of the traction electric motor enters a series of mechanical components and emerges somewhat diminished at the drive axle where it is available to rotate the wheels and propel the vehicle. The mechanical system may employ all of the following components (or their functional equivalents) in series: a torque converter, transmission, drive shaft, final reduction gear, differential, bearings, and seals.

FIGURE 4-14. TYPICAL dc TRACTION MOTOR EFFICIENCIES AS A FUNCTION OF DESIGN LOAD AND SPEED (Ref. 4-59)

The efficiency curve for a torque converter including gearing is shown in Figure 4-15. A peak efficiency of 87 percent is shown at 60- to 70-percent output-input speed ratio. Although torque has its maximum value at zero output speed, efficiency is, of course, zero at that condition.

Table 4-17 presents weight, cost (1973 OEM values), and efficiency estimates for the rear-end components for several applications considered in Reference 4-57. A small reduction in efficiency occurs as gear ratio is increased to accommodate higher-speed, lighter-weight motors, but cost is negligibly affected. An automatic two-speed gear box is shown to be quite inexpensive (\$28 OEM cost) but introduces minimum losses of 8 percent in low gear and 5 percent in high gear. At nonoptimum speeds and part loads, efficiency is lower.

Drivetrain components such as transmissions and differentials are so well developed from conventional automobile technology that there

FIGURE 4-15. EFFICIENCY OF TORQUE CONVERTER PLUS MECHANICAL GEARING OF AN AUTOMOTIVE AUTOMATIC TRANSMISSION (Ref. 4-59)

TABLE 4-17. ESTIMATION OF REDUCTION GEAR, DIFFERENTIAL, BEARINGS, AND HOUSING (Ref. 4-57)

Vehicle or Component Designation	Electrical Motor Maximum Speed, rpm	Weight, lb	Cost, \$	Efficiency, %
City Car	6,000	42	38	97
City Car	9,000	38	39	96.8
City Car	12,000	37	38	96.4
Metro Car	6,000	49	39	97
Metro Car	9,000	45	39	96.8
Metro Car	12,000	43	38	96.4
Delivery Bus	6,000	50	41	97
Delivery Bus	9,000	46	40	96.8
Delivery Bus	12,000	44	40	96.4
Automatic Two-Speed Gear Box	Low Gear	30	28	92
	High Gear	--	--	95

should be little cost differential between conventional components and their EV counterparts. The use of chains and sprockets or belts and pulleys can affect cost and efficiency without major performance advantages. Transmissions have not always been justified in past design studies (Ref. 4-60), but there is little doubt that, once the major system losses are reduced, there will be a benefit from the use of a transmission to reduce peak current draw from the battery.

4.1.2.7 Regenerative Braking

The EV has an advantage over chemically fueled vehicles in its capability of converting vehicle kinetic energy into stored electric energy, rather than dissipating such energy as brake frictional heat when deceleration

is needed. The utility of such regenerative braking depends primarily on the driving cycle. This establishes how much energy is involved in braking relative to the energy expended under acceleration and cruise conditions. Regenerative braking has its greatest energy saving potential where the driving cycle requires a large number of stops per mile and vehicle aerodynamic drag and rolling resistance are low. The utility of regenerative braking also depends strongly on the efficiencies of the involved electrical and mechanical components in capturing the excess vehicle linear and rotational energy (and potential energy where hill descent is involved) and storing it in the battery. Since a significant vehicle speed change is required to recover a substantial fraction of such excess vehicle energy, the components in series between the wheels and battery operate at most only briefly at their ideal efficiency points. Furthermore, the state of charge of the battery determines its readiness to accept charging at rates comparable to its discharge rates during vehicle acceleration. As these rates can be substantially higher than normal battery charging rates, they would either be limited by the controller (i.e., excess potential current rejected) or else result in higher internal losses or reduction in charging efficiency. Theoretical estimates of the amount of recoverable energy range from 10 to 40 percent of the total energy expended (Refs. 4-61 and 4-62). However, the maximum recovery obtained in service seems to be about 12 percent, with 3 or 4 percent being more common (Ref. 4-61). As components increase in efficiency, batteries improve in specific power, and losses due to aerodynamic drag and rolling resistance are reduced, the percentage of battery energy which can be recovered by regenerative braking increases substantially.

The cost of adding regenerative braking capability to a vehicle's conventional braking system depends upon the choice of drive motor and controller. According to the Ford Motor Company study documented in Reference 4-57, no significant special equipment may be required. The 1975 OEM cost estimate for the added equipment in a dc chopper-type controller for a 40-hp dc motor, manufactured in large quantities (1 million units), is

\$91 (Table 4-15). Considering price markup and inflation, the cost to the consumer might approximate \$160. He would also pay indirectly for the weight, volume, and complexity of the equipment. A conventional braking system would also be necessary but would suffer less wear than without regenerative braking. If the cost of energy for operating an EV were 4¢/mi, the \$160 cost could be recovered in 100,000 miles of vehicle operation if only 4 percent of the battery energy were recovered. In Section 5 of this report, the energy savings for the chosen driving cycle is estimated for a range of vehicle parameters.

4.1.2.8 Summary

The driving cycle selected is important in determining vehicle range, performance requirements, and overall drivetrain efficiency. Figure 4-16 from Reference 4-63 indicates drivetrain efficiency measured from the battery output (controller input) to the transmission output (axle input). Some additional loss would be expected in the final reduction gear, differential, and rear axle bearings. The curve shows a full-load efficiency exceeding 75 percent from roughly 20 to 60 mph. This corresponds to maximum acceleration or hill-climbing conditions. However, the efficiency under cruise conditions rises continuously to 75 percent at a maximum speed of 60 mph, for this vehicle design, where road-load power equals maximum drivetrain output capability.

Previous studies have shown that ac motor and controller combinations are somewhat lighter but more costly than their dc counterparts. Table 4-18 provides specific weight, size, and cost estimates for drivetrain components. It indicates that the cost advantage of dc systems is primarily accounted for by the controller. The weight advantage of ac systems is accounted for by the motor.

The efficiency improvements possible in well-designed individual components do not appear great, except perhaps at fractional loads and speeds. The overall efficiency improvement potential is significant and will permit regenerative braking to be quite cost effective for urban driving cycles. The benefits of regenerative braking for the SAE-J227a Schedule D driving cycle will not be as great (Section 5).

At the time of their major introduction into the U.S. transportation system, EV's will be competing primarily with conventional vehicles. Therefore, they must perform like conventional vehicles to be commercially successful and not pose road hazards when mingling with gasoline-powered cars. A representative of Ford Motor Company (Ref. 4-65) has stated the case even more strongly, contending that EV's must provide air conditioning, radio, heater, power steering, and other accessories and be competitive with ICV's on a first cost as well as total cost basis in order to penetrate the conventional vehicle market.

On the other hand, General Research Corporation (GRC) (Ref. 4-66) believes that the EV possesses many advantages which are difficult

FIGURE 4-16. ESTIMATED ELECTRIC VEHICLE DRIVETRAIN EFFICIENCY AT CRUISE AND FULL LOAD (Ref. 4-63)

TABLE 4-18. WEIGHT, SIZE, COST CHARACTERISTICS
VEHICLE DRIVETRAIN COMPONENTS
(Ref. 4-64)

Component	lb/kW	ft ³ /kW	\$/kW
Heat Engine ⁽¹⁾	3.3-5.4	0.09	5
Transmissions ⁽²⁾			
Manual	1-1.5		1.25-1.88
Automatic	1.6-2.1		2.00-2.63
Continuously Variable (CVT)	2-2.7		2.50-3.38
Heavy Duty (Bus)	3.5		4.38
Electrical Components			
Motor/Generator			
dc	5-10	0.08	5-10
ac (Solid Rotor)	1.5-3	0.03	3-6
Power Control Units ⁽³⁾			
dc Motor/Generator	2-3.5	0.03	8-10
ac Motor/Generator	5-7	0.06	12-18

(1) Larger value for smaller engines.

(2) All transmission components priced at \$1.25/lb.

(3) Includes regenerative braking capability.

to quantify in dollars and cents, which will eventually be factors in their selection. In conventional automobiles, the ICE and its subsystems consisting of the cooling system, starter system, ignition system, fuel distribution system, exhaust system, and emissions control system are responsible for 70 percent of all of the maintenance problems and costs associated with owning an ICV. The low-maintenance potential of an EV, which eliminates all of these items, cannot be overstated. It is common for dc motors to give 1000 hr of service between checks, and replacement at that interval is not always

necessary. Other motor types which do not have armature brushes may have even longer service intervals. Although the much more complex electrical system will require maintenance, on balance it will be less troublesome than the ICV power plant, requiring fewer trips to the shop for diagnosis and repair, less expense, and fewer occasions for exploitation by unscrupulous service personnel. As acknowledged by Hamilton of GRC (Ref. 4-66), these factors are difficult to quantify in dollars for the vehicle purchaser and make the first cost of the vehicle an important factor in market penetration.

For the one recent production model of an EV, the Sebring Vanguard, Inc., Citi-Car, a survey has shown that 75 percent of the purchasers said they bought the vehicle for economy. In recent advertising, Rolls Royce has advanced economy as a reason for purchasing its car, contending that it is a lifetime car and cheaper in the long run. The purpose of these examples is to point out that arguments can be made and some market penetration will occur on the basis of those arguments, even if the first cost is not competitive with alternatives.

To capture an ever increasing share of the market while there is still fuel available at reasonable prices for the ICV, the EV must become competitive with the ICV both in initial cost and in pleasure of ownership. As time goes on, however, total cost of ownership (over some reasonable period of time) will be more important as the EV becomes better established and as the advantage of reliability is recognized and sought. One EV fleet operator reports that the economic life of the EV is twice the life of an ICV (Ref. 4-67).

No party to the commercial evolution of the EV is more concerned with consumer attitudes than the manufacturer. An important point made by a representative of Ford Motor Company (Ref. 4-65) is that a new vehicle can represent a \$1 billion gamble for the automobile company in terms of the plant, tooling, and materials required to launch the project. No automobile company can afford such an investment without a fallback position. The vehicle must be capable of being converted to a conventional type if the new concept does not sell. For instance, if Ford markets a rotary,

Sterling, or gas turbine engine in one of its vehicles, it would be designed such that a conventional ICE could be substituted if the new vehicle did not sell. This is not readily achieved for the introduction of an EV where simultaneous major changes in energy storage, drivetrain, and vehicle configuration are inherent. Nevertheless, the overall vehicle configuration must not be so uniquely designed around an electric propulsion system that it cannot be adapted at reasonable expense into a conventional ICV. This appears to be a valid argument for the initial venture into the EV market. If, however, EV's become established in the 1980 to 1985 time frame and capture a portion of the market, it should be possible to design subsequent EV's from the ground up without regard to convertibility.

Some vehicle features which can be improved for general vehicle use and are particularly important for the performance of vehicles having limited power and range are the aerodynamic drag characteristics and tire rolling resistance. These losses combined consume nominally half the energy removed from a traction battery, depending upon the driving cycle. Under high-speed cruise conditions, they represent about 75 percent of the battery output. Most production automobiles have a drag coefficient (at a zero degree angle of attack) in the range of 0.45 to 0.55 (Ref. 4-61). Several production sports cars, including 4-passenger vehicles, have achieved coefficients between 0.35 and 0.40 by moderate overall shape changes (which do not impair functional characteristics or interior room significantly), addition of air dams on the underbody behind the front bumper, and attention to details at edges and interfaces between body sheet metal and glass. Further improvements are distinctly possible by further shape changes, refinement of all interfaces, joints and projections, and possible inclusion of a flow-smoothing underbody pan covering much of the underside of the vehicle. The EV can eliminate the surface discontinuities associated with the air intake for the ICV radiator. A drag coefficient of 0.25 to 0.30 appears a reasonable goal for a commuter-type EV.

In addition to the aerodynamic drag coefficient effect on vehicle drag, there is the equally important vehicle transverse cross sectional (frontal) area to consider. Reduction in vehicle height and width are possible in many domestically manufactured cars. However, the volume requirements for the batteries tend to increase vehicle cross sectional area if the batteries are located beneath the passenger compartment floor or in a longitudinal tunnel. Location forward or aft of the passenger seating area need not increase cross sectional area but would increase vehicle length and weight, with negligible effect on drag coefficient.

The rolling resistance is a factor of potentially greater importance than aerodynamic drag, considering the generally low speeds of urban and commuter driving cycles and the increased EV weight relative to ICV's of similar functional characteristics. Table 4-19 presents 10-year old data on tire characteristics (Ref. 4-68). It reveals that, at some expense in ride quality, it is possible to sharply reduce power consumed in the tires at 50 mph by changing from standard and belted radial designs to low deflection and low aspect ratio designs. Other options may be available in the future (Ref. 4-69).

TABLE 4-19. TIRE PERFORMANCE AND HORSEPOWER LOSS AT 50 mph (Ref. 4-68)

Design Rating	Ride	Wear	Stability	Traction	Total hp Loss for 2500-lb Vehicle
Standard 6.70-13	100	100	100	100	6.0
Belted Radial	80	175	95	105	4.8
Special Compounding	80	140	95	90	3.8
Gauge Reduction	80	130	90	90	3.6
Reduced Deflection	75	140	95	90	2.8
Low Aspect Ratio	65	150	100	95	2.5

Figure 4-17 presents the rolling resistance coefficient (resistance force/vehicle weight) of current tire types as a function of speed. It indicates little variation over the speed range of interest for radial and belted-bias tires. A future tire of acceptable riding comfort could be expected to lower rolling resistance coefficient from about 0.013 to about 0.009 or less, including allowance for friction in wheel bearings and seals.

The improvements in vehicle characteristics described are basically applicable to conventional and hydrogen-powered vehicles as well. For the low-powered, relatively short-range EV, these improvements are second only to battery advances in enhancing its competitive position.

4.2.1 Near-Term Electric Vehicle (1985)

A 4-passenger compact or subcompact commuter automobile has been chosen as the basic vehicle configuration for this study. This passenger capacity, plus a cargo trunk unencumbered by storage batteries or other propulsion components, maximizes vehicle usefulness and is compatible

FIGURE 4-17. ROLLING RESISTANCE COEFFICIENTS OF VARIOUS TIRE TYPES (Ref. 4-70)

with the growing need for carpooling, regardless of energy form. Sufficient power must be provided, at least on a transient basis, to meet the typical acceleration demands of suburban and freeway traffic composed mostly of conventional automobiles and trucks.

Table 4-20 summarizes the principal overall design and performance requirements postulated for near-term, intermediate-term, and advanced EV's. Vehicle range selection for each time period will be made (Section 5), considering the weight and cost implications of seeking higher usefulness through greater design range. The 1985 vehicle characteristics are nominally those which can be achieved now except possibly for the batteries, for which the objectives may not be achieved until that time. The performance criteria are applicable to relatively new batteries in a fully charged state at normal ambient temperatures. A half-discharged state is assumed for the peak battery output requirement.

The accessories noted are assumed to be energy conservative units unless the EV purchaser opts for more powerful units at the expense of vehicle range or enlarged battery capacity. Air conditioning was excluded from consideration in 1985. It would only be practical to include if it could be operated through the use of waste heat from the batteries, controller, and motor.

4.2.2 Intermediate-Term Electric Vehicle (1990)

As indicated in Table 4-20, the 1990 EV has modest performance improvements over the near-term EV except in the area of batteries. The greater capability of the batteries would probably be used to increase vehicle range somewhat while reducing vehicle weight and cost. This EV could accommodate more powerful accessories, but air conditioning is excluded unless the use of zinc/chlorine hydrate batteries can accommodate it or a new waste-heat-powered unit is developed. Vehicle body and chassis design changes might accommodate wider use of lightweight structures using aluminum alloys, fiberglass, and composites.

TABLE 4-20. ELECTRIC VEHICLE DESIGN AND PERFORMANCE CRITERIA

Characteristics	Model Year ^{(1), (2)}		
	1985	1990	2000
Number of Passengers	4	4	4
Cruise Speed, mph	60	60	60
Peak Horsepower/Weight Ratio, hp/lb	0.014	0.014	0.014
Aerodynamic Drag Coefficient (0° Yaw)	0.35-0.40	0.30-0.35	0.25-0.30
Nominal Rolling Resistance Coefficient	0.012	0.010	0.008
Regenerative Braking	✓	✓	✓
Accessories:			
Radio	✓	✓	✓
Heater	✓	✓	✓
Power Steering, Power Brakes	✓	✓	✓
Air Conditioning	x	x	✓
Battery Characteristics	Table 4-9	Table 4-10	Table 4-11
Motor/Controller Peak Efficiency, %	85	86	88
Overall Drivetrain Peak Efficiency, %	75	76	78
Overall Drivetrain Cycle Efficiency, %	64	65	66
On-Board Battery Charger Efficiency, %	90	90	90

(1) Vehicle range selection will be based on tradeoff of usefulness, weight, and cost.

(2) ✓ = Practical Capability; x = Impractical in most applications.

4.2.3 Far-Term Electric Vehicle (2000)

The design and performance criteria for this vehicle are also presented in Table 4-20. They represent moderate projections beyond intermediate-term requirements, but certainly some innovative features will be introduced by then. Vehicle styling, construction, aerodynamics, and specific weight of components should all be improved to the point that adequate EV design range should be achievable with a comfortable vehicle of moderate weight and cost. Regenerative braking should be advantageous with the low road-load losses and the improved electrical system efficiencies including that of the battery. Air conditioning should be feasible whether based on heat rejection to a zinc/chlorine hydrate battery, energy from waste heat, or additional battery capacity.

4.3 OPERATING CHARACTERISTICS

4.3.1 Driving Range

The selection of EV design range is a critical decision (Section 5). Unlike the conventional automobile, which has modest weight, volume, and cost associated with a long-range energy storage system, the EV storage system weight is a substantial fraction of the vehicle weight and increases at a faster rate than the design range. The latter effect results from the secondary weight increases and road-load increase with increasing battery weight. The vehicle range should be evaluated for a selected driving cycle which approximates the expected driving conditions. Design range should correspond to the distance which can be traveled on a fully charged battery, before the cycle acceleration or cruise speed requirements can no longer be satisfied. To provide some performance margin for operation under abnormal environmental conditions and on nonlevel roads, a battery capacity allowance should be made.

Assuming overnight charging, the minimum design range could be as low as that corresponding to a well-defined daily range. This would be practical for many commercial vehicles but would be too restrictive for a

personal passenger automobile. For mass appeal, an EV must be capable of something more than 27 mi/day (10,000 mi/year). Statistical analysis by H. Schwartz of NASA Lewis Research Center (Ref. 4-71) has established a mission usefulness versus design range model. His results indicate that if it were necessary to satisfy the driving requirements of the public on 95 percent of the days of the year, the design range would be 82 mi. Thus, to achieve this high usefulness level, the EV would have three times the average daily requirement. For the near-term EV, this may be too costly a goal. For more advanced EV's, a somewhat higher usefulness might be sought while attaining lower weights than achievable with near-term vehicles. The tradeoffs between range, weight, and cost for different time periods are presented in Section 5 of this report.

For those occasions when an extended vehicle range is desired, it might be feasible for the EV owner to rent a trailer-mounted battery pack, which he would tow. Range extension might be substantial, but lower acceleration and gradeability would be expected because of power limitations in the motor, controller, and other drivetrain components.

4.3.2 Vehicle Life

To achieve a 100,000-mi vehicle life with a single battery is a considerable challenge, especially for near-term batteries other than nickel/iron. It requires a combination of design range and cycle life such as 100-mi and 1000 charge-discharge cycles. Near-term batteries other than nickel/iron have difficulty in achieving this capability, except for oversized batteries, which are not discharged to 80-percent DOD. A range of 100 mi on a lead/acid battery would result in a heavy, costly vehicle, especially if the DOD is not high. A lesser design range would require more cycles than one battery could provide when used at 70- to 80-percent DOD so battery replacement cost also must be considered. In addition to the cycle limitation, a battery in normal use (approximately 10,000 mi/year) cannot be relied upon to last 10 years without substantial deterioration or failure by modes other

than those associated with cycling. As discussed, the original battery could be replaced by an equivalent one or one of lesser capability and cost depending upon the owner's plans for continued vehicle use. An optimization of total battery cost over the lifetime of an EV requires data which are not available on battery cost per kWh versus cycle life and DOD.

4.3.3 Performance

As noted, EV performance must be comparable with ICV performance so that an EV can operate on the streets and highways without becoming a safety hazard both to the EV occupants and the other vehicles on the road. This does not mean that the EV must match the best acceleration available in the ICV population, but certainly, the lower level of performance obtained by ICV's should be matched by the EV. Table 4-21 from Reference 4-72 shows that, for 12 subcompact cars, the time required to accelerate from 0 to 60 mph varied from 14 to 21 sec. A peak horsepower to weight ratio of 0.03 would give nominally equivalent performance (possibly superior performance considering the improved aerodynamics and reduced rolling resistance). However, attainment of such levels with simple battery-powered EV's requires motors, controls, and batteries that are substantially oversized relative to driving cycle requirements. Vehicle weight, cost, size, and operating efficiency would be quite adversely affected. A value of about 0.014 hp/lb is called for by the chosen driving cycle.

Currently, the national speed limit is 55 mph; therefore, top speed capability need not match that of the ICV's. For the EV, cruise speed capability will be 60 mph to limit energy consumption and achieve good battery performance. The vehicle will have transient capability for higher speeds on level roads and short periods of hill climbing and acceleration at high speeds. These capabilities will be limited by a transient peak horsepower of up to 2.7 times the rated cruise horsepower (as called for by the driving cycle acceleration). Vehicle performance capability diminishes as the battery is discharged. It is assumed that the ability to meet the conditions of the

TABLE 4-21. CHARACTERISTICS OF 1974 SUBCOMPACT CARS (Ref. 4-72)

Car	Weight, lb	Advertised Net hp	Acceleration Time, sec (0-60 mph)	Fuel Economy, mpg			Weight to Power Ratio, lb/hp ⁽²⁾	Fuel Consumption, gal/ton-mi ⁽³⁾
				City	Open Road	1972 FTP ⁽¹⁾		
Audi Fox	2125	75	14.5	18	34	20 ⁽⁴⁾	33	0.0412
Chevrolet Vega	2460	75	17	15	29	24.6	36.8	0.0295
Datsun B 210	1950	67	19	19	34	24.9	33.6	0.0357
Datsun 710	2391	93	15.5	15	29	19.5	28.9	0.0381
Dodge Colt	2219	83	16.5	16	33	18.7	30.3	0.0425
Ford Pinto	2450	80	16.5	14	29	22.8	34.4	0.0319
Honda Civic	1650	52	16.5	20	33	29.1	37.5	0.0352
Opel Manta	2245	75	14	17	30	18.2	33.9	0.0432
Subaru	2005	61	19	21	35	21.7	37.8	0.0400
Toyota Corolla 1200	1835	65	21	21	37	27.1	32.8	0.0346
Toyota Corona	2490	97	15	15	27	16.9	28.8	0.0424
Volkswagen Dasher	2108	75	15.5	18	32	22 ⁽⁴⁾	32.1	0.0378

(1) FTP = Federal Test Procedure.

(2) Includes 300-lb payload.

(3) $\text{gal/ton-mi} = \frac{2000 \text{ lb/ton}}{(\text{curb weight} + 300 \text{ lb}) \times 1972 \text{ FTP mpg}}$

selected driving cycle will determine the adequacy of the electric propulsion system (for the purpose of evaluating vehicle range). Satisfaction of the peak horsepower demanded by the constant acceleration phase of the SAE J227a, Schedule D driving cycle will be required at 50-percent battery DOD. The normal range of DOD is 0 to 70 percent. Therefore, depending upon the size and characteristics of the battery, use of the final 20 percent of the battery's normal energy consumption may result in a reduction of the constant acceleration below the cycle demand. However, a change in the acceleration profile may be necessary and is allowable when the battery is in this depleted state as long as the 45-mph cruise speed is attained in 28 ± 2 sec.

4.4 OWNERSHIP COSTS

The costs of ownership of battery-powered vehicles are important to their public acceptance where other alternatives exist. Initial cost, battery replacement cost, and total operating cost are strongly dependent upon vehicle design range, battery type, and performance requirements. These design options are evaluated in detail in Section 5 of this report, leading to estimates of vehicle weight, motor horsepower, and system weights for representative batteries. Cost estimates are then made in a consistent manner, permitting comparison with HV's of the same capabilities and model years.

4.5 ENVIRONMENTAL ASPECTS

In this section, environmental factors likely to be affected by the widespread use of EV's in place of conventional cars are discussed. These factors include air quality, thermal emissions, noise levels, wastes from nuclear power plants, and wastes from the operation and scrapping of automobiles.

4.5.1 Air Quality

The potential impact of EV's on air quality depends upon three factors:

1. The amount of emissions generated by the EV relative to the ICV that it replaces.
2. The increase in emission level resulting from the EV-caused increase in electricity generation.
3. The proportion of these two direct factors relative to total emissions.

Table 4-22, assembled from data contained in References 4-72 and 4-73, presents the projected percentage of total emissions contributed by power plants and vehicular traffic for the years 1980, 1990, and 2000 for Philadelphia, St. Louis, and Los Angeles. Included are oxides of nitrogen (NO_x), total hydrocarbons (THC), carbon monoxide (CO), oxides of sulfur (SO_x) and suspended particulate matter.

The problem in each of the areas is quite different. The power plant emissions of NO_x represent a large proportion of the total in St. Louis and a very small percentage in Philadelphia. The proportion of NO_x contributed by vehicular traffic will almost double in St. Louis between 1980 and 2000 but will be cut in half in Los Angeles. One factor tending to reduce the effect of EV's on total emissions is illustrated in Table 4-23. This table shows that the ICV emission standards have been and will be progressively tightened so that the automobile that the EV replaces will have relatively low emissions.

In the case of CO emissions, however, even though vehicle emissions of CO are reduced they will still represent 100 percent of the CO emissions for the Los Angeles area in the year 2000; it would seem that substituting EV's (or HV's) would practically eliminate this contaminant in that area. Table 4-24 illustrates why this does not happen. The heavy-duty vehicular traffic does not yet have to meet any emissions standards, such as those for light duty vehicles presented in Table 4-23. Therefore, even though the heavy duty traffic only represents 5 percent of the vehicle miles traveled, it will produce 31 percent of the CO emissions in 1980 and 67 percent of the emissions by the year 2000 with no EV's present. Therefore, if all passenger cars in the Los Angeles area were EV's by the year 2000, it would only reduce CO emissions to 67 percent of the baseline case. This is also shown in

TABLE 4-22. PERCENTAGE OF TOTAL EMISSIONS ATTRIBUTABLE TO
VEHICULAR TRAFFIC AND POWER PLANTS FOR PHILADELPHIA,
ST. LOUIS, AND LOS ANGELES, NEGLECTING ELECTRIC VEHICLES
(Refs. 4-72 and 4-73)

Emissions	Philadelphia			St. Louis			Los Angeles		
	1980	1990	2000	1980	1990	2000	1980	1990	2000
NO _x , %									
Vehicular	4.0	3.7	3.8	12.9	13.2	23.8	40.4	19.5	19.3
Power Plant	4.7	2.0	0.86	73.7	70.7	47.2	25.2	30.0	23.5
THC, %									
Vehicular	27.4	15.4	14.8	36.3	21.5	20.8	45.2	26.8	27.8
Power Plant	0.71	0.32	0.14	3.0	2.9	1.2	0	0	0
CO, %									
Vehicular	74.0	52.6	50.2	76.1	54.7	52.5	100	100	100
Power Plant	0.55	0.44	0.20	2.2	3.3	1.4	0	0	0
SO _x , %									
Vehicular	1.1	1.7	2.1	0.2	0.3	0.5	3.5	3.6	4.1
Power Plant	55.9	34.1	18.0	62.4	58.7	35.0	56.5	55.0	49.2
Particles, %									
Vehicular	1.9	2.3	2.5	6.1	7.1	8.1	43.1	43.1	44.0
Power Plant	1.8	1.04	0.46	13.4	11.8	4.9	6.0	5.6	4.5

TABLE 4-23. FEDERAL EMISSION STANDARDS FOR PASSENGER AUTOMOBILES (Ref. 4-72)

Model Year	Pollutant Emissions (g/mi)		
	NO _x	HC	CO
Pre-1968	4.0	11.0	80
1968-1971	-	3.4	34
1972-1974	3.0	3.4	39
1975	3.1	1.5	15
1976	3.1	1.5	15
1977	2.0	1.5	15
1978	2.0	1.5	15
1979	2.0	1.5	15
1980	2.0	0.9	9
1981	2.0	0.9	9
1982	2.0	0.41	3.4

Table 4-25, which illustrates the overall effect of EV populations of 20, 80, and 100 percent in 1980, 1990, and 2000, respectively. These studies concluded (based upon Table 4-25) that the impact of EV's on the air quality of St. Louis, Philadelphia, and Los Angeles under the scenarios postulated is small. By themselves, EV's will probably not cause ambient standards to be satisfied for some pollutants, notably oxidants. Thus, other measures must be considered along with EV's in an integrated strategy designed to improve air quality.

4.5.2 Thermal Emissions

For ICV's, almost all of the heat rejection occurs from the vehicle directly to the air, but for EV's the bulk of the waste heat is produced at the power plant and may be dissipated into the air or into surrounding bodies of water. The method used at the power plant will depend upon the environmental impact as well as cost. Table 4-26 illustrates the effect of increasing water temperature in the Mississippi River on the fish community. Heat rejection into such bodies of water will no doubt be limited by such effects.

TABLE 4-24. FRACTIONAL CONTRIBUTION OF HEAVY DUTY VEHICLES
TO VEHICULAR AND TOTAL BASELINE EMISSIONS FOR
LOS ANGELES AND ENVIRONS (Ref. 4-73)

Year	NO		HC		CO		SO ₂		Particulate Matter	
	Vehicular	Total	Vehicular	Total	Vehicular	Total	Vehicular	Total	Vehicular	Total
1980	0.18	0.07	0.23	0.10	0.31	0.31	0.09	0.003	0.08	0.03
1990	0.31	0.06	0.33	0.09	0.67	0.67	0.09	0.003	0.08	0.03
2000	0.31	0.06	0.33	0.09	0.67	0.67	0.09	0.004	0.08	0.03

TABLE 4-25. RATIO OF EMISSIONS WITH ELECTRIC VEHICLES TO BASELINE EMISSIONS FOR ST. LOUIS, PHILADELPHIA, AND LOS ANGELES, 1980 TO 2000 (Ref. 4-72)

Year and City	NO _x	THC	CO	SO _x	Particulate Matter
1980 (20% EV's)					
St. Louis	1.04	0.94	0.86	1.05	1.00
Philadelphia	1.00	0.94	0.90	1.10	1.00
Los Angeles	0.97	0.93	0.86	1.07	0.96
1990 (80% EV's)					
St. Louis	1.09	0.86	0.83	1.14	1.00
Philadelphia	0.99	0.88	0.82	1.21	0.99
Los Angeles	0.99	0.86	0.74	1.14	0.79
2000 (100% EV's)					
St. Louis	0.94	0.83	0.83	1.09	0.97
Philadelphia	0.97	0.86	0.82	1.03	0.99
Los Angeles	0.88	0.81	0.67	1.07	0.80

From a thermal emissions standpoint, the EV will contribute to such problems by adding to localized heat rejection. For EV's, about three quarters of the total waste heat will be rejected at power plants. For ICV's, about eight times as much heat is rejected on the highways and city streets as is wasted in fuel refining operations. It is conceivable that heat rejected at power plants could be channeled into useful purposes since it is concentrated and could be transported to heat local factories or homes. The heat rejected from ICV's has no such potential. Aside from this potential, however, there is little difference in the total amount of heat rejected for the two cases.

4.5.3 Nuclear Wastes

The increase in nuclear wastes resulting from EV's depends upon the amount of additional energy generated from this source. Table 4-27 from

TABLE 4-26. ESTIMATED EFFECT OF INCREASING WATER TEMPERATURE ON FISH COMMUNITY OF UPPER MISSISSIPPI RIVER (Ref. 4-72)

°C	°F	% of Species Within Preferred Temperature Range	% of Species in Suboptimal Temperature Conditions ⁽¹⁾	% of Species Expected To Be Lost from System ⁽²⁾	Species Expected To Be Lost from System
18	64.4	100	0	0	
20	68.0	98	2	0	
22	71.6	75	25	0	
24	75.2	61	39	0	
26	78.8	49	51	0	
28	82.4	18	82	0	
30	86.0	14	79	7	Shovelnose sturgeon, pallid sturgeon, lake sturgeon, emerald shiner.
32	89.6	7	49	44	Blue sucker, largemouth buffalofish, smallmouth buffalofish, quillback carpsucker, rabbitmouth sucker, silver redhorse, golden redhorse, greater redhorse, blacknose dace, long-nose dace, creek chub, white bass, yellow bass, yellow perch, sauger, walleye, log perch, slenderhead darter, greenside darter, Johnny darter, banded darter
34	93.2	2	35	63	Stoneroller, golden shiner, redbside dace, fathead minnow, bluntnose minnow, bullhead minnow, redfin shiner, mimic shiner, blackchin shiner, ironcolor shiner, spottail shiner
36	96.8	0	12	88	Northern pike, blue catfish, channel catfish, flathead catfish, yellow bullhead, brown bullhead, black bullhead, stonecat, madtom, smallmouth bass, black crappie, white crappie, warmouth, green sunfish
38	100.4	0	2	98	Gizzard shad, carp, largemouth bass, bluegill, orange-spotted sunfish, pumpkinseed
40	104.0	0	0	100	Banded killifish

⁽¹⁾ The temperature range above the preferred temperature and below the lethal temperature.

⁽²⁾ Based on preferred and lethal temperature data for adult and juvenile fish. Where specific data for a species were unavailable, data from closely related species were used.

Reference 4-72 projects certain nuclear power-generating capability by the year 2000 for three cities as a function of the usage level of EV's. The additional nuclear power generation estimated to provide for EV requirements represents a minor fraction of the total.

TABLE 4-27. NUCLEAR POWER UTILIZATION IN YEAR 2000 (Ref. 4-72)

EV Usage Level, %	Percent of Available Capacity ⁽¹⁾		
	St. Louis	Philadelphia	Los Angeles
0	87	83	93
30	90	87	96
100	94	96	100

(1) Nuclear plants are assumed to have a 75% availability.

The nuclear waste problem will have to be solved before this generating capacity is installed; the EV contribution to the problem is minor.

4.5.4 Other Solid and Liquid Waste

Disposable waste from used lubricants, crankcase oil, and oil refineries will probably be reduced by the replacement of the ICV by the EV, according to Reference 4-72.

EV waste from battery cases and electrolyte for a 100-percent EV population would be less than 5 percent of the total waste of this nature and, therefore, is thought to be easily managed (Ref. 4-72). Other wastes from the EV will be generally of the same materials as for the ICV; however, the longer-life potential of the EV may actually reduce the volume of these wastes.

4.5.5 Noise Impact

The EV is claimed to be quieter than the ICV during acceleration. Figure 4-18 from Reference 4-49 illustrates a calculated noise

comparison, but the relative horsepower outputs are not given and the 3000-rpm electric motor rated speed is inherently quieter than other higher-speed options. Under equivalent 35-mph and 65-mph cruise speed conditions, the EV employing a motor rated at 3000 rpm was computed to be about 2.5 dBA noiser than a low-power ICV sedan. With a motor rated at 12,000 rpm, the computed EV noise is higher by 9 dBA at each vehicle cruise speed compared with a 3000-rpm motor (Ref. 4-49). Noise quieting provisions for electric motors may produce a 10-dBA drop in EV noise, which is probably greater than can be achieved in ICV's.

FIGURE 4-18. COMPARISON OF ELECTRIC VEHICLE AND CONVENTIONAL CAR ENGINE NOISE (MAXIMUM ACCELERATION AT LOW SPEEDS) (Ref. 4-49)

In summary, it is not apparent that an EV will be quieter than an ICV or HV under equivalent acceleration and cruise conditions. EV drivetrain choices and design integration efforts can probably reduce the EV to ICV comparison to negligible noise differences relative to the uncontrolled levels of background noise and tire road noise.

4.6 ELECTRIC VEHICLE PRODUCTION ASPECTS

The unit cost of an item is a function of the prorated cost of labor, tooling, materials, and overhead, plus the cost of distribution and allowance for profit. Unit labor and overhead costs can be reduced with investment in more elaborate automatic tooling. Some products lend themselves to mass production techniques more readily than others. In general, if production is large enough, the investment in expensive tooling should bring the unit cost down. The danger, for new emerging technologies, may be that the advancement in the state of the art may be so rapid that the tooling becomes obsolete before it has been amortized.

4.6.1 Batteries

In the case of batteries, there are currently many competing chemical reactions with different manufacturing processes. Conventional lead/acid batteries use injection-molded cases, which require expensive tooling. For small production runs, such as required for the golf cart battery business, this imposes a high unit cost increment on the battery in order to amortize the tooling. For the EV market (assuming millions of vehicles), this could become a trivial cost. If, however, lead/acid battery technology advances so rapidly that battery designs keep changing or if new battery systems replace one another in rapid succession, the tooling cost could remain high.

Robert J. Fedor of Gould, Inc., who is concerned primarily with the practical aspects of production, contends that battery performance is related to electrical system design and the two cannot be separated (Ref. 4-74). System designs to date usually call for high-voltage batteries

which reduce energy and power density, because this makes for smaller cells with a larger proportion of material in cell cases, connectors, and other inert hardware. Lower voltage batteries mean larger cells, fewer connectors, and other advantages and, therefore, higher energy and power densities. This also makes for lower cost since fewer operations are involved in assembling a vehicle battery. Low-voltage systems provide the optimum battery from power density, energy density, and cost standpoints.

The lithium-aluminum/iron sulfide battery system is currently assembled in a glove box, which may make the process more difficult to automate than for other battery types. There are also many other forms of the lithium/sulfur reaction, some using solid electrodes and others using liquid electrodes. Advancement from one form of this battery to another would make the tooling obsolete. For this reason, tooling for early batteries will probably need to be amortized over fewer batteries, driving up the initial cost but allowing a considerable drop in price once the tooling has been amortized.

The major gains in the cost of the battery will probably have to await volume EV production, standardization of packaging and voltage, and a slowdown in the evolution of superior systems.

4.6.2 Motors, Controls, and Transmissions

Transmissions are currently in volume production for automobile use. While the EV transmission may be different from its ICV counterpart, the production techniques are well-established. Once EV production rates become sufficiently high, the EV transmission cost should be comparable to current ICV transmissions.

Electric motors of the type and size required for EV's have not been produced in large volume. Conventional electric motor design may not be optimum to provide the benefits usually associated with large volume production. The disc-type motor being developed at Ford and elsewhere has a flexible design which may offer advantages from a production standpoint. This is reflected in the motor cost in Table 4-16, which estimates that disc

motors will cost one half as much as other motor candidates. Disc motor technology is new, dating only from 1959; therefore, these costs probably have more room to decline than do those of other older types as the technology matures. If this is true, electric motor cost may be reduced, on a cost versus horsepower basis, to levels comparable to ICE's. Since EV's will use much lower horsepower ratings than ICE's, the electric motor may cost considerably less than an ICE.

The solid-state components required for controllers are capable of being produced in large quantities with great reduction in unit cost. Table 4-15, which gives estimates for unit costs in lots of 10,000 and one million, illustrates the benefits of large volume production. In most instances, the unit cost is cut by a factor of two. This industry is very competitive, and costs for new items have been dropping dramatically. Future costs for controllers, therefore, might actually be lower than the 1975 forecasts in Table 4-15.

4.6.3 Vehicle Body and Chassis

The EV structural system, including the body and chassis comprising the frame, steering, suspension, and braking structure, will perform the same fundamental jobs as in the conventional and hydrogen-powered automobiles. It will have a somewhat expanded requirement to house a possibly quite heavy and bulky battery in one or two basic assemblies. Design provisions for the battery will be more demanding than those for the conventional fuel tank because of the greater weight and volume and the need for isolating passengers from the battery's fumes, temperature, and spillage. The body and frame will be somewhat heavier than those of comparable ICV's. The EV is expected to utilize all the evolutionary weight-saving techniques being introduced currently for ICV's, including reduced surface area (decrease in front and rear end overhang); thinner sheet stock; and expanded use of aluminum alloys, plastics, and rubber. The body and frame weight changes for the ICV from recent practice to weight-conscious design and finally to innovative design (involving 10- to 15-percent aluminum and plastic substitution for steel)

will be matched or exceeded by the EV (and the HV), which has more to gain by such improvements. Figure 4-19 from Reference 4-75 indicates these weight changes versus an index of passenger (PAX) compartment size. For the foreseeable future, the structural weight of suspension, steering, and braking provisions is expected to remain constant at about 15 percent of vehicle gross weight for all types of passenger cars (Ref. 4-75). The EV will have some advantage in braking capability since its hydraulic brakes will be supplemented by regenerative braking provisions.

4.6.4 Material Availability

As EV's are introduced in large numbers, there will be dramatic changes in the demand for many materials (Refs. 4-9, 4-72, and 4-73). Also, the material substitutions as vehicle weights are reduced (Ref. 4-75) will involve increased use of higher strength-weight ratio materials. The many possible battery combinations should allow a choice involving materials

FIGURE 4-19. OCCUPANT STRUCTURE WEIGHT VERSUS ROOMINESS INDEX (Ref. 4-75)

which are not in danger of exhaustion and not in short supply because of production inadequacy. The multiple options will not only satisfy personal preferences but minimize demand for particular materials, thereby holding down the cost. Table 4-12 indicates the materials impact of extensive application of EV's. Alternative structural materials are expected to be readily available, with the possible exception of plastics, which are dependent upon petrochemicals.

It also appears that recycling of materials will become much more important in future years; thus, the large raw material demand will be limited to the buildup phase of the EV population.

4.7 SAFETY

The introduction of large numbers of EV's will bring new hazards to the general public and vehicle servicing personnel. The operational hazards and the probable vehicle design provisions to enhance safety are discussed briefly.

4.7.1 Operational Hazards

Compared to conventional automobiles, the EV has increased hazards in its operation and maintenance in some areas and less in others. The EV is free of the potential fire and explosion hazards of the ICV fuel system and the possibility of asphyxiation when the engine is run within an enclosed area.

The EV introduces an increased impact hazard to people and property because of its generally higher weight and kinetic energy. This difference tends to be greatest in the near-term, primarily because of the relatively heavy batteries required. The use of more energetic batteries with moderate increase in design range will mitigate this effect in intermediate- and far-term EV's. The mass of the batteries and their location and mounting provisions will also affect the crashworthiness of the EV, and the resultant crushing hazard to its occupants. Since a small frontal area is important

to minimize aerodynamic drag, the battery is not likely to be located in the floor area. Location behind the passengers appears the least desirable location in the event of a front end crash. The choice is basically between a front-end battery installation and a longitudinal tunnel between the passengers (at or slightly above seat height). The latter installation retains some crushing hazard in lateral impact crashes and increases the required vehicle frontal area. The same basic installation considerations apply to HV's.

The susceptibility of the electrical system to shorting and fire in the case of a crash is another hazard consideration for the EV. This hazard is probably less than the fire hazard from the fuel systems of the ICV and HV.

The hazards from toxic fumes, corrosive liquids, and possibly high-temperature materials are the most important safety concerns for an EV. They will require isolation of the battery from the passenger compartment. Many batteries will not require massive damage before they present safety hazards. Rupture of electrolyte lines, heat exchangers, manifolds, or pump housings could release noxious fluids under pressure.

Other potential hazards such as contact with electrical circuits or battery chemicals while servicing or charging the vehicle will depend to a large degree on builtin safety features. The voltage level used by designers of EV's will primarily determine the shock hazard. Several experts believe that if the voltage is less than 50 V, the danger of a lethal shock is acceptably low. L. E. Unnewehr and H. L. Stadler of Ford Motor Company feel that, from a safety standpoint, low voltage systems (50 V or less) are desirable (Ref. 4-65) and stated that British EV's are using 36 V for this reason.

4.7.2 Possible Safety Provisions and Regulations

As discussed in general terms, there are measures that can be taken to reduce hazards, depending upon the nature of the hazard. The location of the battery pack relative to passengers will determine the hazard from crushing during an accident. The voltage level will determine the lethal hazard from electric shock. The type of battery and chemical reaction will

affect the instrumentation provided and the measures required to mitigate this hazard. For a battery using hydrogen stored under pressure in a tank, certain safety precautions will be required. For the zinc/chlorine battery, the chlorine is stored as a chlorohydrate (an ice, which prevents rapid release of gas). For batteries operating at high temperatures, such as the lithium-aluminum/iron sulfide battery, an assembly of modules will be encased in a double-walled housing. This will provide confinement as well as thermal control. In each instance, the nature of the hazard can be defined and acceptable solutions found. The truly hazardous systems which could cause an explosive reaction will probably be eliminated from consideration long before they become serious candidates for vehicular systems. It is not likely that adequate safety precautions will elude the engineers and regulatory bodies concerned. The problems of an EV are different from those of the conventional ICV and the HV, but do not appear to make the EV significantly more hazardous.

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SECTION 5

TECHNICAL AND ECONOMIC COMPARISON OF HYDROGEN- AND BATTERY-POWERED VEHICLES

In this section, the data assembled in earlier sections, and other data not previously available or assembled, are used to assess the relative weight, size, cost, and energy efficiency of four-passenger hydrogen vehicles (HV's) and electric vehicles (EV's). As much as possible, all vehicle concepts have been given the same overall specifications in interior space, performance (minimum acceleration and cruise speed), lifetime mileage, and aerodynamic and rolling resistance coefficients. The vehicles are defined only to the extent necessary to determine their key features of weight, size, cost, and energy consumption at nominally equivalent design ranges over a selected driving cycle. Sensitivities of key parameters, including vehicle usefulness, to variations in design range, auxiliary power loads, regenerative braking effectiveness, and aerodynamic drag properties are also evaluated. The basic vehicle design options for HV's and EV's at three points in time (1985, 1990, and 2000) are evaluated and compared.

An evaluation of alternative energy sources is presented. Ten fossil and nonfossil energy sources are evaluated in terms of the efficiencies of energy conversion processes, energy transportation and storage, and dispensing of electricity and hydrogen in gaseous or liquid form to the using vehicles. Four to six basic energy conversion/transportation options are evaluated for each energy source, with multiple options for energy storage to accommodate a moderate variation in annual automotive energy consumption. The source-to-vehicle input energy efficiencies are then combined with the energy consumption characteristics of appropriate vehicles to permit comparison of their overall source energy expenditures per vehicle mile, with and without energy storage in the logistic chain.

5.1 VEHICLE DESIGN RANGE SELECTION

5.1.1 Driving Cycle

In order to make a performance and sizing comparison of vehicles, rather than precise predictions of vehicle range, it is necessary to employ a driving cycle that imposes conditions reasonably representative of those expected in the intended vehicle usage. The cycle should be simple to permit ready evaluation of effects of various vehicle designs and parameter changes. The driving cycle defined by the Society of Automotive Engineers (SAE) J227a, Schedule D, fulfills these requirements (Ref. 5-1). It is presented in Figure 5-1. Appendix A contains an analysis of this simple driving cycle, leading to the preparation of Figures 5-2 through 5-7. These figures permit rapid determination of propulsive energy, horsepower, and

FIGURE 5-1. SOCIETY OF AUTOMOTIVE ENGINEERS J227a, SCHEDULE D DRIVING CYCLE (Ref. 5-1)

FIGURE 5-2. PROPULSION ENERGY REQUIREMENTS OF SOCIETY OF AUTOMOTIVE ENGINEERS J227a, SCHEDULE D DRIVING CYCLE

FIGURE 5-3. HORSEPOWER REQUIREMENTS OF SOCIETY OF AUTOMOTIVE ENGINEERS J227a, SCHEDULE D DRIVING CYCLE

FIGURE 5-4. CYCLE DISTANCE FOR SOCIETY OF AUTOMOTIVE ENGINEERS J227a, SCHEDULE D DRIVING CYCLE

FIGURE 5-5. BRAKING ENERGY REQUIREMENTS OF SOCIETY OF AUTOMOTIVE ENGINEERS J227a, SCHEDULE D DRIVING CYCLE ($C_r = 0.012$)

FIGURE 5-6. BRAKING ENERGY REQUIREMENTS OF SOCIETY OF AUTOMOTIVE ENGINEERS J227a, SCHEDULE D DRIVING CYCLE ($C_r = 0.010$)

FIGURE 5-7. BRAKING ENERGY REQUIREMENTS OF SOCIETY OF AUTOMOTIVE ENGINEERS J227a, SCHEDULE D DRIVING CYCLE ($C_r = 0.008$)

braking energy required at the drive wheels and the distance traversed over one driving cycle (the latter varying with coast distance). These parameters are presented as functions of the independent variables, namely, vehicle test weight WT , rolling resistance coefficient C_r , and the product of aerodynamic drag coefficient and frontal area $C_D A$.

The driving cycle imposes only a 45 mph requirement, but 60 mph has been chosen as a minimum cruise speed on a level road. Although the peak cycle horsepower (constant acceleration at 45 mph) is much greater than the 60 mph cruise horsepower used to determine rated motor horsepower for the EV's, it is a transient condition that can usually be satisfied for about 15 sec or more by the battery, controller, and motor, although at reduced efficiencies. Figure 5-8 presents the steady-state drive wheel horsepower required at speeds above the driving cycle cruise speed of 45 mph (66 fps).

FIGURE 5-8. ROAD LOAD VERSUS VEHICLE PARAMETERS AND SPEED

The deliverable energy-per-unit weight of the vehicle energy storage system clearly affects direct and indirect weight growth with increase in vehicle design range. Directly affected weights include those of the battery, hydride supply, tanks, etc. Changes in these result in changes in the weights of suspension systems, drive motors or engines, brakes, etc. Conventional automotive propulsion systems, employing gasoline- or diesel-fueled internal combustion engines (ICE's), are much more energy dense on volumetric and overall weight bases than are the propulsion systems considered in this report. They, therefore, have no significant range limitation, especially in the United States with its ubiquitous "gas" stations.

For all vehicles, weight, size, cost, and energy consumption increase progressively faster as design range is increased. These sensitivities are most evident in near-term, low-energy density battery and metal hydride energy storage systems.

For EV's, a number of design constraints are identified in addition to the most evident one: energy per unit weight. Battery cycle life, for a given depth of discharge (DOD), varies with battery type and design. Therefore, a minimum design range is imposed depending on whether one, two, or possibly three batteries are to be used over the lifetime of the vehicle to satisfy a chosen lifetime mileage (specifically, 100,000 mi in this study). Higher ranges, though otherwise desirable, lead to unnecessary vehicle weight, cost, and energy consumption increases. Another factor that can dictate the minimum design range for a given battery type is the ability of the battery to deliver the power levels necessary to satisfy either the peak acceleration load or the steady-state cruise load (60 mph). The battery size needed to match horsepower requirements may provide more than the needed lifetime mileage and therefore represents a nonoptimum design. The penalties of increasing design range, in terms of weight, energy consumption, and total cost of ownership, may be encountered in another area: vehicle

size. More energy storage capability requires increased volume, which requires an increase in vehicle length, height, or width. If length alone is increased to avoid the direct adverse effect on the $C_D A$ product, and if overhang dimensions are maintained the same to minimize stability and maneuverability problems, the wheelbase must be increased. Although a definite cutoff point is difficult to establish, a 15- to 20-percent (15- to 20-in.) increase begins to affect practicality.

For HV's, cycle life limitations must exist but are not yet well defined. Where they exist in hydrogen storage tanks, for instance, it is likely that added design margin can be provided with minor effects on vehicle weight and cost. These limitations would also be offset by use of longer design ranges allowed by the moderate weight and cost sensitivity of liquid storage hydrogen vehicles (LSHV's). Although periodic purging of metal alloy hydrides under elevated temperature conditions is contemplated to remove impurities affecting hydrogen absorption capability, insufficient data are available to establish a wearout life of the alloys beyond which costly reprocessing would be necessary.

5.1.3 Vehicle Usefulness

The goal of high vehicle design range is, of course, high vehicle mission usefulness. Figure 5-9 presents the curve of vehicle usefulness, defined as the percentage number of days of the year that the vehicle can satisfy typical driving requirements (Ref. 5-2). Usefulness should be as high as possible considering weight, cost, energy, and size implications. A design range merely satisfying the daily average number of miles traveled per vehicle, 27.4 mi (10,000 mi/year, is sufficient only for the small percentage of people with totally predictable lesser requirements. A design range of 85 mi provides 95.1 percent usefulness and so provides a good minimum design range for HV's. It will be shown that EV's will fall in this general area of usefulness as consequences of their energy characteristics and the design constraints discussed. It should be noted that

FIGURE 5-9. VEHICLE MISSION USEFULNESS VERSUS DESIGN RANGE (Ref. 5-2)

usefulness can only be increased about 3 percent by tripling the 85-mi range, at great expense in vehicle design.

5.1.4 Design Range Estimation

The vehicle energy per cycle and horsepower requirements at the wheels, presented in Figures 5-2 through 5-8, can be translated into energy storage capacity requirements by means of overall powertrain efficiencies. The auxiliary power demands for lights, radio, power steering, heating, or air conditioning, etc., are typically supplied by the engine or the

energy storage system and may significantly reduce vehicle range capability, particularly for EV's. The EV's can recover significant kinetic energy during the braking phase of the driving cycle or during any other period of deceleration or hill descent, thereby increasing vehicle range capability. Appendix B provides the derivation of the design range equation for EV's taking account of these factors. For HV's, a somewhat simpler range equation results, based on propulsion-usable hydrogen weight, a powertrain efficiency, and the data from Figures 5-2 through 5-8. The computation of powertrain efficiency is much more complex, however, and is therefore illustrated in Appendix C.

5.2 VEHICLE WEIGHT ESTIMATION EQUATIONS

In earlier sections of this report, much of the data on propulsion system weight and performance characteristics have been presented. This section is concerned with the common method of estimating the weights of HV's and EV's. The method used is basically a modification of the method employed in Reference 5-3 to estimate the weights of gasoline- and diesel-fueled ICE cars. For such vehicles, the curb weight is subdivided into three groups of weights: occupant structural weight W_1 ; suspension, steering, and braking system structural weight W_2 ; and engine and transmission system structural weight W_3 . All vehicle weights are placed in either one or two of these weight categories, i. e., they either belong wholly in one category (as would the body and frame, or the engine) or they can logically be divided between two categories (as can the battery and alternator). The weights are expressed as follows:

W_1 = A tabulated value, dependent upon the number of passengers, weight configuration (current, weight conscious, or innovative), and safety level

W_2 = Suspension system proportionality constant $B_2 \times$ (curb weight $W_{\text{curb}} + W_4$), where W_4 = weight of full load of passengers and options

W_3 = Minimum engine weight $A_3 + B_3 \times$ engine displacement, where B_3 = weight of engine and transmission divided by engine displacement

WT = Vehicle test weight = curb weight $W_{\text{curb}} + 300$ lb.

The resulting equation for curb weight of gasoline- or diesel-fueled ICE cars is:

$$W_{\text{curb}} = \frac{W_1 \left[1 + \left(\frac{B_2 W_4 + A_3 + B_3 \times \frac{\text{cid}}{\text{hp}} \times \frac{\text{hp}}{\text{WT}} \times 300}{W_1} \right) \right]}{1 - B_2 - B_3 \times \frac{\text{cid}}{\text{hp}} \times \frac{\text{hp}}{\text{WT}}}$$

where

hp = engine brake horsepower and

$K = \text{cid}/\text{hp}$

EV's and HV's will be generally heavier than a gasoline-powered ICE car of equivalent payload capability for all significant design ranges. This results primarily from the relatively heavy energy storage systems and the vehicle weight increases induced by these excesses. Appendices D and E provide analyses of weight differences between the gasoline-powered ICE and alternative power plants, permitting curb weight and test weight equations to be derived for each propulsion alternative. In the following subsections, the curb weights for EV's and HV's, as derived in Appendices D and E, respectively, are presented.

5.2.1 Battery-Powered Vehicles

The curb weight equation for EV's is obtained from that of the gasoline ICE car by estimating changes in occupant structural weight W_1 and suspension structural weight W_2 , substituting a suitable expression for the engine and transmission system structural weight W_3 , and adding an

energy storage dependent weight W_5 . The latter weight includes batteries, on-board charger, thermal control provisions, and vehicle weight increment associated with the battery volume requirement. It varies with design range, technology, driving cycle, and regenerative braking. The EV curb weight becomes:

$$W_{\text{curb(EV)}} = \frac{W'_1 + B'_2 W_4 + A'_3 + 300 \times K_0 \times K_1 + W_5}{1 - B'_2 - K_0 K_1}, \text{ lb}$$

where

$$W'_1 = W_1 + \Delta W_1$$

$$B'_2 = B_2 + \Delta B_2$$

$$A'_3 = A_3 + \Delta W_3$$

$$K_0 = \text{Electric motor specific weight} \approx 4.6 \text{ lb/rated hp, including controller and wiring}$$

$$K_1 = \text{Rated motor hp/vehicle test weight, } \frac{\text{hp}_R}{WT}$$

The ΔW values are estimated by considering each of the vehicle weight elements that constitute the various structural weights. The rated motor power requirement is obtained from the road load under 60 mph level cruise conditions divided by the efficiency of the transmission and drive axle assembly.

5.2.2 Hydrogen-Powered ICE Vehicle

The curb weight equation for the HV car has the same basic form as that of the gasoline car except for the addition of an energy storage dependent weight W_5 . The latter includes the weight of the hydrogen energy storage system (hydrogen-containing material, supply tank, heat exchangers, piping, thermal control provisions, etc.) and a vehicle weight increment

associated with the storage system volume requirement. The weight W_5 is simply represented as

$$W_5 = A_5 + B_5 W_H$$

where W_H is the total hydrogen weight capacity, and A_5 and B_5 are constants estimated for different hydrogen storage systems.

The resulting curb weight equation is:

$$W_{\text{curb(HV)}} = \frac{W_1 + B_2 W_4 + A_3 + 300 B_3 K \left(\frac{\text{hp}}{WT} \right) + A_5 + B_5 W_H}{1 - B_2 - B_3 K \left(\frac{\text{hp}}{WT} \right)}$$

where A_3 , B_3 , and K are engine parameters that depend upon the hydrogen admission technique and the temperature of the hydrogen entering the engine or its compressor.

5.3 VEHICLE SIZING, PERFORMANCE, COST, AND ENERGY ANALYSES

5.3.1 Battery-Powered Vehicles

5.3.1.1 Sizing and Performance Analyses

Data assembled during the EV technology assessment are used as inputs for weight estimation and propulsion system parameter selection, enabling analysis of vehicle design range, test weight, length, and lifetime mileage as functions of battery weight. Battery characteristics are presented in Table 5-1. The higher performance values of the model year 2000 lithium-aluminum/iron sulfide battery are used in the results reported. An additional analysis is made using the lower values tabulated to determine the effects upon vehicle characteristics.

Table 5-2 presents the drivetrain efficiency values used in the study. For the purpose of determining range, the drivetrain efficiency over

TABLE 5-1. ASSUMED AUTOMOBILE BATTERY CHARACTERISTICS

Model Year	1977	1985			1990		2000	
Battery Type	Lead/Acid	Lead/Acid	Nickel/Iron	Nickel/Zinc	Zinc/Chlorine Hydrate	Lithium-Aluminum/Iron Sulfide	Zinc/Chlorine Hydrate	Lithium-Aluminum/Iron Sulfide
Specific Energy (100% Depth of Discharge), Wh/kg	30	50	60	90	150	145	165-180	160-175
Specific Power, W/kg								
Sustained	15	25	50	50	100		110-120	
Peak (50% charge)	50	150	200	200	150	200	165-180	220-240
Energy Efficiency, % ⁽¹⁾	65	70	70	70	65(est)	75	65-78	75-90
Cycle Life (80% Depth of Discharge)	700	1000	2000	700	1000	1000	1000-1200	1000-1200
Cost, \$/kWh (1980 Dollars)	50	40	50-60	50-60	50	50	40-60	40-60

⁽¹⁾ Overall charge-discharge efficiency of the battery excluding charger and power controller losses.

TABLE 5-2. ELECTRIC CAR DRIVETRAIN EFFICIENCY PROJECTIONS

Model Year	1985	1990	2000
Motor/Controller Peak Efficiency, %	85	86	88
Overall Drivetrain Efficiency, % ⁽¹⁾			
Peak (35-40 mph, full load)	75	76	78
Rated (60 mph, full load)	72	73	75
Cruise (45 mph)	69-70	70-71	71-72
Cruise (30 mph)	67-68	68-69	69-70
Cycle (SAE J227a, Schedule D)	64	65	66

⁽¹⁾ Includes motor, controller, two-speed gearbox, reduction gear, differential, and rear axle bearings - from controller input to drive wheels.

the driving cycle (ramp acceleration plus 45 mph cruise) is assumed to be 85 percent of the peak drivetrain efficiency under full-load motor conditions. Vehicle performance is predicated on new batteries. Effective battery lifetime mileage, however, is based on a nominal 20-percent loss of battery capacity over its lifetime. The lifetime mileage is approximated by the following: $0.9 \times \text{cycle life} \times \text{design range}$.

The goal in vehicle sizing is to satisfy the power demands of the driving cycle and of a 60 mph cruise speed with a battery suitable for 100,000 mi of vehicle operation. If this is infeasible, the goal would be reduced to 50,000 mi. The batteries considered for the 1985 model year cars are the lead/acid battery and the nickel/zinc battery. The former has modest energy density or specific energy (50 Wh/kg) and modest power density or specific power (25 W/kg) but good cycle life (1000 cycles to 70 percent DOD). The nickel/zinc battery has moderate energy density (90 Wh/kg) and moderate power density (50 W/kg) but modest cycle life (700 cycles to 70 percent DOD).

The nominal values of the C_{DA} product used for all vehicles are 8, 7 and 6 ft², respectively, for model years 1985, 1990, and 2000. These values are perturbed, where noted, to determine range sensitivity. The values of the rolling resistance coefficient used for all vehicles are 0.012, 0.010, and 0.008 lb/lb, respectively, for model years 1985, 1990, and 2000. Regenerative braking is not assumed for vehicle sizing, but range sensitivity is determined for all EV's. A basic auxiliary power requirement of 250 W is assumed for all EV's.

Figure 5-10 presents the parametric results for the lead/acid battery. Range vs battery weight is presented for a normal auxiliary power load of 250 W and for 10 times this value as might be necessary to include air conditioning or electric heating of the passenger compartment. The range implication of high auxiliary power requirements is clearly seen. The effect of regenerative braking effectiveness on design range is also shown. The recovery factor values noted are the fractions of the potentially recoverable

FIGURE 5-10. 1985 MODEL YEAR ELECTRIC VEHICLE CHARACTERISTICS - LEAD/ACID BATTERY

braking energy (reduced by driveline losses and battery charge-discharge losses) that can be recycled for propulsive purposes. The recovery factor RF is equal to the effective energy recovered from the battery per driving cycle divided by the product of the braking energy required per cycle, the normal drivetrain efficiency, and the normal battery charge-discharge efficiency. It therefore is meant to account for the more difficult-to-calculate effects of current and voltage limits and reduced drivetrain component efficiencies over the wide braking speed range. The effect of a reduction in $C_D A$ product from 8 to 7 ft² is also shown. All curves and subsequent discussions assume an auxiliary power load of 250 W unless otherwise noted.

It is seen from the cruise speed curve that the 60 mph requirement cannot be satisfied with a battery weighing less than 887 kg. The battery lifetime mileage at this point is only 57,790 mi. Figure 5-11 plots design range and vehicle length increase (relative to a gasoline-powered car) vs vehicle test weight. The minimum battery size point is noted. It is clear that if battery size is increased to get a design range sufficient to yield a lifetime mileage of 100,000 mi, the result would be excessive vehicle weight (over 12,000 lb) and length increment (over 90 in.). Therefore, a replacement battery of equal power capability is necessary and would be installed at about 50,000 mi of vehicle life.

Figure 5-12 summarizes the results of calculations for the 1985 model year nickel/zinc EV's. Because of its improved power density, the nickel/zinc battery is able to satisfy 60 mph cruise loads at all battery weights considered. The modest cycle life would require a very heavy battery to achieve 100,000 mi of operation, so a replacement battery is necessary. A 500-kg battery was selected, since it should provide slightly over 50,000 mi before needing replacement.

For the 1990 model year car, the zinc/chlorine hydrate battery is analyzed. Figure 5-13 presents the results. It is seen that a

FIGURE 5-11. 1985 MODEL YEAR LEAD/ACID BATTERY
ELECTRIC VEHICLE WEIGHT, RANGE,
AND LENGTH RELATIONSHIPS

FIGURE 5-12. 1985 MODEL YEAR ELECTRIC VEHICLE CHARACTERISTICS - NICKEL/ZINC BATTERY

FIGURE 5-13. 1990 MODEL YEAR ELECTRIC VEHICLE CHARACTERISTICS - ZINC/CHLORINE HYDRATE BATTERY

battery weighing at least 313 kg is needed to satisfy the peak cycle horsepower requirement. However, the battery needed to achieve 100,000 mi of lifetime mileage weighs 358 kg, so it was chosen. This battery delivers a design range of 111 mi, significantly greater than that provided by the 1985 battery choices.

The projected characteristics for a lithium-aluminum/iron sulfide battery are used for the definition of the 2000 model year EV. The absence of a specific power value for the battery under sustained loads precludes verification of 60 mph speed capability. Instead, the specific power requirement is computed. Values of 33 to 68 W/kg are found necessary over the battery weight range from 400 to 175 kg. As seen in Figure 5-14, a 175-kg battery is sufficient to satisfy the 100,000-mi vehicle lifetime mileage. Since this battery size is selected, a specific power of 68 W/kg will have to be realized in an advanced lithium-aluminum/iron sulfide battery if a 60 mph cruise speed is to be achieved.

Table 5-3 summarizes the characteristics of the selected EV's. Several observations can be made in addition to those made in the preceding discussion. An accessory power level of 2.5 kW can trim 7 to 24 mi off the vehicle design range with the greatest effect occurring in future vehicles with low propulsion demands. Regenerative braking provides significant range increases, particularly if as much as 80 percent of the recoverable energy is reused. The calculated percentage improvement is 8 to 9 percent through 1990 but rises to 13 percent if the predicted 90-percent battery charge-discharge efficiency is achieved for the lithium-aluminum/iron sulfide battery. Required driving cycle peak horsepower-to-weight ratio remains nominally constant at 0.014. However, the excess power margin of advanced batteries is much less than that of near-term batteries. Significantly more difficult driving cycles could not be satisfied by the zinc/chlorine hydrate and lithium-aluminum/iron sulfide batteries without oversizing them, increasing vehicle cost. Finally, only the lithium-aluminum/iron sulfide battery results in a moderate vehicle length increase.

FIGURE 5-14. 2000 MODEL YEAR ELECTRIC VEHICLE CHARACTERISTICS - LITHIUM-ALUMINUM/IRON SULFIDE BATTERY

TABLE 5-3. SUMMARY OF ELECTRIC VEHICLE DESIGN AND PERFORMANCE CHARACTERISTICS

Model Year	1985	1985	1990	2000
Battery	Lead/Acid	Nickel/Zinc	Zinc/Chlorine Hydrate	Lithium-Aluminium/Iron Sulfide
No. Batteries Required for 100,000 mi	2	2	1	1
Battery Weight, kg/lb	887/1956	500/1102	358/789	175/386
Vehicle Resistance Characteristics, C_R/C_{DA} , (lb/lb)/ft ²	0.012/8	0.012/8	0.010/7	0.008/6
Vehicle Test Weight, WT, lb	5018	3799	3553	2449
Vehicle Miles/Battery, mi	57,790	50,900	100,000	100,510
Battery Capacity, kWh	44.3	45	53.7	30.6
Design Range for 0.25 kW Accessory Power Load, mi ⁽¹⁾	64.2	80.8	111.1	93.1
Usefulness Factor, % of Days of Year	91.3	94.6	96.5	96.0
Range Penalty for 2.5 kW Power Load, mi/%	7.0/14.1	13.7/17.0	22.1/19.9	23.72/25.5
Range Increase with Regenerative Braking, mi/% Recovery Factor = 0.5 Recovery Factor = 0.8	3.5/5.5 5.8/9.0	3.9/4.8 6.5/8.0	5.9/5.3 ⁽²⁾ 9.7/8.7	7.2/7.7 12.1/13.0
Drive Motor Rated Horsepower @ 60 mph, hp _R	25.31	22.55	18.86	14.06
Driving Cycle Peak Motor Horsepower, hp _P	68.76	53.43	48.5	33.57
hp _P /WT	0.0137	0.0141	0.0137	0.0137
Battery-Limited hp _P /WT	0.0257	0.0255	0.0148	0.0172
Vehicle Length Increase Over Gasoline Powered Car, in. ⁽³⁾	26.1	18.4	23.1	8.6

(1) Society of Automotive Engineers J227a, Schedule D Driving Cycle.

(2) Not currently feasible without on-board chiller for hydrate ice.

(3) Gasoline engine powered four-passenger car (Ref. 5-3):
1980-1990: 1) hp/WT = 0.015, WT = 2239 lb, 2) hp/WT = 0.030, WT = 2293 lb
2000: 1) hp/WT = 0.015, WT = 2048 lb, 2) hp/WT = 0.030, WT = 2097 lb
Length = 159.5 in., Wheelbase = 97.0 in., Height = 53.0 in., Width = 60.8 in.

5.3.1.2 Cost Analysis

Table 5-4 presents the assumptions used in estimating EV original equipment manufacturer (OEM) cost. This data is combined with vehicle characteristics from Table 5-3 to accommodate the comparative cost evaluation presented in Table 5-5. Although the near-term vehicles offer less than 95-percent usefulness, they require the greatest investment and experience the highest depreciation. The 2000 model year vehicle offers good usefulness for reasonable investment and depreciation costs.

5.3.1.3 Energy Consumption

For vehicles equivalent in passenger and cargo capacity, ability to do a driving cycle, and design range, it is useful to compare their input energy requirements per mile of travel. For EV's where input energy is (arbitrarily) measured as the output of a battery charger, which may be stationary or on board the vehicle, the input energy per vehicle mile can be expressed as follows:

$$\frac{\text{energy}}{\text{vehicle mile}} = \frac{E_P}{D\eta_{C-D}\eta_{DT}} + \frac{P_{aux}T_C}{D}$$

where

E_P = propulsion energy per driving cycle measured at drive wheels (Figure 5-2)

D = driving cycle range (Figure 5-4)

η_{C-D} = battery charge-discharge efficiency

η_{DT} = overall drivetrain efficiency

P_{aux} = auxiliary power level

T_C = cycle duration

TABLE 5-4. ASSUMPTIONS FOR ELECTRIC VEHICLE
ORIGINAL EQUIPMENT MANUFACTURER
COST (1980 Dollars)

	1985	1990	2000
Batteries	Lead/Acid: \$40/kWh Nickel/Zinc: \$50-60/kWh	Zinc/Chlorine Hydrate: \$50/kWh Consider \$60/kWh also	Lithium-aluminum/iron sulfide: \$40/kWh Consider \$60/kWh also
Motor	\$6.00/hp	\$6.00/hp	\$6.00/hp
Controller	\$100 + \$7.50/hp	\$100 + \$7.50/hp	\$100 + \$7.50/hp
Other	\$1.50/lb	\$1.50/lb	\$1.50/lb

TABLE 5-5. WEIGHTS AND COSTS OF BATTERY-POWERED,
FOUR-PASSENGER CARS (1)

Battery Type	Lead/ Acid	Nickel/Zinc		Zinc/Chlorine Hydrate		Lithium-Aluminum/ Iron Sulfide	
Vehicle Range, R, mi	64.2	80.8		111.1		93.1	
Model Year	1985	1985		1990		2000	
Vehicle Test Weight, WT, lb	5018	3799		3553		2449	
Battery Weight, lb	1956	1102		789		386	
Battery Cost/kWh, \$/kWh	40	50	60	50	60	40	60
Initial OEM Battery Cost, \$	1772	2250	2700	2685	3222	1224	1836
Motor Rated Horsepower, hp _R	25.3	22.6		18.9		14.1	
OEM Motor Cost @ \$6/hp, \$	152	136		113		85	
OEM Motor Controller Cost @ \$100 + \$7.50 x hp _R , \$	290	270		242		206	
Vehicle Purchase Price, W/O Transp., Taxes, \$(2)	7910	7800	8380	8460	9160	5150	5950
Replacement Battery Purchase Price, Allowing Salvage, \$	1770	2250	2700	-	-	-	-
Total Investment, \$	9680	10,050	11,080	8460	9160	5150	5950
Salvage Value of Battery @ 10%, \$	180	220	270	270	320	120	180
Total Salvage Value @ 100,000 mi, \$(2)	450	460	510	520	570	300	360
Total Vehicle Depreciation, \$	9230	9590	10,570	7940	8590	4850	5590
Depreciation/Mile, ¢/mi.	9.23	9.59	10.57	7.94	8.59	4.85	5.59

(1) 1980 dollars.

(2) OEM cost of nonpropulsion weight = \$1.50/lb, salvage = \$0.10/lb.

After vehicle sizing and performance analysis, it is more convenient to use the following form, which includes the effect of auxiliary power consumption or regenerative braking energy savings through their effects on the calculated design range R.

$$\frac{\text{energy}}{\text{vehicle mile}} = \frac{\text{battery capacity in kWh} \times \text{DOD}}{R \eta_{C-D}}$$

where

battery capacity = battery weight $\times$ specific energy (Table 5-1)

DOD = 0.70

5.3.1.4 Total Cost of Electric Vehicle Ownership

The cost of vehicle ownership is assumed to consist of direct operating costs, indirect operating costs, and depreciation. All costs are expressed in 1980 dollars, effectively compensating for unpredictable inflationary effects. The cost of financing was neglected since financing requirements are more dependent upon the purchaser than the vehicle.

The direct operating costs include the battery charging energy cost; and the costs of repairs and maintenance, tires, and accessories and oil. Charging energy costs over the 100,000-mi vehicle lifetime are approximated by:

$$\frac{\text{energy cost}}{\text{mile}} = \frac{\text{battery capacity} \times \text{DOD} \times \text{power cost/kWh}}{0.90 R \eta_{C-D} \eta_{\text{charger}}}$$

where

Power Cost/kWh = assumed energy cost to consumer of
4¢ to 8¢/kWh

0.90 R = mean range of vehicle over battery lifetime, mi

η_{charger} = battery charger efficiency ≈ 0.90

Other direct operating costs are estimated from the following data obtained from Reference 5-4:

	<u>Cost/mi, ¢</u>
Repairs and Maintenance	0.01
Tires	0.42
Accessories and Oil	<u>0.075</u>
Total	1.50

These data are assumed applicable to all EV's regardless of battery and system complexity and vehicle weight.

Indirect operating expenses associated with taxes, registration, and insurance total about 4¢/mi according to Reference 5-4. This is assumed uniformly applicable despite the wide range of vehicle characteristics.

The operating and depreciation costs for a 100,000-mi vehicle lifetime are presented for all EV's studied, in Table 5-6. Two values of electric power cost are shown for each vehicle, and they result in significant differences in total ownership cost. A range of battery costs per kilowatt hour of battery capacity is shown for all but the lead/acid battery EV. The effect on depreciation was 1¢/mi or less.

5.3.2 Hydrogen-Powered Vehicles

5.3.2.1 Sizing and Performance Analyses

In order to determine vehicle performance, the data previously presented must be supplemented with engine performance projections for naturally aspirated and direct (cylinder) injection (DI) schemes. The differing hydrogen supply conditions provided by the cryogenic and hydride storage options have strong impacts on engine efficiency, displacement, and weight for a given horsepower. In addition to full load (acceleration) conditions, it is necessary to estimate engine efficiency under cruise conditions, which typically demand a combination of reduced fuel/air ratio (to an equivalence

TABLE 5-6. TOTAL COST PER MILE FOR
BATTERY-POWERED CARS

Characteristics and Costs	BATTERY			
	1985 Lead/Acid	1985 Nickel/Zinc	1990 Zinc/ Chlorine Hydrate	2000 Lithium- Aluminum/Iron Sulfide
Capacity, kWh	44.3	45	53.7	30.6
Design Range, mi	64.2	80.8	111.1	93.1
Efficiencies of Battery and Charger, %	70/90	70/90	65/90	90/90
Charge Energy @ 70% Depth of Discharge, kWh	49.2	50.0	64.3	26.4
Charges/100,000 mi ⁽¹⁾	1730	1375	1000	1193
Charge Energy Cost at 4¢/ kWh and 8¢/kWh, ¢/mi ⁽¹⁾	3.4/6.8	2.8/5.5	2.6/5.1	1.3/2.5
Total Operating Cost ¢/mi ⁽²⁾	8.9/12.3	8.2/11.0	8.1/10.6	6.8/8.0
Battery Cost, \$/kWh (1980 Dollars)	40	50-60	50-60	40-60
Vehicle Depreciation Including Salvage, ¢/mi	9.2	9.6-10.6	7.9-8.6	4.9-5.6
Cost of Ownership, ¢/mi				
Power Cost = 4¢/kWh	18.1	17.8-18.8	16.0-16.7	11.6-12.4
Power Cost = 8¢/kWh	21.5	20.6-21.6	18.5-19.2	12.9-13.6

(1) Assumes vehicle has 100,000-mi lifetime with battery output declining linearly by 20 percent over the battery cycle life.

(2) Includes costs of charging energy plus 5.5¢/mi for repairs, maintenance, tires, accessories, oil, taxes, registration, and insurance (Ref. 5-4).

ratio of approximately 0.4:1) and throttling of the air flow. No attempt is made to optimize parameters in the engine thermodynamic cycle analyses, so engine performance capability is expected to be greater than that presented here.

Table 5-7 summarizes the results of the full load (equivalence ratio $\phi = 1.0$) engine analyses for two basic types of engines: naturally aspirated and DI engines. The near-term, naturally aspirated engine cylinders receive a mixture of hydrogen and air at about 1 atm from a mixing valve or as a result of mixing of the airstream and low-pressure hydrogen injected at the intake valve seat or immediately upstream of it. The more advanced concept of direct cylinder injection of hydrogen gas into compressed air requires a means of compressing the hydrogen to pressures substantially above the air pressure in the cylinder. The means of compressing the hydrogen is of utmost importance in determining engine thermal efficiency, and this depends directly upon the condition of the hydrogen available to the compression unit. It was assumed that hydrogen is available at 1 atm from all energy storage systems. The temperature, however, can be as low as -423°F for liquid hydrogen to over 400°F from an advanced magnesium alloy hydride. For the near term, iron-titanium hydride or liquid hydrogen, gasified and heated, can supply approximately 80°F hydrogen to the engine. For the DI engines of 1990 and beyond, the hydrogen compressor can be supplied with about 80°F gas from iron-titanium hydride, or high-temperature hydrogen from the advanced hydride can be cooled to about 200°F in a heat exchanger before admission to the compressor. A hydrogen pump could be supplied with a fluid at any temperature above -423°F .

An engine compression ratio of 14:1 is assumed for all engines since this is a modest extrapolation of currently demonstrated capability and has good ideal thermal efficiency. Hydrogen injection pressure is set at 1000 psi, which should suffice for the expected air compression pressure of 534 psi, considering some latitude in choice of injection time. To minimize

TABLE 5-7. RESULTS OF HYDROGEN ENGINE CYCLE ANALYSES

	Naturally Aspirated ICE	Direct Cylinder Injection ICE		
		Compressed Hydrogen		Pumped Hydrogen
Inlet Hydrogen Pressure and Temperature, psia/°F	14/80	14/80	14/200	14/≥ -423
Temperature of Inlet Mix, °F	108	-	-	-
Ideal Cylinder Charge Density, lb/ft ³	0.0482 (mixture)	0.0652 (air) 0.0671 (corr. for H ₂)	0.0652 (air) 0.0671 (corr. for H ₂)	0.0652 (air) 0.0671 (corr. for H ₂)
H ₂ Injection Pressure and Temperature, psia/°F	-	1000/697	1000/853	1000/80
Compression Work, Btu/lb				
Air	-	339	339	339
Hydrogen	-	4682	5219	100
Mixture or Total	444	461	476	332
Air Pressure and Temperature Before Mixing, psia/°F	-	534/1288	534/1288	534/1288
Pressure and Temperature After Compression and Mixing, psia/°F	529/1233	741/1249	766/1306	615/958
Expansion Work After Constant Volume Combustion, Btu/lb	898	904	907	879
Net Work, Btu/lb	454	443	431	547
Thermal Efficiency	0.312	0.305	0.280	0.376
Relative Thermal Efficiency	1.000	0.976	0.897	1.205
Relative Displ. /Charge Mass	1.000	0.718	0.718	0.718
Relative Engine Mech. Effic.	1.000	1.062	1.062	1.057
Relative hp/Displacement	1.000	1.444	1.327	1.773
Relative Total Displacement Including Compressor or Pump	1.000	1.001	1.158	0.6204

(1) Compression ratio = 14:1.
 Inlet air pressure and temperature = 14 psia and 120°F.
 Fuel/air ratio = 0.029:1; $\phi = 1.0$.
 Compression and expansion efficiencies = 0.75.
 Two-stage hydrogen compressor with intercooler for 200°F inlet to second stage.

compression work, two stages of compression are assumed with an intermediate heat exchanger. Table 5-7 indicates the results of the computations. The key points are the charge densities for the two basic types of engines and the sharp differences in hydrogen compression work for the DI engine options. These factors account for large variations in thermal efficiency and displacement per unit horsepower. Engine size and weight factors resulting from this analysis are given in Appendix E.

Appendix C presents an illustration of the overall vehicle sizing, engine analysis, and range estimation methodology employed for the hydrogen vehicles. The relative efficiency and displacement factors from Table 5-7 are applied to correct the idealized performance of naturally aspirated hydrogen ICE's after first applying a factor of 0.75 to the ideal efficiency and brake mean effective pressure values. Driving cycle range estimation requires an estimate of the average powertrain efficiency considering the fairly high equivalence ratio for vehicle acceleration (quality governed, $\phi \approx 0.75$) and the reduced fuel requirements for cruising at 45 mph (air throttling at minimum $\phi \approx 0.4$). Using the brake thermal efficiency variation with throttling for a modern gasoline-powered ICE as a guide, the fuel consumption during acceleration and cruise phases is estimated. It is found that the cycle average powertrain efficiency is about 85 percent of the value at peak cycle horsepower conditions. By coincidence, this is the same value that has been selected for EV's.

Figure 5-15 presents vehicle weight vs design range for all hydrogen vehicles. Straight line approximations for near-term and advanced gasoline-powered cars are also presented for comparison. As expected, LSHV's are heavier than conventional cars and are more sensitive to range, but they are much lighter than gaseous storage hydrogen vehicles (GSHV's). LSHV's have dramatic weight advantages over GSHV's at design ranges over 200 mi. Figure 5-16 permits more accurate determination of the hydrogen load needed to achieve any design range. Figures 5-17, 5-18, and 5-19 present the weight, length, and design range comparisons between HV's and EV's for 1985, 1990, and 2000 model years, respectively. The principal

FIGURE 5-15. WEIGHT OF HYDROGEN-POWERED INTERNAL COMBUSTION ENGINE FOUR-PASSENGER CARS

FIGURE 5-16. DESIGN RANGE VERSUS HYDROGEN CAPACITY FOR FOUR-PASSENGER CARS

FIGURE 5-17. 1985 MODEL YEAR FOUR-PASSENGER VEHICLE CHARACTERISTICS

FIGURE 5-18. 1990 MODEL YEAR FOUR-PASSENGER VEHICLE CHARACTERISTICS

FIGURE 5-19. 2000 MODEL YEAR FOUR-PASSENGER VEHICLE CHARACTERISTICS

observations for 1985 and 1990 vehicles are the substantially greater weight and length values for the EV's and the corresponding need to limit EV's to lower design ranges. In 2000, however, the lithium-aluminum/iron sulfide EV is intermediate in weight between the LSHV and the advanced hydride GSHV at ranges up to 135 mi.

5.3.2.2 Cost Analysis

In Table 5-8, the weights and costs of HV's using each of the hydrogen storage techniques are presented for two design ranges at three points in time. The light weight of LSHV's, with their low-pressure supply tank, results in attractive values of purchase price and depreciation per mile. The GSHV's are burdened with high weights, expensive hydride loads and high-pressure tanks (for rapid charging), and more expensive engines. Hydride salvage for recycling may be very helpful in reducing the depreciation cost of iron-titanium GSHV's, but depreciation cost per mile will still be 57 to 229 percent higher than for LSHV's. Purchase price for either GSHV considered would appear to limit the vehicle to low or intermediate design range.

The weight advantage of LSHV's is partially offset by the energy costs to liquefy hydrogen. These costs are presented in Table 5-9. Process efficiencies are not expected to increase greatly, so conversion energy cost will remain almost proportional to the unit cost of electricity. The delivered cost of liquid hydrogen is presented as a function of the costs of hydrogen and electricity in Table 5-10. The energy costs assumed for the operating costs of HV's and EV's are shown in Table 5-11.

The hydrogen cost data are combined with vehicle hydrogen refill weight estimates to get the energy cost per mile values shown in Table 5-12. There is a surprisingly narrow predicted range of fuel cost per mile for all vehicle types and ranges, from 1.9¢ to 3.0¢/mi. A LSHV is the least expensive vehicle to operate at a range of 200 mi. Other operating costs, including repairs, maintenance, tires, accessories, oil, taxes,

TABLE 5-8. WEIGHTS AND COSTS OF HYDROGEN-POWERED VEHICLES

Hydrogen Storage System Type	Liquid Hydrogen						Iron-Titanium Hydride ⁽¹⁾				Advanced Hydride ⁽¹⁾			
Vehicle Design Range, mi	85			200			85		200		85		200	
Model Year	1985	1990	2000	1985	1990	2000	1985	1990	1985	1990	1990	2000	1990	2000
Vehicle Test Weight, lb	2520	2400	2195	2700	2510	2290	3240	3040	5300	4285	2965	2640	3980	3440
Weight of Hydride Alloy, lb	-	-	-	-	-	-	401	302	1352	886	108	91	310	260
OEM Cost of Hydride Alloy, \$	-	-	-	-	-	-	1404	1057	4732	3101	162	137	465	390
OEM Cost of Supply Tank, Heat Exchanger, etc., \$ ⁽²⁾	450	400	380	670	540	500	1830	1380	6180	4050	1610	1350	4600	3860
Engine Brake Horsepower, hp	59.2	54.7	47.6	62.4	57.2	49.7	73.9	68.1	117.1	94.3	66.4	57.3	88.0	75.7
OEM Engine Cost Incl. Injector Valves, Pump, Compressor, \$ ⁽³⁾	651	752	674	686	779	697	813	949	1288	1237	930	830	1168	1033
Vehicle Purchase Price, W/O Transportation, Taxes, \$ ⁽⁴⁾⁽⁵⁾	4990	4890	4390	5580	5260	4700	9110	8190	20660	15300	7330	6330	12810	10850
Salvage Value of Hydride Alloy, \$ ⁽⁶⁾	-	-	-	-	-	-	0-800	0-600	0-2700	0-1770	0-50	0-40	0-150	0-130
Total Salvage Value @ 100,000 mi, W/O Hydride Salvage, \$	220	210	190	240	220	200	250	240	360	310	260	230	340	290
Total Salvage Value @ 100,000 mi, W/Hydride Salvage, \$							1050	840	3070	2080	310	270	490	420
Total Vehicle Depreciation, W/O Hydride Salvage, \$	4770	4680	4200	5340	5040	4500	8860	7950	20300	14990	7070	6100	12470	10560
Total Vehicle Depreciation, W/Hydride Salvage, \$							8060	7350	17590	13220	7020	6060	12320	10430
Depreciation/Mile, W/O Hydride Salvage, ¢/mi	4.8	4.7	4.2	5.34	5.04	4.50	8.9	7.9	20.30	14.99	7.1	6.1	12.47	10.56
Depreciation/Mile, W/Hydride Salvage, ¢/mi							8.1	7.3	17.59	13.22	7.0	6.1	12.32	10.43

(1)

Cost of iron-titanium alloy = \$3.50/lb; cost of advanced magnesium alloy = \$1.50/lb.

(2)

Supply tanks, heat exchanger, plumbing, fill and vent valves have OEM cost of \$10/lb.

(3)

Engine OEM cost W/O transmission = \$11/hp for naturally aspirated engine. Add net \$100 for injection system, \$50 for liquid hydrogen pump, or \$100 for gaseous hydrogen compressor.

(4)

1980 dollars.

(5)

OEM cost of other vehicle weight = \$1.50/lb; salvage value = \$0.10/lb.

(6)

Hydride alloy salvage values: iron-titanium = 0 to \$2.00/lb; advanced alloy = 0 to \$0.50/lb.

TABLE 5-9. LIQUEFACTION EFFICIENCY

Process Parameter	Process Efficiency	Process Work Input ⁽¹⁾ kWh/lb (Btu/lb)	Conversion Efficiency	Conversion Energy Cost at 3¢/kWh \$/10 ⁶ Btu
Ideal Liquefaction	1.00	1.773 (6051)	0.895	1.03
Current Large Plant	0.36	4.925 (16,809)	0.754	2.86
High Feed Pressure (575 psia)	0.362	4.898 (16,716)	0.755	2.85
High Recycle Pressure (50 psia)	0.365	4.878 (16,579)	0.757	2.84
Ultimate Plant	0.40	4.433 (15,128)	0.773	2.58

(1) Assumes use of electricity to supply energy. If gaseous hydrogen were used to generate electricity, the hydrogen energy required would be about three times as high. Current plant conversion efficiency would drop from 75 to 50 percent.

TABLE 5-10. LIQUID HYDROGEN
COST (Ref. 5-5)

Hydrogen Feed Gas Cost		Delivered Liquid Hydrogen Cost, \$/10 ⁶ Btu ^{(1), (2)}		
\$/10 ⁶ Btu	(\$/lb)	2¢/kWh	3¢/kWh	4¢/kWh
2.50	(0.129)	7.30	8.15	8.95
5.00	(0.258)	9.45	10.3	11.15
6.65	(0.343)	10.85	11.75	12.5
10.00	(0.516)	13.80	14.65	15.5

(1) 1985 technology.

(2) Includes liquefaction, storage, distribution, investment and operating costs.

TABLE 5-11. ENERGY COST ASSUMPTIONS

	1985	1990	2000
Cost of Electricity, ¢/kWh (1977 Dollars) ⁽¹⁾			
Industrial	2	3	4
Residential	4	6	8
Cost of Coal, 1977 Dollars/10 ⁶ Btu	1.0	1.5	2.0
Production Cost of Gaseous Hydrogen, \$/10 ⁶ Btu			
From Coal (1977 Dollars)	4.50 (K-T)	4.90 (U-Gas)	5.85 (U-Gas)
(1980 Dollars)	5.21	5.67	6.77
Electrolytic (1977 Dollars)	13.00 (Lurgi)	12.40 (GE-SPE)	16.3 (GE-SPE)
(1980 Dollars)	15.05	15.52	18.88
Cost of Transmitted Gaseous Hydrogen From Coal, 1980 Dollars/10 ⁶ Btu	5.81	6.27	7.37
Cost of Distributed Hydrogen From Coal, 1980 Dollars/10 ⁶ Btu			
Gaseous	6.97	7.52	8.84
Liquid	10.15	11.41	13.13

(1) ¢/kWh × 2.929 = \$/10⁶ Btu

TABLE 5-12. TOTAL COST PER MILE FOR HYDROGEN-POWERED
INTERNAL COMBUSTION ENGINE CARS

Propulsion System	Hydrogen Cost, \$/lb	Design Range, mi	Energy Cost/ mi, ¢/mi	Total Operating Cost/mi, ¢/mi ⁽¹⁾	Depreciation Cost/mi, ¢/mi		Total Cost/mi, ¢/mi	
					With Hydride Salvage ⁽²⁾	W/O Hydride Salvage	With Hydride Salvage ⁽²⁾	W/O Hydride Salvage
1985 Liquid Hydrogen	0.524	85	2.7	8.2	-	4.8	-	13.0
		200	2.7	8.2	-	5.4	-	13.6
1985 Iron-Titanium Hydride	0.360	85	2.1	7.6	8.1	8.9	15.6	16.4
		200	3.0	8.5	17.7	20.4	26.2	28.9
1990 Liquid Hydrogen	0.589	85	2.0	7.5	-	4.7	-	12.2
		200	2.1	7.6	-	5.1	-	12.7
1990 Iron-Titanium Hydride	0.388	85	1.9	7.4	7.3	7.9	14.7	15.3
		200	2.4	7.9	13.3	15.1	21.2	23.0
1990 Advanced Hydride	0.388	85	2.3	8.3	7.0	7.1	15.3	15.4
		200	2.9	8.9	12.4	12.5	21.3	21.4
2000 Liquid Hydrogen	0.678	85	2.0	7.5	-	4.2	-	11.7
		200	2.1	7.6	-	4.6	-	12.2
2000 Advanced Hydride	0.456	85	2.3	8.3	6.1	6.1	14.4	14.4
		200	2.8	8.8	10.5	10.6	19.3	15.4

(1) Total operating cost/mi = hydrogen energy cost/mi + taxes, registration, and insurance of 4¢/mi + repairs, maintenance, tires, accessories, and oil cost of 1.5¢/mi for liquid hydrogen and iron-titanium hydride cars and 2¢/mi for advanced hydride cars.

(2) Assumed salvage values of metal hydrides: iron-titanium hydride \$2.00/lb, advanced hydride \$0.50/lb.

registration, and insurance are equated to the values for EV's except for an additional 0.5¢/mi allowed for repairs and maintenance of the complex advanced hydride propulsion systems. Table 5-12 concludes with the total estimated cost per mile, which clearly favors LSHV's.

5.3.2.3 Energy Consumption

For HV's where input energy is measured as the lower heating value of the net hydrogen mass introduced into the vehicle storage tanks

$$\frac{\text{energy}}{\text{vehicle mile}} = \frac{E_p}{D\eta_{PT}} \times \frac{W_{H(\text{refill})}}{W_{H(\text{usable})}} = \frac{15.12 W_{H(\text{refill})}}{R}, \text{ kWh/mi}$$

where

E_p = propulsion energy per driving cycle measured at drive wheels (Figure 5-2), kWh

D = driving cycle range (Figure 5-4), mi

η_{PT} = overall powertrain efficiency

$W_{H(\text{refill})}$ = weight of hydrogen added to vehicle storage tanks, lb

$W_{H(\text{usable})}$ = weight of hydrogen usable for propulsion, lb

R = design range for refill weight, mi

The refill hydrogen weight is assumed to have the following percentage of the hydrogen capacity of the storage tank:

	<u>1985</u>	<u>1990</u>	<u>2000</u>
Liquid Hydrogen	90	95	95
Iron-titanium Hydride	80	90	90
Advanced Hydride	-	90	90

It should be remembered that only 85 percent of the hydrogen consumed (refilled) by the advanced hydride GSHV is usable for propulsion, the remainder being used to aid hydride dissociation.

5.4 SOURCE ENERGY CONVERSION, TRANSMISSION, STORAGE, AND DISTRIBUTION

An evaluation is made of the efficiencies of converting and delivering energy derived from the principal fossil and nonfossil energy sources to the using vehicles. Table 5-13 indicates the applicable resources in the time period from the present to the year 2000. Disregarding the efficiencies of resource extraction and transportation to the first major conversion step, efficiencies are presented for the generation of electricity, generation of gaseous hydrogen, and liquefaction of hydrogen. The energy conversion efficiency is defined as the total plant output energy, including the heating value of product hydrogen and/or electricity, divided by the total plant input energy, including the heating value of fuel or hydrogen, electricity, steam, sensible heat, shaft work, hydroenergy, etc. For hydrogen

TABLE 5-13. CONVERSION PROCESS EFFICIENCIES

Energy Sources	Generation of Electricity	Generation of Hydrogen	Liquefaction of Hydrogen
<u>Fossil</u>			
Petroleum	0.39 (Steam Turbine Plant)	<0.74 (Partial Oxidation and Steam Reformation)	1985: 0.754 1990: 0.76 2000: 0.773
Natural Gas	0.39 (Steam Turbine Plant)	0.74 (Steam Reformation)	↓
Coal	0.37 (Steam Turbine Plant)	1980-1985: 0.57 (Koppers-Totzek) 1990: 0.63 (Steam-Iron) 2000: 0.66 (U-Gas)	
Shale Oil	0.39 (Steam Turbine Plant)	<0.74 (Partial Oxidation and Steam Reformation)	
<u>Nonfossil</u>			
Nuclear	1980-1985: 0.31 (LWR); 1990: 0.33 2000: 0.40 (Gas Turbine Cycle), 0.50 (Bottoming Cycle)	1980-1985: 0.79 (Electrolysis) 1990-2000: 0.865 (Electrolysis)	
Hydro	0.85 (Turbine Plant)	↓	
Solar	0.17 (Paraboloidal Dish, Steam Turbine); 0.19 (Central Receiver, Steam Turbine) [5-6] ⁽¹⁾		
Wind	0.40		
Geothermal	0.84 (Organic Fluid-Rankine Cycle Turbine Plant) [5-7] ⁽¹⁾		
Solid Waste	0.25 (Combined with Coal-Fired Steam Turbine Plant) (Proportioned to Reference 5-7 Data)		

(1) [] = reference numbers.

liquefaction, the efficiency is evaluated as the heating value of liquid hydrogen divided by the sum of the heating value of the incoming gaseous hydrogen and the net electric energy needed to drive the compressors. Specific estimates for the efficiencies of hydrogen generation from petroleum, shale oil, and the methane content of some geothermal sources were omitted to minimize effort, recognizing that these processes have efficiencies between those for natural gas (steam reformation) and coal gasification.

Table 5-14 presents estimates of the efficiencies of long-distance energy transmission, storage (if needed), distribution over intermediate distances, and local distribution to dispensing stations. Overall efficiencies for each energy form and transportation option are presented, with and without storage at 10 percent of average annual automotive usage. The marine and rail liquid hydrogen transmission modes are presumed to require a storage step involving the entire quantity of liquid hydrogen before starting the distribution process.

TABLE 5-14. ENERGY TRANSPORT AND STORAGE EFFICIENCIES

Form	Transmission ⁽¹⁾	Storage	Dis- tribution	Local Dis- tribution	Overall	Overall, With Storage ⁽²⁾
Electricity	(300 mi)	1) Batteries (0.65-0.75) [5-8] ⁽³⁾ 2) Electrolysis (0.8), Hydriding (0.98), Gas Turbine/Gen. (0.34) [5-10] = 0.267 ⁽³⁾			0.90 [5-9] ⁽³⁾	1) 0.869-0.878 2) 0.834
Gaseous Hydrogen Pipeline	0.93 (1000 mi)	1) Underground (Non- Electrolytic H ₂) 0.90 for Aquifer, Salt Cavern or Mined Cavern 2) Linepack (0.90) 3) Pressure Vessel (0.95) 4) Metal Hydride (0.98)	0.99	0.99	0.911	1) 0.902 2) 0.902 3) 0.907 4) 0.910
Liquid Hydrogen Pipeline	0.95 (<100 mi)	Large Storage Tank (0.98) with Distribution Tanks (0.97) = 0.951	1) 0.99 2) 0.96 (Truck)	1) 0.99 -	1) 0.931 -	1) 0.926 2) 0.867
Liquid Hydrogen Marine	0.95 (1000 mi)	↓	0.96 (Truck)	-	-	0.867
Liquid Hydrogen Rail	0.95 (1000 mi)	↓	0.98 (Truck)	0.98 (Truck)	-	0.868
Liquid Hydrogen Truck	0.92 (1000 mi)	↓	0.96	-	0.883	0.879

(1) Nominal transmission distances in parentheses.

(2) Storage capacity assumed equal to 10 percent of annual consumption; based on relatively consistent automotive demand compared to highly seasonal natural gas usage, which required 25 percent storage capacity.

(3) [] = reference numbers.

The efficiency of dispensing station operations and their interfacing with the vehicles during energy charging is estimated in Table 5-15. There is substantial uncertainty in station operations, depending upon the pressure level at which gaseous hydrogen is received, the pressures needed for rapid vehicle hydride tank charging, and the use made of the vehicle hydride heat of formation. Liquid hydrogen dispensing is susceptible to substantial losses in tank chilldown and fueling connections.

TABLE 5-15. VEHICLE ENERGY CHARGING EFFICIENCY

Form	Dispensing Station	Vehicle Charging	Overall
Electricity	1) Residential Power Outlet (1.0)	1) Battery Charger (0.90)[5-11] ⁽¹⁾	1) 0.90
	2) Residential Electrolyzer (0.6-0.75)	2) Vehicle Hydride Tank (0.98)	2) 1985: 0.588 1990: 0.662 2000: 0.735
Gaseous Hydrogen	1) Compression (0.95) 2) Hydride Storage and Compression (0.95)	Vehicle Hydride Tank (0.98)	0.931
Liquid Hydrogen	Storage and Dispensing (0.98)	Vehicle Tank (0.95)	0.931

⁽¹⁾[] = reference number.

Tables 5-16, 5-17, 5-18, and 5-19 present the overall efficiencies of the processes from the energy source through the input to the vehicle energy storage unit, for coal, nuclear, natural gas and hydro energies, respectively. All previously identified options in energy conversions, transportation, storage, and energy dispensing are included under six basic standardized options:

1. Generation of electricity ultimately used to charge EV batteries
2. Generation of electricity used to operate a residential electrolyzer for charging GSHV hydride tanks
3. Generation of electricity to operate industrial electrolyzers and ultimately charge GSHV hydride tanks

TABLE 5-16. EFFICIENCY OF PROCESSES FROM ENERGY SOURCE TO VEHICLE
ENERGY STORAGE INPUT - ENERGY SOURCE: COAL

Option Number	1			2			3			4			5			6		
	1985	1990	2000	1985	1990	2000	1985	1990	2000	1985	1990	2000	1985	1990	2000	1985	1990	2000
<u>Energy Conversion</u>																		
Electricity Generation	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37	0.37						
Hydrogen Generation							0.79	0.865	0.865	0.79	0.865	0.865	0.57	0.63	0.66	0.57	0.63	0.66
Hydrogen Liquefaction										0.754	0.76	0.773				0.754	0.76	0.773
Overall Conversion Efficiency	0.37	0.37	0.37	0.37	0.37	0.37	0.292	0.320	0.320	0.220	0.243	0.247	0.57	0.63	0.66	0.430	0.479	0.510
Product	Electricity			Electricity			Electrolytic Gaseous Hydrogen			Liquid Hydrogen			Gaseous Hydrogen			Liquid Hydrogen		
<u>Energy Transportation & Storage</u>																		
Powerline	0.90	0.90	0.90	0.90	0.90	0.90												
Storage Option 1) Batteries	0.869	0.873	0.878	0.869	0.873	0.878												
Storage Option 2) Electrolysis	0.834	0.834	0.834	0.834	0.834	0.834												
Gaseous Hydrogen Pipeline							0.911	0.911	0.911				0.911	0.911	0.911			
Storage Option 1) Underground													0.902	0.902	0.902			
Storage Option 2) Linepack							0.902	0.902	0.902				0.902	0.902	0.902			
Storage Option 3) Press. Vessel							0.907	0.907	0.907				0.907	0.907	0.907			
Storage Option 4) Metal Hydride							0.910	0.910	0.910				0.910	0.910	0.910			
a) Liquid Hydrogen Pipeline										a)0.931	0.931	0.931				a)0.931	0.931	0.931
b) Storage Option 1) Tanks										b)0.926	0.926	0.926				b)0.926	0.926	0.926
c) Storage Option 2) Tanks, Truck Distribution										c)0.867	0.867	0.867				c)0.867	0.867	0.867
d) Liquid Hydrogen - Marine (W/Storage, Truck Distribution)										d)0.867	0.867	0.867				d)0.867	0.867	0.867
e) Liquid Hydrogen - Rail (W/Storage, Local Truck Distribution)										e)0.868	0.868	0.868				e)0.868	0.868	0.868
f) Liquid Hydrogen - Truck										f)0.883	0.883	0.883				f)0.883	0.883	0.883
g) Liquid Hydrogen - Truck (W/Storage)										g)0.879	0.879	0.879				g)0.879	0.879	0.879
<u>Energy Dispensing & Vehicle Recharge</u>																		
Residential or On-Board Charger	0.90	0.90	0.90															
Residential Electrolyzer/Vehicle Hydride Tank				0.588	0.662	0.735												
Station Gaseous Hydrogen Storage, Compr./Vehicle Hydride Tank							0.931	0.931	0.931				0.931	0.931	0.931			
Station Liquid Hydrogen Storage, Dispens./Vehicle Liquid Hydrogen Tank										0.931	0.931	0.931				0.931	0.931	0.931
<u>Overall Source-To-Vehicle Storage Input</u>																		
Storage Option 1)	0.300	0.300	0.300	0.196	0.220	0.245	0.248	0.272	0.272	a)0.191	0.211	0.214	0.483	0.535	0.560	a)0.373	0.415	0.442
Storage Option 2)	0.289	0.291	0.292	0.189	0.214	0.239				b)0.190	0.209	0.213	0.479	0.529	0.554	b)0.371	0.413	0.440
Storage Option 3)	0.278	0.278	0.278	0.181	0.204	0.227	0.245	0.269	0.269	c)0.178	0.196	0.199	0.479	0.529	0.554	c)0.347	0.387	0.412
Storage Option 4)							0.247	0.270	0.270	d)0.178	0.196	0.199	0.481	0.532	0.557	d)0.347	0.387	0.412
							0.247	0.271	0.271	e)0.178	0.196	0.200	0.482	0.534	0.559	e)0.347	0.387	0.412
										f)0.181	0.200	0.203				f)0.353	0.394	0.419
										g)0.180	0.199	0.202				g)0.352	0.392	0.417

TABLE 5-17. EFFICIENCY OF PROCESSES FROM ENERGY SOURCE TO VEHICLE
ENERGY STORAGE INPUT - ENERGY SOURCE: NUCLEAR

Option Number	1			2			3			4		
	1985	1990	2000	1985	1990	2000	1985	1990	2000	1985	1990	2000
<u>Energy Conversions</u>												
Electricity Generation ⁽¹⁾	0.31	0.33	0.40/0.50	0.31	0.33	0.40/0.50	0.31	0.33	0.40/0.50	0.31	0.33	0.40/0.50
Hydrogen Generation							0.79	0.865	0.865	0.79	0.865	0.865
Hydrogen Liquefaction										0.754	0.76	0.773
Overall Conversion Efficiency	0.31	0.33	0.40/0.50	0.31	0.33	0.40/0.50	0.245	0.285	0.346/0.433	0.185	0.217	0.267/0.334
Product	Electricity			Electricity			Electrolytic Gaseous Hydrogen			Liquid Hydrogen		
<u>Energy Transportation & Storage</u>												
Powerline	0.90	0.90	0.90	0.90	0.90	0.90						
Storage Option 1) Batteries	0.869	0.873	0.878	0.869	0.873	0.878						
Storage Option 2) Electrolysis	0.834	0.834	0.834	0.834	0.834	0.834						
Gaseous Hydrogen Pipeline							0.911	0.911	0.911			
Storage Option 1) Underground												
Storage Option 2) Linepack							0.902	0.902	0.902			
Storage Option 3) Press. Vessel							0.907	0.907	0.907			
Storage Option 4) Metal Hydride							0.910	0.910	0.910			
a) Liquid Hydrogen Pipeline										a)0.931	0.931	0.931
b) Storage Option 1) Tanks										b)0.926	0.926	0.926
c) Storage Option 2) Tanks, Truck Distribution										c)0.867	0.867	0.867
d) Liquid Hydrogen-Marine (W/Storage, Truck Distribution)										d)0.867	0.867	0.867
e) Liquid Hydrogen-Rail (W/Storage, Local Truck Distribution)										e)0.868	0.868	0.868
f) Liquid Hydrogen-Truck										f)0.883	0.883	0.883
g) Liquid Hydrogen-Truck (W/Storage)										g)0.879	0.879	0.879
<u>Energy Dispensing & Vehicle Recharge</u>												
Residential or On-Board Charger	0.90	0.90	0.90									
Residential Electrolyzer/Vehicle Hydride Tank				0.588	0.662	0.735						
Station Gaseous Hydrogen Storage, Compr./Vehicle Hydride Tank							0.931	0.931	0.931			
Station Liquid Hydrogen Storage, Dispen./Vehicle Liquid Hydrogen Tank										0.931	0.931	0.931
<u>Overall Source-to-Vehicle Storage Input</u>												
	0.251	0.267	0.324/0.405	0.164	0.197	0.265/0.331	0.208	0.242	0.293/0.367	a)0.160	0.188	0.232/0.290
Storage Option 1)	0.242	0.259	0.316/0.395	0.158	0.191	0.258/0.323				b)0.159	0.187	0.231/0.288
Storage Option 2)	0.233	0.248	0.300/0.375	0.152	0.182	0.245/0.306	0.206	0.240	0.291/0.363	c)0.149	0.175	0.216/0.270
Storage Option 3)							0.207	0.241	0.292/0.365	d)0.149	0.175	0.216/0.270
Storage Option 4)							0.207	0.242	0.293/0.366	e)0.149	0.175	0.216/0.270
										f)0.152	0.178	0.220/0.275
										g)0.151	0.178	0.217/0.274

(1) High-temperature, gas-cooled reactor/systems in year 2000 use either a simple gas turbine cycle ($\eta = 0.40$) or add a bottoming cycle ($\eta = 0.50$).

TABLE 5-18. EFFICIENCY OF PROCESSES FROM ENERGY SOURCE TO VEHICLE
ENERGY STORAGE INPUT - ENERGY SOURCE: NATURAL GAS

Option Number	1			2			3			4			5			6		
	1985	1990	2000	1985	1990	2000	1985	1990	2000	1985	1990	2000	1985	1990	2000	1985	1990	2000
Energy Conversions																		
Electricity Generation ⁽¹⁾	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39						
Hydrogen Generation							0.79	0.865	0.865	0.79	0.865	0.865	0.74	0.74	0.74	0.74	0.74	0.74
Hydrogen Liquefaction										0.754	0.76	0.773				0.754	0.76	0.773
Overall Conversion Efficiency	0.39	0.39	0.39	0.39	0.39	0.39	0.308	0.337	0.337	0.232	0.256	0.261	0.74	0.74	0.74	0.558	0.562	0.572
Product	Electricity			Electricity			Electrolytic Gaseous Hydrogen			Liquid Hydrogen			Gaseous Hydrogen			Liquid Hydrogen		
Energy Transportation & Storage																		
Powerline	0.90	0.90	0.90	0.90	0.90	0.90												
Storage Option 1) Batteries	0.869	0.873	0.878	0.869	0.873	0.878												
Storage Option 2) Electrolysis	0.834	0.834	0.834	0.834	0.834	0.834												
Gaseous Hydrogen Pipeline							0.911	0.911	0.911				0.911	0.911	0.911			
Storage Option 1) Underground													0.902	0.902	0.902			
Storage Option 2) Linepack							0.902	0.902	0.902				0.902	0.902	0.902			
Storage Option 3) Press. Vessel							0.907	0.907	0.907				0.907	0.907	0.907			
Storage Option 4) Metal Hydride							0.910	0.910	0.910				0.910	0.910	0.910			
a) Liquid Hydrogen Pipeline										a)0.931	0.931	0.931				a)0.931	0.931	0.931
b) Storage Option 1) Tanks										b)0.926	0.926	0.926				b)0.926	0.926	0.926
c) Storage Option 2) Tanks, Truck Distribution										c)0.867	0.867	0.867				c)0.867	0.867	0.867
d) Liquid Hydrogen - Marine (W/Storage, Truck Distribution)										d)0.867	0.867	0.867				d)0.867	0.867	0.867
e) Liquid Hydrogen - Rail (W/Storage, Local Truck Distribution)										e)0.868	0.868	0.868				e)0.868	0.868	0.868
f) Liquid Hydrogen - Truck										f)0.883	0.883	0.883				f)0.883	0.883	0.883
g) Liquid Hydrogen - Truck (W/Storage)										g)0.879	0.879	0.879				g)0.879	0.879	0.879
Energy Dispensing & Vehicle Recharge																		
Residential or On-Board Charger	0.90	0.90	0.90															
Residential Electrolyzer/Vehicle Hydride Tank				0.588	0.562	0.735												
Station Gaseous Hydrogen Storage, Compr./Vehicle Hydride Tank							0.931	0.931	0.931				0.931	0.931	0.931			
Station Liquid Hydrogen Storage, Dispen./Vehicle Liquid Hydrogen Tank										0.931	0.931	0.931				0.931	0.931	0.931
Overall Source-to-Vehicle Storage Input																		
Storage Option 1)	0.316	0.316	0.316	0.206	0.232	0.258	0.261	0.286	0.286	a)0.201	0.222	0.226	0.628	0.628	0.628	a)0.484	0.487	0.496
Storage Option 2)	0.305	0.306	0.308	0.199	0.225	0.252				b)0.200	0.221	0.225	0.621	0.621	0.621	b)0.481	0.485	0.493
Storage Option 3)	0.293	0.293	0.293	0.191	0.215	0.239	0.259	0.283	0.283	c)0.188	0.207	0.210	0.621	0.621	0.621	c)0.450	0.454	0.462
Storage Option 4)							0.260	0.285	0.285	d)0.188	0.207	0.210	0.625	0.625	0.625	d)0.450	0.454	0.462
							0.261	0.286	0.286	e)0.188	0.207	0.211	0.627	0.627	0.627	e)0.451	0.454	0.462
										f)0.191	0.211	0.214				f)0.459	0.462	0.470
										g)0.190	0.210	0.213				g)0.457	0.460	0.468

⁽¹⁾ Table also approximately valid for electricity from petroleum, shale oil, and wind.

TABLE 5-19. EFFICIENCY OF PROCESSES FROM ENERGY SOURCE TO VEHICLE
ENERGY STORAGE INPUT - ENERGY SOURCE: HYDRO

Option Number	1			2			3			4		
	1985	1990	2000	1985	1990	2000	1985	1990	2000	1985	1990	2000
<u>Energy Conversions</u>												
Electricity Generation ⁽¹⁾	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85	0.85
Hydrogen Generation							0.79	0.865	0.865	0.79	0.865	0.865
Hydrogen Liquefaction										0.754	0.76	0.773
Overall Conversion Efficiency	0.85	0.85	0.85	0.85	0.85	0.85	0.671	0.735	0.735	0.506	0.559	0.568
Product	Electricity			Electricity			Electrolytic Gaseous Hydrogen			Liquid Hydrogen		
<u>Energy Transportation & Storage</u>												
Powerline	0.90	0.90	0.90	0.90	0.90	0.90						
Storage Option 1) Batteries	0.869	0.873	0.878	0.869	0.873	0.878						
Storage Option 2) Electrolysis	0.834	0.834	0.834	0.834	0.834	0.834						
Gaseous Hydrogen Pipeline							0.911	0.911	0.911			
Storage Option 1) Underground												
Storage Option 2) Linepack							0.902	0.902	0.902			
Storage Option 3) Press. Vessel							0.907	0.907	0.907			
Storage Option 4) Metal Hydride							0.910	0.910	0.910			
a) Liquid Hydrogen Pipeline										a)0.931	0.931	0.931
b) Storage Option 1) Tanks										b)0.926	0.926	0.926
c) Storage Option 2) Tanks, Truck Distribution										c)0.857	0.867	0.867
d) Liquid Hydrogen Marine (W/Storage, Truck Distribution)										d)0.867	0.867	0.867
e) Liquid Hydrogen-Rail (W/Storage, Local Truck Distribution)										e)0.868	0.868	0.863
f) Liquid Hydrogen-Truck										f)0.883	0.883	0.883
g) Liquid Hydrogen-Truck (W/Storage)										g)0.879	0.879	0.879
<u>Energy Dispensing & Vehicle Recharge</u>												
Residential or On-Board Charger	0.90	0.90	0.90									
Residential Electrolyzer/Vehicle Hydride Tank				0.588	0.662	0.735						
Station Gaseous Hydrogen Storage, Compr./Vehicle Hydride Tank							0.931	0.931	0.931			
Station Liquid Hydrogen Storage, Dispen./Vehicle Liquid Hydrogen Tank										0.931	0.931	0.931
<u>Overall Source-to-Vehicle Storage Input</u>												
	0.689	0.689	0.689	0.450	0.506	0.562	0.570	0.624	0.624	a)0.439	0.484	0.493
Storage Option 1)	0.665	0.668	0.672	0.434	0.491	0.549				b)0.436	0.482	0.490
Storage Option 2)	0.638	0.638	0.638	0.417	0.469	0.521	0.564	0.617	0.617	c)0.409	0.451	0.455
Storage Option 3)							0.567	0.621	0.621	d)0.409	0.451	0.455
Storage Option 4)							0.569	0.623	0.623	e)0.409	0.451	0.455
										f)0.416	0.459	0.467
										g)0.414	0.457	0.465

(1) Table also approximately valid for electricity from geothermal source (Rankine cycle, organic fluid).

4. Generation of electricity to operate industrial electrolyzers and liquefy hydrogen ultimately charged into LSHV tanks
5. Generation of gaseous hydrogen ultimately charged into GSHV hydride tanks
6. Generation of gaseous hydrogen that is subsequently liquefied and ultimately charged into LSHV tanks.

Only the first four options, involving generation of electricity, are open to nuclear, hydro, wind, solar, and most geothermal sources. To minimize effort, only the first four options are considered for petroleum, shale oil, geothermal, and solid waste energy sources. The possibilities of higher electric generating station efficiencies using combined gas turbine and closed cycle (steam or other) power plants, are also disregarded.

A few brief comments are in order for each of the tables.

Table 5-16 clearly indicates that the most efficient use of coal in connection with HV's begins with coal gasification. Options 5 and 6 will have an increasing efficiency advantage over Option 1 (electricity) with time. Table 5-17 shows that nuclear energy is best used to generate electricity for EV's, but industrially produced electrolytic hydrogen for GSHV's becomes increasingly more competitive. As expected, Table 5-18 shows that natural gas is most efficiently employed for HV's after gasification by steam reformation. The high overall efficiency, however, is of little importance considering the dwindling gas supply, its anticipated need for other purposes, and the comparative abundance of coal. Petroleum, shale oil, and wind have about the same efficiencies of generating electricity as does natural gas, so they are listed on this table for Options 1 through 4. Table 5-19 shows high overall efficiency for all options depending upon a hydro turbogenerator. Since a geothermal source applying its heat to a closed cycle turbogenerator using a selected hydrocarbon working fluid can achieve about the same efficiency according to Reference 5-7, it is listed here as well. Battery charging in all cases is the best way to use such resources, but the total energy readily available is not great (and not constant for hydro).

The vehicle energy consumption characteristics and the overall efficiencies of source energy conversion, transport, storage, and dispensing can now be combined to obtain the source energy consumption per vehicle mile traveled. Table 5-20 presents the results of such a combination for all the hydrogen vehicles at two design ranges, assuming use of the two principal energy sources for this application — coal and nuclear energy. It is seen that LSHV's have the lowest vehicle energy consumptions at all times and are least sensitive to design range. However, in 1985, the iron-titanium GSHV requires less source energy primarily because of the avoidance of the liquefaction process. At all other conditions the LSHV consumes the least source energy. Nuclear reactors require 1.5 to 2.3 times as much fuel energy as do coal conversion plants.

Tables 5-21, 5-22, and 5-23 provide similar data, respectively, for 1985, 1990, and 2000 model year HV's and EV's assuming coal as the energy source. At their selected minimum design ranges, it is seen that the EV's require the least input energy at each point in time. However, in 1985, the least source energy is required by the iron-titanium GSHV, followed by the nickel/zinc EV, the LSHV, and the lead/acid EV, in that order. The entire spread is from 1.80 to 2.3 kWh/mi, without energy storage. In 1990, the LSHV consumes the least source energy, followed by iron-titanium and advanced hydride GSHV's and the zinc/chlorine hydrate EV. The spread is from 1.27 to 1.74 kWh/mi. In 2000, the lithium-aluminum/iron sulfide EV is the most efficient user of coal energy, followed by the LSHV and the advanced hydride GSHV for the largest overall spread of 0.85 to 1.37 kWh/mi.

Tables 5-24, 5-25, 5-26, and 5-27 present equivalent data assuming nuclear fuel energy. At all times, the EV's have decisive advantages in source energy consumption with energy spreads of 2.22 to 5.05 kWh/mi in 1985, 1.95 to 3.77 kWh/mi in 1990, and 0.79 to 2.62 kWh/mi in 2000 (for simple gas turbine cycle). Clearly, the time frame and the source of the energy determine the preferred vehicle from the standpoint of energy use.

TABLE 5-20. VEHICLE AND SOURCE ENERGY UTILIZATION
FOR HYDROGEN-POWERED CARS

Propulsion System	Vehicle Energy/mi, kWh/mi		Source Energy/Vehicle Mile, kWh/mi			
	Range = 85 mi	Range = 200 mi	Range = 85 mi		Range = 200 mi	
			Coal	Nuclear	Coal	Nuclear
1985 Liquid Hydrogen	0.768	0.782	2.059	4.800	2.097	4.887
1985 Iron-Titanium Hydride	0.868	1.246	1.797	4.173	2.580	5.990
1990 Liquid Hydrogen	0.525	0.539	1.265	2.793	1.299	2.867
1990 Iron-Titanium Hydride	0.736	0.919	1.376	3.041	1.718	3.797
1990 Advanced Hydride	0.913	1.109	1.706	3.773	2.072	4.583
2000 Liquid Hydrogen	0.439	0.460	0.994	1.892 (simple) 1.514 (bottoming)	1.042	1.983 (simple) 1.586 (bottoming)
2000 Advanced Hydride	0.768	0.932	1.372	2.621 (simple) 2.093 (bottoming)	1.665	3.181 (simple) 2.540 (bottoming)

TABLE 5-21. 1985 MODEL YEAR VEHICLE ENERGY COMPARISONS -
ENERGY SOURCE: COAL

Vehicle Type	Design Range, mi	Recharge Energy ⁽¹⁾	Vehicle Energy/mi kWh/mi	Source-Vehicle Input Energy Efficiency		Source Energy/Vehicle Mile	
				W/O Storage	W/Storage ⁽²⁾⁽³⁾	W/O Storage kWh/mi	W/Storage kWh/mi ⁽³⁾
<u>Hydrogen Vehicles⁽⁴⁾</u>							
Liquid Hydrogen Pipeline	85	4.32	0.768	0.373	0.371 ^(a) ; 0.347 ^(b)	2.059	2.070 ^(a) ; 2.213 ^(b)
Marine				-	0.347 ^(b)	-	2.213 ^(b)
Rail				-	0.347 ^(b)	-	2.213 ^(b)
Truck				0.353	0.352 ^(b)	2.176	2.182 ^(b)
Iron-Titanium Hydride (Gaseous Hydrogen Pipeline)	85	4.88	0.868	0.483	0.479 ^(c) ; 0.479 ^(d) 0.481 ^(e) ; 0.482 ^(f)	1.797	1.812 ^(c) ; 1.812 ^(d) 1.805 ^(e) ; 1.801 ^(f)
<u>Battery Vehicles</u>							
Lead/Acid	64.2	44.3	0.690	0.300	0.289 ^(g) ; 0.278 ^(h)	2.300	2.388 ^(g) ; 2.482 ^(h)
Nickel/Zinc	80.8	45.0	0.557	0.300	0.289 ^(g) ; 0.278 ^(h)	1.856	1.927 ^(g) ; 2.003 ^(h)
<p>⁽¹⁾ Recharge Energy: Hydrogen refill weight in lb = C x Capacity; C = 0.90 and 0.95 for liquid hydrogen in 1985 and later, respectively; C = 0.80 for iron-titanium hydride in 1985; C = 0.90 for all hydrides in 1990 and 2000. Energy from charger in kWh = depth of discharge x capacity/battery efficiency.</p> <p>⁽²⁾ Nonessential energy storage = 10% of directly transmitted energy.</p> <p>⁽³⁾ Storage and distribution options: (a) Liquid hydrogen tank; (b) Liquid hydrogen tank and truck distribution; (c) Underground; (d) Linepack; (e) Pressure vessel; (f) Metal hydride; (g) Batteries; (h) Electrolytic hydrogen stored in hydride until used to fuel turbogenerator.</p> <p>⁽⁴⁾ Hydrogen assumed derived from coal gasification because of much higher efficiency than for industrial or residential electrolysis.</p>							

TABLE 5-22. 1990 MODEL YEAR VEHICLE ENERGY COMPARISONS -
ENERGY SOURCE: COAL

Vehicle Type	Design Range, mi	Recharge Energy ⁽¹⁾	Vehicle Energy/mi kWh/mi	Source-Vehicle Input Energy Efficiency		Source Energy/Vehicle Mile	
				W/O Storage	W/Storage ⁽²⁾⁽³⁾	W/O Storage kWh/mi	W/Storage kWh/mi ⁽³⁾
<u>Hydrogen Vehicles⁽⁴⁾</u>							
Liquid Hydrogen Pipeline	85	2.95	0.525	0.415	0.413 ^(a) ; 0.387 ^(b)	1.265	1.271 ^(a) ; 1.356 ^(b)
Marine				-	0.387 ^(b)	-	1.356 ^(b)
Rail				-	0.387 ^(b)	-	1.356 ^(b)
Truck				0.394	0.392 ^(b)	1.332	1.339 ^(b)
Iron-Titanium Hydride (Gaseous Hydrogen Pipeline)	85	4.14	0.736	0.535	0.529 ^(c) ; 0.529 ^(d) 0.532 ^(e) ; 0.534 ^(f)	1.376	1.392 ^(c) ; 1.392 ^(d) 1.384 ^(e) ; 1.379 ^(f)
Advanced Hydride (Gaseous Hydrogen Pipeline)	85	5.13	0.913	0.535	0.529 ^(c) ; 0.529 ^(d) 0.532 ^(e) ; 0.534 ^(f)	1.706	1.725 ^(c) ; 1.725 ^(d) 1.715 ^(e) ; 1.709 ^(f)
<u>Battery Vehicle</u>							
Zinc/Chlorine Hydrate	111.1	57.8	0.521	0.300	0.291 ^(g) ; 0.278 ^(h)	1.735	1.789 ^(g) ; 1.872 ^(h)

(1) Recharge Energy:

Hydrogen refill weight in lb = C x Capacity; C=0.90 and 0.95 for liquid hydrogen in 1985 and later, respectively; C=0.80 for iron-titanium hydride in 1985; C=0.90 for all hydrides in 1990 and 2000.

Energy from charger in kWh = depth of discharge x capacity/battery efficiency.

(2) Nonessential energy storage = 10% of directly transmitted energy.

(3) Storage and distribution options:

(a) Liquid hydrogen tank; (b) Liquid hydrogen tank and truck distribution; (c) Underground; (d) Linepack; (e) Pressure vessel; (f) Metal hydride;

(g) Batteries; (h) Electrolytic hydrogen stored in hydride until used to fuel turbogenerator.

(4) Hydrogen assumed derived from coal gasification because of much higher efficiency than for industrial or residential electrolysis.

TABLE 5-23. 2000 MODEL YEAR VEHICLE ENERGY COMPARISONS -
ENERGY SOURCE: COAL

Vehicle Type	Design Range, mi	Recharge Energy ⁽¹⁾	Vehicle Energy/mi kWh/mi	Source-Vehicle Input Energy Efficiency		Source Energy/Vehicle Mile	
				W/O Storage	W/Storage ⁽²⁾⁽³⁾	W/O Storage kWh/mi	W/Storage kWh/mi ⁽³⁾
<u>Hydrogen Vehicles</u> ⁽⁴⁾							
Liquid Hydrogen Pipeline	85	2.47	0.439	0.442	0.440 ^(a) ; 0.412 ^(b)	0.994	0.999 ^(a) ; 1.066 ^(b)
Marine				-	0.412 ^(b)	-	1.066 ^(b)
Rail				-	0.412 ^(b)	-	1.066 ^(b)
Truck				0.419	0.417 ^(b)	1.049	1.054 ^(b)
Advanced Hydride (Gaseous Hydrogen Pipeline)	85	4.32	0.768	0.560	0.554 ^(c) ; 0.554 ^(d) 0.557 ^(e) ; 0.559 ^(f)	1.372	1.387 ^(c) ; 1.387 ^(d) 1.380 ^(e) ; 1.375 ^(f)
<u>Battery Vehicle</u>							
Lithium-aluminum/iron sulfide	93.1	23.8	0.256	0.300	0.292 ^(g) ; 0.278 ^(h)	0.852	0.875 ^(g) ; 0.920 ^(h)
<p>(1) Recharge Energy: Hydrogen refill weight in lb = Cx Capacity; C = 0.90 and 0.95 for liquid hydrogen in 1985 and later, respectively; C = 0.80 for iron-titanium hydride in 1985; C = 0.90 for all hydrides in 1990 and 2000. Energy from charger in kWh = depth of discharge x capacity/battery efficiency.</p> <p>(2) Nonessential energy storage = 10% of directly transmitted energy.</p> <p>(3) Storage and distribution options: (a) Liquid hydrogen tank; (b) Liquid hydrogen tank and truck distribution; (c) Underground; (d) Linepack; (e) Pressure vessel; (f) Metal hydride; (g) Batteries; (h) Electrolytic hydrogen stored in hydride until used to fuel turbogenerator.</p> <p>(4) Hydrogen assumed derived from coal gasification because of much higher efficiency than for industrial or residential electrolysis.</p>							

TABLE 5-24. 1985 MODEL YEAR VEHICLE ENERGY COMPARISONS -
ENERGY SOURCE: NUCLEAR (LIGHT WATER REACTOR)

Vehicle Type	Design Range, mi	Recharge Energy ⁽¹⁾	Vehicle Energy/mi kWh/mi	Source-Vehicle Input Energy Efficiency		Source Energy/Vehicle Mile	
				W/O Storage	W/Storage ⁽²⁾⁽³⁾	W/O Storage kWh/mi	W/Storage kWh/mi ⁽³⁾
Hydrogen Vehicles							
Liquid Hydrogen	85	4.32	0.768				
Pipeline				0.160	0.159 ^(a) ; 0.149 ^(b)	4.800	4.830 ^(a) ; 5.154 ^(b)
Marine				-	0.149 ^(b)	-	5.154 ^(b)
Rail				-	0.149 ^(b)	-	5.154 ^(b)
Truck				0.152	0.151 ^(b)	5.053	5.086 ^(b)
Iron-Titanium Hydride	85	4.88	0.868	0.208	0.206 ^(d) ; 0.207 ^(e) ;	4.173	4.214 ^(d) ; 4.193 ^(e) ;
(Gaseous Hydrogen Pipeline)					0.207 ^(f)		4.193 ^(f)
Battery Vehicles							
Lead/Acid	64.2	44.3	0.690	0.251	0.242 ^(g) ; 0.233 ^(h)	2.749	2.851 ^(g) ; 2.961 ^(h)
Nickel/Zinc	80.8	45.0	0.557	0.251	0.242 ^(g) ; 0.233 ^(h)	2.219	2.302 ^(g) ; 2.391 ^(h)

(1) Recharge Energy:
Hydrogen refill weight in lb = Cx Capacity; C = 0.90 and 0.95 for liquid hydrogen in 1985 and later, respectively; C = 0.80 for iron-titanium hydride in 1985; C = 0.90 for all hydrides in 1990 and 2000.
Energy from charger in kWh = depth of discharge x capacity/battery efficiency.

(2) Nonessential energy storage = 10% of directly transmitted energy.

(3) Storage and distribution options:
(a) Liquid hydrogen tank; (b) Liquid hydrogen tank and truck distribution; (c) Underground; (d) Linepack; (e) Pressure vessel; (f) Metal hydride;
(g) Batteries; (h) Electrolytic hydrogen stored in hydride until used to fuel turbogenerator.

TABLE 5-25. 1990 MODEL YEAR VEHICLE ENERGY COMPARISONS -
ENERGY SOURCE: NUCLEAR (LIGHT WATER
REACTOR)

Vehicle Type	Design Range, mi	Recharge Energy ⁽¹⁾	Vehicle Energy/mi kWh/mi	Source-Vehicle Input Energy Efficiency		Source Energy/Vehicle Mile	
				W/O Storage	W/Storage ⁽²⁾⁽³⁾	W/O Storage kWh/mi	W/Storage kWh/mi ⁽³⁾
<u>Hydrogen Vehicles</u>							
Liquid Hydrogen Pipeline	85	2.95	0.525	0.188	0.187 ^(a) ; 0.175 ^(b)	2.793	2.807 ^(a) ; 3.000 ^(b)
Marine				-	0.175 ^(b)	-	3.000 ^(b)
Rail				-	0.175 ^(b)	-	3.000 ^(b)
Truck				0.178	0.177 ^(b)	2.949	2.966 ^(b)
Iron-Titanium Hydride (Gaseous Hydrogen Pipeline)	85	4.14	0.736	0.242	0.240 ^(c) ; 0.240 ^(d) ; 0.241 ^(e) ; 0.242 ^(f)	3.041	3.067 ^(c) ; 3.067 ^(d) ; 3.054 ^(e) ; 3.041 ^(f)
Advanced Hydride (Gaseous Hydrogen Pipeline)	84	5.13	0.913	0.242	0.240 ^(c) ; 0.240 ^(d) ; 0.241 ^(e) ; 0.242 ^(f)	3.773	3.804 ^(c) ; 3.804 ^(d) ; 3.788 ^(e) ; 3.773 ^(f)
<u>Battery Vehicle</u>							
Zinc/Chlorine Hydrate	111.1	57.8	0.521	0.267	0.259 ^(g) ; 0.248 ^(h)	1.951	2.012 ^(g) ; 2.101 ^(h)

(1) Recharge Energy:
Hydrogen refill weight in lb = C x Capacity; C = 0.90 and 0.95 for liquid hydrogen in 1985 and later, respectively; C = 0.80 for iron-titanium hydride in 1985; C = 0.90 for all hydrides in 1990 and 2000.
Energy from charger in kWh = depth of discharge x capacity/battery efficiency.

(2) Nonessential energy storage = 10% of directly transmitted energy.

(3) Storage and distribution options:
(a) Liquid hydrogen tank; (b) Liquid hydrogen tank and truck distribution; (c) Underground; (d) Linepack; (e) Pressure vessel; (f) Metal hydride; (g) Batteries; (h) Electrolytic hydrogen stored in hydride until used to fuel turbogenerator.

TABLE 5-26. 2000 MODEL YEAR VEHICLE ENERGY COMPARISONS -
ENERGY SOURCE: NUCLEAR (HIGH TEMPERATURE,
GAS-COOLED REACTOR, SIMPLE GAS TURBINE CYCLE)

Vehicle Type	Design Range, mi	Recharge Energy ⁽¹⁾	Vehicle Energy/mi kWh/mi	Source-Vehicle Input Energy Efficiency		Source Energy/Vehicle Mile	
				W/O Storage	W/Storage ⁽²⁾⁽³⁾	W/O Storage kWh/mi	W/Storage kWh/mi ⁽³⁾
<u>Hydrogen Vehicles</u>							
Liquid Hydrogen Pipeline	85	2.47	0.439	0.232	0.231 ^(a) ; 0.216 ^(b)	1.892	1.900 ^(a) ; 2.032 ^(b)
Marine				-	0.216 ^(b)		2.032 ^(b)
Rail				-	0.216 ^(b)		2.032 ^(b)
Truck				0.220	0.219 ^(b)	1.995	2.005 ^(b)
Advanced Hydride (Gaseous Hydrogen Pipeline)	85	4.32	0.768	0.293	0.291 ^(c) ; 0.291 ^(d) ; 0.292 ^(e) ; 0.293 ^(f)	2.621	2.639 ^(c) ; 2.639 ^(d) ; 2.630 ^(e) ; 2.621 ^(f)
<u>Battery Vehicle</u>							
Lithium-aluminum/iron sulfide	93.1	23.8	0.256	0.324	0.316 ^(g) ; 0.300 ^(h)	0.790	0.810 ^(g) ; 0.853 ^(h)

(1) Recharge Energy:
Hydrogen refill weight in lb = C x Capacity; C = 0.90 and 0.95 for liquid hydrogen in 1985 and later, respectively; C = 0.80 for iron-titanium hydride in 1985; C = 0.90 for all hydrides in 1990 and 2000.
Energy from charger in kWh = depth of discharge x capacity/battery efficiency.

(2) Nonessential energy storage = 10% of directly transmitted energy.

(3) Storage and distribution options:
(a) Liquid hydrogen tank; (b) Liquid hydrogen tank and truck distribution; (c) Underground; (d) Linepack; (e) Pressure vessel; (f) Metal hydride;
(g) Batteries; (h) Electrolytic hydrogen stored in hydride until used to fuel turbogenerator.

TABLE 5-27. 2000 MODEL YEAR VEHICLE ENERGY COMPARISONS -
ENERGY SOURCE: NUCLEAR (HIGH TEMPERATURE,
GAS-COOLED REACTOR, BOTTOMING CYCLE)

Vehicle Type	Design Range, mi	Recharge Energy ⁽¹⁾	Vehicle Energy/mi kWh/mi	Source-Vehicle Input Energy Efficiency		Source Energy/Vehicle Mile	
				W/O Storage	W/Storage ⁽²⁾⁽³⁾	W/O Storage kWh/mi	W/Storage kWh/mi ⁽³⁾
<u>Hydrogen Vehicles</u>							
Liquid Hydrogen Pipeline	85	2.47	0.439	0.290	0.288 ^(a) ; 0.270 ^(b)	1.514	1.514 ^(a) ; 1.626 ^(b)
Marine				-	0.270 ^(b)	-	1.626 ^(b)
Rail				-	0.270 ^(b)	-	1.626 ^(b)
Truck				0.275	0.274 ^(b)	1.596	1.602 ^(b)
Advanced Hydride (Gaseous Hydrogen Pipeline)	85	4.32	0.768	0.357	0.363 ^(d) ; 0.365 ^(e) 0.366 ^(f)	2.093	2.116 ^(d) ; 2.104 ^(e) 2.098 ^(f)
<u>Battery Vehicle</u>							
Lithium-aluminum/iron sulfide	93.1	23.8	0.256	0.405	0.395 ^(g) ; 0.375 ^(h)	0.632	0.648 ^(g) ; 0.683 ^(h)

(1) Recharge Energy:
Hydrogen refill weight in lb = C x Capacity; C = 0.90 and 0.95 for liquid hydrogen in 1985 and later, respectively; C = 0.80 for iron-titanium hydride in 1985; C = 0.90 for all hydrides in 1990 and 2000.
Energy from charger in kWh = depth of discharge x capacity/battery efficiency.

(2) Nonessential energy storage = 10% of directly transmitted energy.

(3) Storage and distribution options:
(a) Liquid hydrogen tank; (b) Liquid hydrogen tank and truck distribution; (c) Underground; (d) Linepack; (e) Pressure vessel; (f) Metal hydride;
(g) Batteries; (h) Electrolytic hydrogen stored in hydride until used to fuel turbogenerator.

A broader picture of overall source energy consumption is seen by disregarding the effects of energy storage and the multiplicity of transportation options and focusing on the most efficient use of each energy source in satisfying the energy needs of each vehicle. This comparison is presented in Table 5-28. As previously noted, petroleum and shale oil resources were evaluated considering usage in electric power plants, so they appear most suitable for EV's. However, with hydrogen production efficiencies between those of natural gas and coal, these resources would, in 1985, be better suited to supplying hydrogen to iron-titanium GSHV's. In 1990 they would be more efficiently applied to any of the HV's than to the zinc/chlorine EV. In the year 2000, however, all energy sources are most efficiently used if applied to electricity generation for the lithium-aluminum/iron sulfide EV.

5.6

VEHICLE COMPARISON SUMMARY

Table 5-29 is the final summary comparison of all vehicles investigated. Key characteristics of all minimum design range vehicles are presented along with the implications of increasing the range to 200 mi. Principal features projected for each vehicle type considered in this study are presented in the following sections.

5.6.1

Liquid Hydrogen-Fueled ICE Cars

These vehicles are always the lightest, have the lowest total cost of ownership, are the most suitable for design ranges above the minimum, and have the lowest source energy consumption for the 1990 model year. Because of their small engine size, they are best suited for higher engine horsepower, if desired. The need for heating of the liquid hydrogen to gasify or heat it provides an opportunity for a simple, lightweight air conditioning system.

TABLE 5-28. COMPARISON OF OVERALL SOURCE ENERGY CONSUMPTION
VERSUS VEHICLE TYPE - MINIMUM DESIGN RANGE

Propulsion System	Vehicle Input Energy/ mi kWh/mi ⁽¹⁾	Overall Source Energy Expenditure/Vehicle Mile, kWh/mi ^{(2), (3)}							
		Coal (Hydrogen, Electricity)	Nuclear (Electricity) ⁽⁴⁾	Natural Gas (Hydrogen, Electricity)	Petroleum & Shale Oil (Electricity)	Hydro & Geothermal (Electricity)	Wind (Electricity)	Solid Waste (Electricity)	Solar Electricity ⁽⁵⁾
<u>1985 Model Year</u>									
Liquid Hydrogen ICE	0.768	2.059	4.800	1.587	3.821	1.749	3.718	5.948	7.826
Iron-Titanium Hydride ICE	0.868	1.797	4.173	1.382	3.326	1.523	3.236	5.178	6.813
Lead/Acid Battery	0.690	2.300	2.749	2.184	2.184	1.001	2.694	3.405	4.480
Nickel/Zinc Battery	0.557	1.856	2.219	1.763	1.763	0.808	1.718	2.749	3.617
<u>1990 Model Year</u>									
Liquid Hydrogen ICE	0.525	1.265	2.793	1.078	2.365	1.085	2.305	3.688	4.853
Iron-Titanium Hydride ICE	0.736	1.376	3.041	1.172	2.573	1.179	2.506	4.010	5.277
Advanced Hydride ICE	0.913	1.706	3.773	1.454	3.192	1.463	3.109	4.975	6.546
Zinc/Chlorine Hydrate Battery	0.521	1.735	1.951	1.649	1.649	0.756	1.607	2.571	3.383
<u>2000 Model Year</u>									
Liquid Hydrogen ICE	0.439	0.994	1.892 1.514	0.885	1.942	0.890	1.892	3.028	3.984
Advanced Hydride ICE	0.768	1.372	2.621 2.093	1.223	2.685	1.231	2.615	4.185	5.506
Lithium-Aluminum/Iron Sulfide Battery	0.256	0.852	0.790 0.632	0.810	0.810	0.372	0.790	1.263	1.662

- (1) Minimum Range = 85 mi for hydrogen-powered vehicles. For battery-powered vehicles, minimum range of 64.2 to 111.1 mi is established by power requirements, cycle life, and number of batteries needed to achieve vehicle lifetime mileage of 100,000 mi.
- (2) Neglects storage capability in energy transportation.
- (3) Terms in parentheses indicate initial energy conversion product. Where two energy products are indicated, the most efficient is chosen for each vehicle type.
- (4) Nuclear electricity generation efficiencies in 2000 are assumed to be 0.40 (Simple Turbine Cycle) and 0.50 (Bottoming Turbine Cycle).
- (5) Solar energy conversion by a central receiver of reflected energy, with a steam turbine is assumed to have an efficiency of 0.19.

TABLE 5-29. COMPARISON OF KEY CHARACTERISTICS OF HYDROGEN- AND BATTERY-POWERED CARS

Propulsion System	Design Range mi	Usefulness % of Days	Curb Weight lb	Total Cost of Ownership ¢/mi	Vehicle Input Energy kWh/mi	Source Energy/ Vehicle Mile kWh/mi		Wheelbase Increase Over Gasoline ICE Car, in.	Effects of Range Increase to 200 mi.		
						Coal	Nuclear		Curb Wt Increase lb	Ownership Cost Increase ¢/mi	Wheelbase Increase in.
<u>1985 Model Year</u>											
Liquid Hydrogen ICE	85	95.1	2220	13.0	0.768	2.059	4.800	3.5	180	0.6	5.0
Iron-Titanium Hydride ICE	85	95.1	2940	16.4	0.868	1.797	4.173	4.8	2060	12.5	11.2
Lead/Acid Battery	64.2	91.3	4718	18.1-21.5	0.690	2.300	2.749	26.1	Practically Impossible		
Nickel/Zinc Battery	80.8	94.6	3499	17.8-21.6	0.557	1.856	2.219	18.4	Practically Impossible		
<u>1990 Model Year</u>											
Liquid Hydrogen ICE	85	95.1	2100	12.2	0.525	1.265	2.793	2.3	110	0.5	3.3
Iron-Titanium Hydride ICE	85	95.1	2740	14.7-15.3	0.736	1.376	3.041	3.0	1245	6.4-7.7	6.2
Advanced Hydride ICE	85	95.1	2665	15.3-15.4	0.913	1.706	3.773	6.8	1015	6.0	12.5
Zinc/Chlorine Hydrate Battery	111.1	96.5	3253	16.0-19.2	0.521	1.735	1.951	23.1	3450		48
<u>2000 Model Year</u>											
Liquid Hydrogen ICE	85	95.1	1895	11.7	0.439	0.994	1.892 - 1.514	2.0	95	0.5	2.7
Advanced Hydride ICE	85	95.1	2340	14.4	0.768	1.372	2.621 - 2.093	5.5	800	4.9-5.0	10.6
Lithium-Aluminum/Iron Sulfide Battery	93.1	96.0	2149	11.6-13.6	0.256	0.852	0.790 - 0.632	8.6	1570		17

5.6.2 Gaseous Hydrogen-Fueled ICE Cars

On balance, the iron-titanium alloy and advanced-magnesium alloy hydride systems are comparable, except for the better use of coal energy by iron-titanium vehicles. A simple, lightweight air conditioning system is also an inherent capability of the iron-titanium hydride system. Neither hydride system is competitive in the 2000 model year.

5.6.3 Lead/Acid Battery-Powered Car

This vehicle has the highest weight, greatest length, highest cost of ownership, lowest usefulness, highest source energy consumption, and is least adaptable to range extension.

5.6.4 Nickel/Zinc Battery-Powered Car

This vehicle has a high weight, high length, high cost of ownership, and limited range extendability. However, it makes the best use of nuclear energy or other electric energy sources in 1985.

5.6.5 Zinc/Chlorine Hydrate Battery-Powered Car

This vehicle is characterized by high minimum range, weight, length, and cost of ownership. It has poor adaptability to range extension; however, it makes the best use of nuclear energy or electric energy sources in 1990. The vehicle accommodates a simple, lightweight air conditioning system option.

5.6.6 Lithium-Aluminum/Iron Sulfide Battery-Powered Car

This vehicle is lightweight, moderate in length, low in ownership cost, and moderately adaptable to range extension. Its primary advantages are outstanding values of vehicle energy economy and utilization of all energy resources.

The authors believe there is a generally uniform degree of optimism in the assumptions underlying the performance projected for each vehicle system considered in this report; however, the energy subsystem that probably appears most favorably treated is the model year 2000 lithium-aluminum/iron sulfide battery. Since no substantiation was offered for the battery's assumed 20-percent improvement of all major parameters relative to its 1990 counterpart, it was felt to be helpful to determine the impacts of more conservative assumptions. Therefore, the minimum range vehicle characteristics were obtained assuming that specific energy and specific power were improved only 10 percent (equivalent to a 10-percent weight reduction), and that cycle life, energy efficiency, and specific cost remained the same. The following changes, relative to the tabulated model year 2000 lithium-aluminum/iron sulfide battery car, were determined:

1. A 19.3-percent increase in design range due to a 16.7-percent reduction in cycle life
2. A 42.7-percent increase in battery weight due to the increase in design range (item 1), to an 8.6-percent reduction in specific energy (watt hours per kilogram), and to a 13.1-percent increase in vehicle test weight (a 15.0-percent increase in curb weight)
3. A 31.2-percent increase in energy expenditure per unit distance due to the increases in design range and battery weight (items 1 and 2, respectively) and a 16.7-percent reduction in battery efficiency
4. A 3.4-percent increase (3.6 in.) in vehicle wheelbase due to the larger battery
5. A 15.3- to 17.4-percent increase in vehicle purchase price assuming the same battery specific costs (\$40 and \$60/kWh)
6. A 10- to 13-percent increase in cost of ownership (1.2¢ to 1.8¢/mi) depending on battery specific cost and power cost.

Consequently, compared to the LSHV's and advanced hydride HV's of the year 2000, the conservative lithium-aluminum/iron sulfide EV is the heaviest, longest, most range sensitive, and possibly the most costly

to own. However, it retains a significant advantage in input energy per mile, a pronounced advantage in the effective use of all electric energy sources, and has an effectiveness between the values for the HV's in the use of coal resources.

5.6.7 Regenerative Braking and Accessory Power Effects

The EV's have an advantage over engine driven vehicles in the ease with which they can accommodate regenerative braking. Such braking is a practical means for increasing the minimum range by up to 8 to 13 percent depending upon the type of battery and the vehicle technology level (a function of the year). However, all EV's suffer substantial range loss (14 to 25 percent at minimum design range depending upon the same factors) at an accessory power level of 2.5 kW, which could easily be required when heating is needed.

5.7 CONCLUSIONS

The low energy density of the battery and hydrogen energy storage systems considered in this study, compared to that of a gasoline-filled tank, leads to vehicle weights substantially greater than those of gasoline-fueled vehicles of the same passenger capacity at all times. A portion of the increase in vehicle weight results from the increase in vehicle length required to accommodate the volume of the energy storage system. As design range is increased, vehicle weight for the options considered in the study increases much faster than is the case for a gasoline-fueled vehicle.

This study of four-passenger HV's and EV's has shown that, in the period from 1985 to 2000, vehicles using liquid hydrogen energy storage would be the lightest, least range sensitive, and least expensive to own. Only the LSHV exhibits acceptable weight, length, and ownership cost increases at ranges over 200 mi. However, there is substantial concern for

the safety aspects of the fueling, operation, and garaging of such vehicles. A great expansion of the infrastructure for producing, transmitting, and distributing liquid hydrogen would be needed with its associated high capital outlays and long time delays.

Although EV's at minimum design ranges are heavier than HV's, and therefore have higher road loads, their superior propulsion efficiencies result in the lowest vehicle input energy per mile of vehicle travel. For fossil energy sources, however, the overall efficiency of the logistic chains for supplying the cars with hydrogen (via gasification) or electricity strongly favors HV's. This study indicates that the combination of these two factors, which constitute the source energy expenditure per vehicle mile, shows decided advantages for HV's in 1985 and 1990 when making best use of fossil fuels. By 2000, however, short range EV's are projected to have such an advantage in input energy per mile that they will make better use of every energy resource than HV's. They will remain bulkier and more sensitive to requirements for increased range, speed, and acceleration.

The greatest drawback to the use of liquid hydrogen in cars is the uncertainty regarding safety hazards — not the commonly cited energy losses or added costs associated with liquefaction, which have been shown to be more than offset by the advantageous physical and performance characteristics of LSHV's. Additional study is warranted regarding the safe fueling, operation, garaging, and maintenance of such passenger cars; their susceptibility to damage in collisions; and the consequences of substantial liquid hydrogen spills under various degrees of fuel confinement.

The production of hydrogen by electrolysis, with efficiencies of 79 to 87 percent for industrial equipment or 60 to 75 percent estimated for residential units, is a less efficient (and more costly) use of electricity from any energy source than the efficient charging of EV's. However, other considerations, such as transmission of energy over long distances (more than 1000 mi) or over water from nuclear energy islands, or superior vehicle operating characteristics, could favor generation of electrolytic hydrogen over electricity.

5.8

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APPENDIX A

DRIVING CYCLE ANALYSIS OF LOSSES AND HORSEPOWER REQUIREMENTS

A.1 ASSUMPTIONS

1. Cycles typically correspond to level roads, so disregard grade term in power and energy equations.
2. Drag resistance force of tires is linear with velocity but may be considered constant and proportional to vehicle weight. Disregard losses associated with turning, accelerating, braking, and transverse aerodynamic loading of vehicle.
3. Aerodynamic drag force is proportional to relative wind velocity squared and drag coefficient, which may be assumed constant. Wind effects at high speeds can be quite important, particularly crosswinds. For commuter and urban cycles, wind effects are disregarded, and aerodynamic drag force is assumed proportional to vehicle speed squared and acting opposite to the direction of motion. It is further assumed that vehicle performance is measured at sea level on a standard day with a temperature of 60°F.

A.2 KINETIC ENERGY TERMS OR INERTIA LOSSES

$$\text{Horsepower} = \frac{maV}{375} + \frac{\sum_0^n (I\omega)_n}{375}$$

where V is in mph.

Linear acceleration a , angular acceleration α , and rotational rate ω are interrelated by the gear ratios of the transmission and drive axle, and the tire diameter. A multispeed gear box is often provided in an electric vehicle (EV) as in conventional vehicles. The inertia elements -- motor, transmission, drive shaft, wheels, and tires, primarily -- are matters of

designer's choice and have no fixed relationship to the mass of the vehicle. However, for a simplified analysis, assume that the rotational inertia horsepower is always equal to 10 percent of the linear acceleration horsepower. The speed-time relationships for most driving cycles are assumed to have constant slopes, which is unrealistic but easier to analyze. For the Society of Automotive Engineers (SAE) J227a driving cycles, the linear speed buildup vs time is intended for evaluation of the electric powertrain system.

For constant and negative slopes, the so-called inertia loss power or required acceleration power is zero. Negative slopes associated with coasting and braking of the vehicle involve variable braking force or torque, since aerodynamic and tire drag forces are also acting.

Positive acceleration energy is most readily evaluated from the kinetic energy change

$$\Delta KE = \frac{1}{2} m(V_2^2 - V_1^2)$$

For the SAE J227a Schedule D driving cycle, the acceleration phase is a linear increase in speed from zero to 45 ± 1.0 mph in 28 ± 2 sec. The average acceleration is 1.607 mph/sec or 2.357 ft/sec^2 . Allowing 10 percent for rotational inertia, the total inertia energy at 45 mph (66 fps)

$$KE_{\text{peak}} = \frac{1}{2} (1.1) \frac{W}{g} 66^2 = 74.4 W \text{ ft lb}$$

where vehicle weight W is in lb. The peak acceleration horsepower requirement

$$hp_{\text{accel}} = \frac{FV}{550} = 1.1 \frac{WaV}{g(550)} = \frac{1.1(2.357)66 W}{550g} = 0.00966 W$$

To achieve moderate acceleration capability, the engine or electric motor would be sized to provide a peak (transient) horsepower/vehicle weight ratio of up to 0.03. Rated electric motor power may be only one-half to one-third the level computed using this ratio.

A.3 TIRE ROLLING RESISTANCE

The rolling resistance F_r at constant speed on a noncurving road depends primarily on the road surface, tire design and inflation, the weight of the vehicle, and its load distribution, and secondarily on vehicle velocity. The tire power loss is the rolling resistance force times the vehicle velocity. The total tire energy loss is the integral of the resistance force-distance integral

$$\int F_r dS = \int F_r V dt$$

Although tire power loss is sometimes described by a high order equation involving velocity to the fourth power, the limited speed range of interest and the uncertainty of tire improvement projections allow use of constant rolling resistance coefficients C_r

$$F_r = C_r W$$

where $C_r = 0.012$, 0.010 , and 0.008 for 1985, 1990, and 2000, respectively.

$$hp_r = \frac{F_r V}{550}$$

where F_r is in lb and V is in fps. Energy loss is

$$E_r = \int C_r W V dt = C_r W \int V dt$$

Energy losses occur in the tires whenever the vehicle is moving:

- a. During the constant acceleration phase ($V = at$)

$$E_r = C_r a W \int t dt = \frac{C_r a W t^2}{2}$$

$$E_r = \frac{66(28)}{2} C_r W = 924 C_r W \text{ ft lb}$$

over the 924-ft distance.

- b. During the 50-sec cruise phase ($V = 66 \text{ fps}$)

$$E_r = 66(50) C_r W = 3300 C_r W \text{ ft lb}$$

over the 3300-ft distance.

- c. During the 10-sec coast phase, the velocity varies with time as a function of the vehicle's aerodynamic and rolling resistance forces and its inertia

$$V_t = V_o - \int (F_D + F_r) \frac{g}{1.1W} dt$$

$$V_t = 66 - \frac{g}{1.1W} \int F_D dt - \frac{C_r}{1.1} gt$$

where the drag force F_D varies with V_t^2

$$E_r = C_r W \int V dt$$

- d. During the 9-sec braking phase the vehicle's velocity drops to zero due to the action of the constant rolling resistance force and the variable aerodynamic and braking forces. The latter may be a combination of regenerative and hydraulic braking efforts. If the braking deceleration is forced to be constant, the energy consumed in rolling resistance can be calculated

$$E_r = \frac{C_r a W t^2}{2} = \frac{V_c^2 9^2 C_r W}{9(2)} = 4.5 V_c^2 C_r W$$

where V_c is the velocity at the end of the coast phase.

A. 4

AERODYNAMIC DRAG

Minimum drag load and energy loss will be evaluated assuming a constant drag coefficient C_D and no winds or precipitation. Evaluation will be made at sea level, standard atmospheric conditions. Drag force

$$F_D = \rho \frac{C_D A V^2}{2} = \frac{(0.0765) C_D A V^2}{(2)(32.2)} = 0.00119 C_D A V^2 \text{ lb}$$

where V is velocity in feet per second, and A is vehicle frontal area in square feet, drag horsepower

$$hp_D = \frac{F_D V}{550} = 2.164 \times 10^{-6} C_D A V^3$$

Energy is expended in overcoming drag whenever the vehicle is in motion.

$$E_D = \int F_D V dt = 0.00119 C_D A \int V^3 dt$$

- a. For the 28-sec constant acceleration phase ($V = at$)

$$E_D = 0.00119 C_D A \left(\frac{66}{28} \right)^3 \frac{t^4}{4} = 2394.8 C_D A \text{ ft lb}$$

- b. For the 50-sec cruise phase

$$E_D = 0.00119 C_D A (66)^3 50 = 17,106 C_D A \text{ ft lb}$$

- c. For the 10-sec coast phase, the vehicle decelerates under the actions of the constant rolling resistance force and the diminishing drag force

$$\frac{dV}{dt} = \frac{-C_r g}{1.1} - \frac{0.00119 C_D A V^2 g}{1.1 W}$$

$$\frac{dV}{dt} = -29.3 C_r - 0.0348 \frac{C_D A V^2}{W}$$

The solution to this equation is

$$V = \sqrt{\frac{29.3 C_r W}{0.0348 C_D A}} \tan \left[\tan^{-1} \left(\frac{V_o}{\sqrt{\frac{29.3 C_r W}{0.0348 C_D A}}} \right) - \sqrt{\frac{29.3 C_r W}{0.0348 C_D A}} \left(\frac{0.0348 C_D A}{W} \right) t \right]$$

The velocity of the end of the coast phase V_c is evaluated using $V_o = 66 \text{ fps}$ and $t = 10 \text{ sec}$.

The energy expended in overcoming aerodynamic drag during the coasting phase is given by

$$E_D = 0.00119 C_D A \int V^3 dt$$

$$= 0.00119 C_D A \left(\frac{29.3 C_r W}{0.0348 C_D A} \right)^{3/2} \int \tan^3(C_1 + C_2 t) dt$$

where

$$C_1 = \tan^{-1} \left(\frac{V_o}{\sqrt{\frac{29.3 C_r W}{0.0348 C_D A}}} \right) \quad \text{and}$$

$$C_2 = - \frac{0.0348 C_D A}{W} \sqrt{\frac{29.3 C_r W}{0.0348 C_D A}}$$

The solution to this equation is given by

$$E_D = 28.791 \frac{C_r W^2}{C_D A} \left[\frac{0.0005938 C_D A V_o^2}{C_r W} \right.$$

$$- 0.5 \tan^2(C_1 + C_2 t)$$

$$\left. - L_n \left(\frac{\cos(C_1 + C_2 t)}{\cos C_1} \right) \right] \text{ ft lb}$$

The rolling resistance energy expended during the coast phase is the constant rolling resistance force times the coast distance D_c .

$$E_r = C_r W \int V dt = C_r W D_c$$

$$D_c = \sqrt{\frac{29.3 C_r W}{0.0348 C_D A}} \int \tan[\tan^{-1} C_1 + C_2] dt$$

The solution to the latter equation is

$$D_c = \frac{W}{0.0348 C_D A} L_n \left(\frac{\cos(C_1 + C_2 t)}{\cos C_1} \right) \text{ ft.}$$

Therefore,

$$E_r = \frac{C_r W^2}{0.0348 C_D A} L_n \left(\frac{\cos(C_1 + C_2 t)}{\cos C_1} \right) \text{ ft. lb}$$

- d. During the 9-sec braking phase, the deceleration a_b is assumed to be constant.

$$a_b = \frac{-V_c}{9} \text{ ft per sec}^2$$

The distance traveled is

$$D_b = \frac{1}{2} a_b t^2 = 4.5 V_c \text{ ft}$$

The velocity is simply

$$V_b = V_c \left(1 - \frac{t}{9} \right) \text{ fps}$$

The energy consumed by aerodynamic drag is

$$E_D = 0.00119 C_D A \int v_c^3 \left(1 - \frac{t}{9}\right)^3 dt$$

This reduces to the following for $t = 9$ sec

$$E_D = 0.002678 C_D A v_c^3 \text{ ft lb}$$

The energy consumed in rolling resistance is

$$E_r = C_r W D_b = 4.5 V_c C_r W \text{ ft lb}$$

A. 5

BRAKING

The braking energy required E_b is the total propulsion energy applied to the drive wheels E_p in the acceleration and cruise phases minus the total rolling and aerodynamic drag resistance energies over the driving cycle.

$$E_b = E_p - \sum (E_r + E_D)$$

$$E_p = 74.4 W + 4224 C_r W + 19,501 C_D A \text{ ft lb}$$

Some fraction of the braking energy is potentially recoverable by the use of regenerative braking. The recoverable fraction depends upon the state of battery charge, charge current limits, and the efficiencies of the electrical and mechanical components in this mode. The maximum recoverable fraction of the braking energy is equal to the battery charging efficiency times the overall drivetrain efficiency η_{DT} . The maximum braking energy that could be returned and stored in the battery is approximately

$$E_b \eta_{DT} \sqrt{\eta_{C-D}}$$

where η_{C-D} is the battery charge-discharge efficiency.

The total amount of recovered braking energy that could be put back into the drivetrain is

$$E_b \eta_{DT} \eta_{C-D}^{RF}$$

where RF is a recovery factor depending upon state of battery charge, current limits, and reduction of component efficiencies in this variable speed mode.

APPENDIX B

ELECTRIC VEHICLE RANGE ESTIMATION

The energy output of an on-board or stationary battery charger ultimately satisfies the propulsion requirements, the auxiliary power requirements (unless a separate fueled heater is provided), and all energy losses in the system. The battery initially stores the charger output E_{charger} diminished by the battery's charging efficiency η_C .

$$E_{\text{charger}} \eta_C = \Delta E_{\text{battery}} = \text{energy increment stored in the battery}$$

A fully charged battery can deliver an amount of its stored energy $E_{\text{charger}} \eta_C$ diminished by its discharge efficiency η_D . This capacity divided by battery weight W_{battery} defines the battery specific energy SE

$$SE = \frac{E_{\text{charger}} \eta_C \eta_D}{W_{\text{battery}}} = \frac{\text{capacity}}{W_{\text{battery}}}$$

where $\eta_C \eta_D = \eta_{C-D}$.

Over the design range R of the vehicle consisting of n driving cycles of distance D, the battery will deliver an amount of its stored energy limited by the chosen depth of discharge DOD. The energy from the battery is

$$W_{\text{battery}} \times SE \times DOD$$

where DOD is the battery design output energy/battery capacity.

Braking of electric vehicles (EV's) can be done, at least partially, by using the drivetrain components and returning a portion of the

energy to the battery for reuse. The amount of such energy that can be subsequently removed from the battery is

$$\Delta E_{\text{battery regen.}} = E_b n \eta_{DT} \eta_{C-D} RF$$

where

E_b = theoretical braking energy required per driving cycle

n = number of driving cycles corresponding to the design range

η_{DT} = overall drivetrain efficiency from controller input to drive wheels

RF = energy recovery factor recognizing voltage and current limits, reduced charging efficiency, and reductions in drivetrain efficiency with reversed torques and current flow.

The EV propulsion energy requirement from the battery over the design range is

$$E_p n / \eta_{DT}$$

where E_p is the propulsion energy required per cycle at drive wheels. The auxiliary power loads supplied by the main or an auxiliary battery are assumed to be constant and consume an amount of energy equal to

$$E_{ap} n$$

where E_{ap} is the average auxiliary power level times driving cycle time. The overall energy balance over the design range R is

$$W_{\text{battery}} \times SE \times DOD + E_b n \eta_{DT} \eta_{C-D} RF = \frac{E_p n}{\eta_{DT}} + E_{ap} n$$

Substituting $R = nD$

$$\frac{R}{D} \left[\frac{E_p}{\eta_{DT}} + E_{ap} - E_b \eta_{DT} \eta_{CD}^{RF} \right] = W_{battery} \times SE \times DOD$$

$$R = \frac{W_{battery} \times SE \times DOD \times D}{\frac{E_p}{\eta_{DT}} + E_{ap} - E_b \eta_{C-D} \eta_{DT}^{RF}}$$

APPENDIX C

SIZING AND RANGE ESTIMATION PROCEDURE FOR HYDROGEN-POWERED CAR

This appendix provides an illustrative calculation such as was done for each vehicle design point where a direct (cylinder) injection (DI), spark-ignited engine was used. Calculation of naturally aspirated engine characteristics is an essential step in this procedure before correction for DI effects on displacement and efficiency. Therefore, the simpler procedure for naturally aspirated hydrogen vehicles (HV's) is also illustrated.

The procedure starts with the basic design choices for the engine and energy storage system for a four-passenger car and an arbitrarily selected weight of stored hydrogen. Values of weight, power, size, efficiency, and propulsion energy all derive directly from these choices, permitting computation of vehicle design range.

C.1 VEHICLE DESIGN CHOICES

Model year: 1990

Hydrogen source: iron-titanium hydride

Engine type: DI

Hydrogen temperature entering compressor: 80°F

C.2 VEHICLE WEIGHT AND SIZE

W_H , weight of hydrogen in vehicle: 5 lb

W_{HU}/W_H , fraction of hydrogen usable for propulsion: 0.90

Constants in equation for W_5 from final table in Appendix E:

$$A_5 = 0$$

$$B_5 = 111.7$$

W_5 , energy storage dependent weight = $A_5 + B_5 W_H$: 558 lb

W_1 , occupant compartment structural weight: 1160 lb

Constants in equation for weight of engine and transmission from first table in Appendix E:

$$A_3 = 370 \text{ lb}$$

$$B_3 = 2.30 \text{ lb/in}^3 \text{ of displacement}$$

$$K = 0.92 \text{ in}^3/\text{hp}$$

$$W_1 + 135 + A_3 + 300 B_3 K (\text{hp}/\text{WT}) + A_5 + B_5 W_H: 2238 \text{ lb}$$

$$0.85 - B_3 K (\text{hp}/\text{WT}): 0.8013$$

$$W_{\text{curb}}, \text{ vehicle curb weight: } 2238/0.8013 = 2793 \text{ lb}$$

$$\text{WT, vehicle test weight} = W_{\text{curb}} + 300: 3093 \text{ lb}$$

$$W_{E4}/W_H, \text{ vehicle weight increment per pound of hydrogen: } 15$$

$$\Delta l, \text{ vehicle length increase over gasoline car} = W_{E4}/22.2: 3.4 \text{ in.}$$

C.3

DESIGN POINT: MAXIMUM BRAKE MEAN
EFFECTIVE PRESSURE @ 45 MPH

$$C_r, \text{ vehicle rolling resistance coefficient: } 0.010$$

$$C_D A, \text{ vehicle aerodynamic resistance product: } 7 \text{ ft}^2$$

$$\text{hp}_W, \text{ driving cycle peak hp @ wheels (from Figure 5-3 in Section 5): } 37.9 \text{ hp}$$

$$\eta_{DL}, \text{ drivetrain efficiency: } 0.90$$

$$\text{Bhp}_R, \text{ required engine brake horsepower} = \text{hp}_W/\eta_{DL}: 42.11 \text{ hp}$$

$$\text{Bhp}_{\text{design}}, \text{ design engine Bhp} = 1.2 \times \text{Bhp}_R: 50.53$$

$$\text{CR, compression ratio: } 14:1$$

$$\phi, \text{ equivalence ratio} = \text{fuel-air ratio/stoichiometric fuel-air ratio: } 1.0$$

Assuming naturally aspirated engine:

IMEP_i, ideal indicated mean effective pressure (from Figure 3-26 in Section 3): 207 psi

IMEP, actual IMEP = 0.75 IMEP_i: 155.3 psi

η_{Ti} , ideal thermal efficiency (from Figure 3-26 in Section 3): 0.495

η_T , actual thermal efficiency = 0.75 η_{Ti} : 0.371

PS, mean piston speed = 2600 fpm $\times$ 45 mph/70 mph: 1671 fpm

cid, displacement = $678.6 (PS/N)^3 = (14,684/N)^3 \text{ in}^3$ for four-cylinder engine with bore = stroke

N, engine speed = $792,000 \text{ Bhp} / \eta_M \text{ IMEP (cid)}$

$$= \sqrt{\frac{\eta_M \text{ IMEP } (14,684)^3}{792,000 \text{ Bhp}}} = 2000 \sqrt{\frac{\eta_M (\text{IMEP})}{\text{Bhp}}}, \quad \text{rpm}$$

Estimated η_M , mechanical efficiency from the Society of Automotive Engineers (SAE) J816b (Table 1): 0.858

BMEP, brake mean effective pressure = $\eta_M (\text{IMEP})$: 133.2 psi

N: 3247 rpm

η_M from SAE J816b (Table 1): 0.858

cid = $(14,684/N)^3$: 92.5 in³

η_{BT} , brake thermal efficiency = $\eta_T \eta_M$: 0.319

Corrections for DI engine (from Table 5-7 in Section 5):

C_1 , relative displacement at given hp = $\text{cid}_{DI} / \text{cid}_{NA}$: 1.000/1.444 = 0.692

cid: 64.0 in³

C_1 , relative thermal efficiency = η_{TDI} / η_{TNA} : 0.976

C_2 , relative mechanical efficiency = η_{MDI} / η_{MNA} : 1.062

$\eta_{BT} = C_1 C_2 \eta_{BTNA}$: 0.3302

C.4

PEAK CYCLE HORSEPOWER POINT @ 45 MPH

Bhp_R : 42.11 hp

Assuming naturally aspirated engine:

$BMEP = 792,000 Bhp_R / N \text{ (cid): } 111.0 \text{ psi}$

η_M from SAE J816b (Table 1): 0.829

$IMEP = BMEP / \eta_M$: 133.9 psi

$IMEP_i = IMEP / 0.75$: 178.5 psi

ϕ (from Figure 3-26 in Section 3): 0.75

η_{Ti} : 0.52

$\eta_T = 0.75 \eta_{Ti}$: 0.390

η_{BT} : 0.323

Corrections for DI engine (from Table 5-7 in Section 5)

C_1 : approximately 0.976

C_2 : approximately 1.062

$\eta_{BT} = C_1 C_2 \eta_{BTNA}$: 0.335

η_{PT} , powertrain efficiency = drivetrain efficiency $\times \eta_{BT}$:
 $0.90 \times 0.335 = 0.302$

C.5

MAXIMUM ENGINE HORSEPOWER CAPABILITY
 @ 70 MPH (ASSUMED MAXIMUM SPEED
 WITHOUT OVERDRIVE)

$\phi = 1.0$

Assuming naturally aspirated engine:

η_T : 0.371

$IMEP$: 155.3 psi

$N = N @ 45 \text{ mph} \times 70/45$: 5051 rpm

Estimated η_M : 0.778

$$\text{BMEP} = \eta_M \text{IMEP}: 120.8 \text{ psi}$$

$$\eta_M \text{ from SAE J816b (Table 1): } 0.778$$

$$\text{Bhp} = \text{BMEP (N) cid}/792,000: 71.3 \text{ hp}$$

$$\eta_{BT} = \eta_T \eta_M: 0.289$$

Corrections for DI engine (from Table 5-7 in Section 5):

$$C \approx 0.98 \times C @ 45 \text{ mph}: 0.98 \times 0.692 = 0.678$$

$$C_1: 0.976$$

$$C_2 \approx 1.02 \times C_2 @ 45 \text{ mph}: 1.02 \times 1.062 = 1.083$$

$$\text{Bhp} \approx 1.02 \times \text{Bhp}_{NA}: 72.7 \text{ hp}$$

$$\eta_{BT} = C_1 C_2 \eta_{BTNA}: 0.305$$

$$\text{Bhp}/\text{WT}: 0.0235$$

$$K = \text{cid}/\text{Bhp}: 64.0/72.7 = 0.880 \text{ in}^3/\text{hp}$$

C.6

DRIVING CYCLE

$$\eta_{PT}, \text{ average powertrain efficiency} \approx 0.85 \times \eta_{PT} @ \text{ cycle peak}: \\ 0.85 \times 0.302 = 0.257$$

$$E_P, \text{ propulsion energy/cycle @ wheels (from Figure 5-4 in Section 5): } 0.186 \text{ kWh}$$

$$W_H/\text{cycle}, \text{ hydrogen consumed/cycle} = E_P/15.12 \eta_{PT}: 0.0479 \text{ lb}$$

$$D, \text{ cycle distance (from Figure 5-4 in Section 5): } 0.9702 \text{ mi}$$

$$W_{HU}, \text{ hydrogen weight usable for propulsion} = W_H \times W_{HU}/W_H: \\ 5.0 \times 0.90 = 4.5 \text{ lb}$$

$$R, \text{ vehicle design range} = W_{HU} \times D/(W_H/\text{cycle}): 91.1 \text{ mi}$$

$$U, \text{ usefulness (from Figure 5-4 in Section 5): } 95.7 \text{ percent of days of year}$$

APPENDIX D

WEIGHT OF BATTERY-POWERED CAR

Subsection 5.2 presented the methodology of vehicle weight estimation as derived for hydrocarbon-powered, internal combustion engine (ICE) cars in Reference D-1,¹ and summarized the modifications made to the vehicle curb weight estimation equations for applicability to electric vehicles (EV's) and hydrogen vehicles (HV's). This appendix provides for EV's, the specific equations used in estimating horsepower and weights, and the propulsion efficiency values selected for the years 1985, 1990, and 2000. It also provides a discussion of the many differences in vehicle hardware relative to the baseline ICE car, which led to the estimates for the EV.

D.1 CALCULATION OF HORSEPOWER AND TEST WEIGHT

The curb weight $W_{\text{curb EV}}$ is the sum of the occupant compartment structural weight W'_1 , the suspension, steering, and braking system structural weight W'_2 , the electrical equivalent of the engine/transmission system structural weight W'_3 , and the energy storage dependent weight W_5

$$W_{\text{curb(EV)}} = W'_1 + W'_2 + W'_3 + W_5$$

Due to the interrelationship of the terms, the form used to evaluate the ICE curb weight

$$W_{\text{curb(ICE)}} = \frac{W_1 + B_2 W_4 + A_3 + B_3 K \times \frac{\text{hp}}{\text{WT}} \times 300}{1 - B_2 - B_3 K \times \frac{\text{hp}}{\text{WT}}}$$

will be used, with modification, to represent the EV

¹ The Report by the Federal Task Force on Motor Vehicle Goals Beyond 1980, Vol. II, Task Force Report, Draft (2 September 1976).

$$W_{\text{curb(EV)}} = \frac{W_1' + B_2' W_4 + A_3' + 300 K_0 K_1 + W_5}{1 - B_2' - K_0 K_1}$$

where

$$W_1' = W_1 + \Delta W_1; \Delta W_1 \text{ was found to be negligible, so}$$

$$W_1' = W_1 = 1160 \text{ lb for weight-conscious design in 1985 and 1990 model years, and 1000 lb for innovative design in 2000 model year.}$$

$$B_2' = B_2 + \Delta B_2; \Delta B_2 = 0, \text{ so}$$

$$B_2' = B_2 = 0.15$$

$$W_4 = \text{weight of full load of passengers and options} = 900 \text{ lb}$$

$$A_3' = A_3 + \Delta W_3$$

$$A_3 = 310 \text{ lb for ICE}$$

$$\Delta W_3 \text{ was found to be approximately } -335 \text{ lb, so}$$

$$A_3' = -25 \text{ lb}$$

$$K_0 = \text{electric motor and controller specific weight} \approx 4.6 \text{ lb/rated hp, including wiring}$$

$$K_1 = \text{rated motor hp/vehicle test weight}$$

$$= \frac{\text{hp}_R}{WT}$$

$$W_5 = \text{weight of batteries, on-board charger, thermal control provisions, and weight increment associated with the battery volume requirement, discussed in Subsection D.2}$$

Rated motor horsepower is that which satisfies the vehicle road load under 60 mph level cruise conditions

$$\text{hp}_R = \text{hp}_{\text{wheels}} \times \frac{\eta_{M/C}}{\eta_{DT}}, \text{ evaluated at 60 mph cruise}$$

$$\begin{aligned} \text{hp}_{\text{wheels}} &= C_r \text{WT} \frac{(88)}{550} + 2.164 \times 10^{-6} C_D A (88)^3 \\ &= 0.160 C_r \text{WT} + 1.4747 C_D A \end{aligned}$$

$\eta_{M/C}$ = motor/controller efficiency = 0.85, 0.86, and 0.88 for 1985, 1990, and 2000, respectively

η_{DT} = drivetrain efficiency = 0.72, 0.73, and 0.75 for 1985, 1990, and 2000, respectively.

Substituting into the curb weight equation for the EV

$$W_{\text{curb(EV)}} = \text{WT} - 300 = \frac{W_1 + 0.15(900) - 25 + 300(4.6)K_1 + W_5}{1 - 0.15 - 4.6 K_1}$$

$$K_1 = \frac{\text{hp}_R}{\text{WT}} = \frac{\eta_{M/C}}{\eta_{DT}} \frac{(0.160 C_r \text{WT} + 1.4747 C_D A)}{\text{WT}}$$

$$\text{WT} - 300 = \frac{W_1 + 135 - 25 + 1380 K_1 + W_5}{0.85 - 4.6 K_1}$$

$$\text{WT}(0.85 - 4.6 K_1) = W_1 + 365 + W_5$$

$$0.85 \text{WT} - 4.6 \frac{\eta_{M/C}}{\eta_{DT}} (0.160 C_r \text{WT} + 1.4747 C_D A) = W_1 + 365 + W_5$$

$$\text{WT}(0.85 - 4.6 \frac{\eta_{M/C}}{\eta_{DT}} \times 0.160 C_r) - 4.6 \frac{\eta_{M/C}}{\eta_{DT}} \times 1.4747 C_D A = W_1 + 365 + W_5$$

$$WT = \frac{W_1 + 365 + W_5 + 6.784 \frac{\eta_{M/C}}{\eta_{DT}} C_D A}{0.85 - 0.736 \frac{\eta_{M/C}}{\eta_{DT}} C_r}, \quad lb$$

For 1985 model year cars, typical values would be $C_D A$ is 8 ft^2 and C_r is 0.012

$$\begin{aligned} WT_{1985} &= \frac{1160 + 365 + W_5 + 6.784 \frac{(0.85)}{0.72} 8}{0.85 - 0.736 \frac{(0.85)}{0.72} 0.012} \\ &= \frac{1589 + W_5}{0.8396} \\ &= 1893 + 1.191 W_5, \quad lb \end{aligned}$$

For 1990 model year cars, typical values would be $C_D A$ is 7 ft^2 and C_r is 0.010

$$\begin{aligned} WT_{1990} &= \frac{1160 + 365 + W_5 + 6.784 \frac{(0.86)}{0.73} 7}{0.85 - 0.736 \frac{(0.86)}{0.73} 0.010} \\ &= \frac{1581 + W_5}{0.8513} \\ &= 1879 + 1.189 W_5, \quad lb \end{aligned}$$

For 2000 model year cars, typical values would be $C_D A$ is 6 ft^2 and C_r is 0.008

$$\begin{aligned}
 WT_{2000} &= \frac{1000 + 365 + W_5 + 6.784 \frac{(0.88)}{0.75} 6}{0.85 - 0.736 \frac{(0.88)}{0.75} 0.008} \\
 &= \frac{1413 + W_5}{0.8431} \\
 &= 1676 + 1.186 W_5 \quad , \quad lb
 \end{aligned}$$

D.2

DISCUSSION OF CURB WEIGHT COMPONENTS

The components W'_1 , W'_2 , W'_3 , and W_5 , which constitute the EV curb weight, will be separately discussed using the terminology and component breakdowns of Reference D-1. W_5 is a new term, defined within this appendix.

D.2.1

Occupant Compartment Structural Weight W'_1

Following are the elements that constitute W'_1 and comments on their applicability to an EV.

1. Body and Frame. Configurational changes caused by motor and battery package. The motor/controller (silicon controlled rectifiers) could allow weight reduction. The battery volume requirements are treated in the energy storage dependent weight. Disregard change.
2. Heating, ventilating, and air conditioning. Only 20 lb allowed for heating and ventilating in gasoline-powered vehicle for fan, ducting, heater, hose, and valves. Assume motors, controls, and some batteries require forced cooling (Ref. D-2).² This will satisfy some heating requirements if suitably ducted into compartment. Add insulation, radiant heat panels, and in-seat heating coils. Assume these provisions add 30 lb to the system and require 0.5 kW of electrical input from the batteries, to be considered in sizing battery. (Ford, Ref. D-2, added 20 lb for blowers.)

²L. R. Foote, et al., Electric Vehicle Systems Study, SR-73-132, Ford Motor Co., Dearborn, Michigan (October 1973).

3. Instruments and electrical distribution. Power plant considerations are not included here. Increase displays by about 15 lb for state-of-charge indicator, temperature indicators for batteries, motor and controller (Ford allowed 15 lb for instrument panel.)
4. Fifty percent of battery and alternator. Eliminate alternator, reduce battery capacity to satisfy lighting and standby heating or ventilating only. Let battery be recharged at night with main batteries and receive auxiliary charge from them when required on road. Cut this weight item by 60 percent (retain 20-lb battery).

$$\Delta W = -0.60 \times 0.50 \times 50 = -15 \text{ lb}$$

5. Eight percent of front end sheet metal. Not spelled out in table of Reference D-1. Assume included in body. In place of open radiator grill, add sheet metal. Net effect is negligible, but C_D is improved.
6. Fifty percent of exhaust system. Eliminate entirely

$$\Delta W = -0.50 \times 30 = -15 \text{ lb}$$

7. Twenty percent of fuel system. Eliminate entirely

$$\Delta W = -0.20 (100) = -20 \text{ lb}$$

8. Fifty percent of steering system. No change assumed. The net change in occupant compartment structural weight is

$$\Delta W_1 = +30 + 15 - 15 - 15 - 20 = -5 \text{ lb}$$

This is so small a predicted change it should be disregarded ($\Delta W_1 = 0$).

D.2.2 Suspension, Steering, Braking System Structural Weight W'_2

No change expected for any of the following elements:

1. Suspension, wheels and tires, brakes
2. Fifty percent of steering system
3. Eighty percent of rear axle
4. Twenty percent of front end sheet metal
5. Fifty percent of the transmission and clutch (61 lb and 27 lb, respectively, according to Reference D-2).

D.2.3 Engine/Transmission System Structural Weight W'_3

1. Engine. Eliminate 293-lb engine weight and substitute weight of electric motor and its controller, control logic unit, contactors. (For Reference D-2 allowances, see Table D-1). The electrical weights depend upon motor type, rating, operating speed, possible use of a gear box, and controller type and rating. Wiring harness should be added here rather than in energy storage since it is power-dependent (Reference D-2 allowed 20 lb for cables for 35-hp system).
2. Fifty percent of transmission and clutch. No change.
3. Cooling system. No separate item was listed in Reference D-1, so it must be a part of the engine weight, all of which was removed. Cooling of motor is by integral fan. Controller and battery are cooled by outside air flow, aided by ducted fan when required. This fan also accommodates compartment heating and ventilating, and its weight is included in that part of W_1 .
4. Fifty percent of exhaust system. Eliminate entirely.

$$\Delta W = -0.50 \times 30 = -15 \text{ lb}$$

5. Twenty percent of rear axle. No change assumed.
6. Eighty percent of fuel system and fuel. Eliminate entirely.

$$\Delta W = -0.80 (100) = -80 \text{ lb}$$

7. Fifty percent of battery and alternator. Reduce 15 lb as in W_1 .

The net change in W_3 is

$$\Delta W_3 = -293 + W_m + W_{\text{controller}} + W_{\text{wiring}} - 15 - 80 - 15$$

$$\Delta W_3 = -403 \text{ lb} + W_m + W_{\text{controller}} + W_{\text{wiring}}$$

Remove additional 15 lb for the driveshaft

$$\Delta W_3 \approx -418 + W_m + W_{\text{controller}} + W_{\text{wiring}}$$

TABLE D-1. WEIGHT OF MOTOR AND CONTROLS FROM 1973 FORD MOTOR COMPANY REPORT, lb (Ref. D-2)

Components	35 Horsepower	85 Horsepower
Disc Motor	90	230
Controls	40	60
Contactors	40	40
Choke	45	115
Cutout Switch	<u>8</u>	<u>8</u>
Subtotal	133	223
Cables	20	30

Examination of the data in the table indicates the following approximate relationships:

Motor weight, $W_m \approx 2.6 \times \text{hp}$

Motor control system weight, $W_{\text{cont}} \approx 70 + 1.8 \times \text{hp}$

Cable weight, $W_{\text{wiring}} \approx 13 + 0.2 \text{ hp}$

Total electrical power-dependent weight

$$= 70 + 13 + \text{hp} (2.6 + 1.8 + 0.2)$$

$$= 83 + 4.6 \text{ hp}$$

The net change in W_3 is therefore

$$\Delta W_3 = -418 + 83 + 4.6 \times \text{hp}$$

$$= -335 + 4.6 \times \text{hp}$$

D.2.4

Energy Storage Dependent Weight W_5

W_5 = weight of energy storage system +
additional vehicle weight to provide
storage volume

Energy storage system = batteries + on-board charger + thermal
control provisions, if needed

$$W_5 = W_{E1} + W_{E2} + W_{E3} + W_{E4}$$

Battery weight depends upon the propulsion requirements, the
auxiliary power requirements, and the energy recovered by regenerative
braking. The battery weight W_{E1} is given by

$$W_{E1} = \frac{n}{SE} \left[\frac{E_p}{\eta_{DT}} + E_{ap} - \eta_{C-D} \eta_{DT} E_b RF \right]$$

where

n = number of driving cycles needed to attain the
design range R

SE = battery specific energy, Wh/kg

E_p = propulsion energy per driving cycle measured at the
wheels, kWh

E_{ap} = auxiliary power requirements per cycle, kWh
= power level times cycle duration, kWh

E_b = braking energy required per cycle, measured at the
wheels, kWh

η_{C-D} = battery charge-discharge efficiency

η_{DT} = drivetrain efficiency from input to motor/controller to drive wheels, averaged over the driving cycle

RF = energy recovery factor for the battery recognizing current and voltage limits and reduced efficiencies in drivetrain components in this mode over a wide speed range

W_{E2} = On-board battery charger weight ≈ 2 lb/kWh

W_{E3} = Weight of thermal control provisions if needed to isolate battery from vehicle structure. Assume negligible for ambient and low-temperature batteries but allow 0.5 lb/kWh for high-temperature batteries

W_{E4} = Weight increment for battery storage volume ≈ 37 lb/ft³ of battery volume $\times W_{E1}/\rho_{\text{battery}}$, where ρ_{battery} is battery density in lb/ft³.

APPENDIX E

WEIGHT OF HYDROGEN-FUELED, SPARK-IGNITED ICE CAR

Section 5.2 presented the methodology of vehicle weight estimation as derived for hydrocarbon-powered, internal combustion engines (ICE's) in Reference E-1,¹ and summarized the modifications made to the vehicle curb weight estimation equations for applicability to electric vehicles (EV's) and hydrogen vehicles (HV's). This appendix provides, for HV's, the specific equations used in estimating weights, volumes, and engine displacements for the several alternatives in energy storage systems and engine fuel induction technique. It also provides a discussion of the differences in vehicle hardware relative to the baseline ICE car that led to the estimates for the HV.

E.1 CALCULATION OF TEST WEIGHT

The only change required in the ICE vehicle curb weight equation from the form used for the gasoline-fueled baseline car is the addition of the energy storage dependent weight W_5

$$W_5 = A_5 + B_5 W_H$$

where W_H is the total hydrogen weight capacity, and A_5 and B_5 are constants estimated for different hydrogen storage systems at the conclusion of this appendix. The resulting curb weight equation is

¹ The Report by the Federal Task Force on Motor Vehicle Goals Beyond 1980, Vol. II, Task Force Report, Draft (2 September 1976).

$$\begin{aligned}
W_{\text{curb(HV)}} &= W'_1 + W'_2 + W'_3 + W_5 \\
&= W'_1 + B'_2 (W_{\text{curb}} + W_4) + A'_3 + B'_3 K' \left(\frac{\text{hp}}{\text{WT}} \right) (W_{\text{curb}} + 300) \\
&\quad + A_5 + B_5 W_H \\
W_{\text{curb(HV)}} &= \frac{W'_1 + B'_2 W_4 + A'_3 + 300 B'_3 K' \left(\frac{\text{hp}}{\text{WT}} \right) + A_5 + B_5 W_H}{1 - B'_2 - B'_3 K' \left(\frac{\text{hp}}{\text{WT}} \right)}
\end{aligned}$$

where

$$W'_1 = W_1 + \Delta W_1; \Delta W_1 \text{ was found to be negligible, so}$$

$$W'_1 = W_1 = 1160 \text{ lb for weight-conscious design in 1985 and 1990 model years and 1000 lb for innovative design in 2000 model year}$$

$$B'_2 = B_2 + \Delta B_2; \Delta B_2 = 0, \text{ so}$$

$$B'_2 = B_2 = 0.15$$

$$W_4 = \text{weight of full load of passengers and options} \\ = 900 \text{ lb}$$

$$A'_3, B'_3, \text{ and } K' = \text{engine parameters evaluated in Section E.2.3 of this appendix}$$

$$A_5 = 30 \text{ lb for liquid hydrogen and approximately zero for other storage forms}$$

$$B_5 = 21.2 \text{ for liquid hydrogen}$$

$$= 114.0 \text{ for iron-titanium hydride in 1985 model year}$$

$$= 111.7 \text{ for iron-titanium hydride in 1990 and 2000 model years}$$

$$= 76.0 \text{ for high-temperature hydrides}$$

Substituting into the curb weight equation,

$$W_{\text{curb(HV)}} = \frac{W_1 + 135 + A'_3 + 300 B'_3 K' \frac{\text{hp}}{\text{WT}} + A_5 + B_5 W_H}{0.85 - B'_3 K' \frac{\text{hp}}{\text{WT}}}, \text{ lb}$$

$$\text{WT} = W_{\text{curb}} + 300, \text{ lb}$$

E. 2

DISCUSSION OF CURB WEIGHT COMPONENTS

The components W'_1 , W'_2 , W'_3 , and W_5 , which constitute the HV curb weight, will be separately discussed, using the terminology and component breakdowns of Reference E-1. W_5 is a new term, defined within this appendix.

E. 2. 1

Occupant Compartment Structural Weight W'_1

Following are the elements that constitute W'_1 and comments on their applicability to an HV.

1. Body and frame. The energy storage volume requirements will be treated in the energy storage dependent weight. Disregard change.
2. Heating, ventilating, and air conditioning. If air conditioning is included as a vehicle option, there is no change in weight for this item.
3. Instruments and electrical distribution. Negligible increase to add hydrogen pressure indicator, valve position indicators, and warning lights.
4. Fifty percent of battery and alternator. No change.
5. Eighty percent of front end sheet metal. No change.
6. Fifty percent of exhaust system. Changes will be charged to energy storage weight.
7. Twenty percent of fuel system. Let this represent the water injection system that has been added.
8. Fifty percent of steering system. No change.

The net change in occupant compartment structural weight is

$$\Delta W_1 = 0$$

E.2.2 Suspension, Steering, Braking System Structural
Weight W'_2

No change expected for any of the following elements:

1. Suspension, wheels and tires, brakes
2. Fifty percent of steering system
3. Eighty percent of rear axle
4. Twenty percent of front end sheet metal
5. Fifty percent of the transmission and clutch (61 lb and 27 lb, respectively, according to Reference E-2).²

E.2.3 Engine/Transmission System Structural Weight W'_3

This weight may change in a number of ways for a given horsepower.

$$(W_3 = A_3 + B_3 \times \text{cid})$$

1. New components are substituted for gasoline components. Hydrogen injectors, hydrogen pump or compressor, hydrogen gas cooler or heater, pressure regulator, water injectors, water injection pump and valves, etc., replace the gasoline carburetor, fuel pump, and the exhaust emission control system. For naturally aspirated or low-pressure hydrogen injection engines, the changes are believed to have little net weight impact. For direct (cylinder) injection (DI) engines, substantial changes occur due to the changes in engine thermal efficiency, charge density, and hardware needs that are directly related to the energy storage concept employed.

²L. R. Foote, et al., Electric Vehicle Systems Study, SR-73-132, Ford Motor Co., Dearborn, Michigan (October 1973).

Engine design changes because of the probable need for cooled valves, provisions for ducting hydrogen to inlet valves or directly into the cylinder, and changes in compression ratio. In Table E-1, modified coefficients are provided to permit computation of the combined engine and transmission weight.

2. A reduction in water cooling system capacity might be allowed by the heat absorption by the cryogenic or hydride tank. However, the cryogenic tank might employ electrical or exhaust heating for vaporization. Advanced hydrides require exhaust heat. Iron-titanium hydrides could use either water or exhaust. Since engine cooling is required even when the hydride may not require heating, make no change in the cooling system.
3. The exhaust system design can be expected to change to accommodate heating the hydrogen source. However, the changes are being charged to the energy storage system.
4. The gasoline fuel system and fuel are eliminated, but a more or less equivalent water injection system is substituted. The required capacity is presently unknown, so there is no change.
5. The rear axle weight is not expected to change because of the switch to hydrogen.
6. The battery and alternator weights are not affected unless the liquid hydrogen tank is electrically heated (which is unwise for the primary heating load with so much waste heat available) or the hydrogen pump or compressor is electrically driven (which appears unwise for the potentially large power required). Assume no change.

E. 2. 4

Energy Storage Dependent Weight W_5

W_5 = weight of hydrogen energy storage system + added vehicle weight to provide the storage volume.

$$W_5 = W_{E1} + W_{E2} + W_{E3} + W_{E4}$$

W_{E1} = weight of hydrogen-containing material including the hydrogen.

W_{E2} = weight of supply tank with associated heat exchanger and integral piping, fill and vent valves, pressure and temperature transducers, and lines to engine.

TABLE E-1: WEIGHT OF ENGINE AND TRANSMISSION

Engine Type	A ₃ (lb)	B ₃ (lb/cid)	K (cid/hp)	B ₃ K (lb/hp)	W ₃ for 100 hp ⁽¹⁾ (lb)
Gasoline Engine [E-1] ⁽²⁾	310	1.92	1.30	2.50	560
Naturally Aspirated Hydrogen Engine Hydrogen Temperature = 80°F	310	1.92	1.34	2.57	567
Direct Injection Hydrogen Engine Hydrogen Temperature = 80°F					
Cryogenic Supply	340	2.00	0.75	1.50	490
Metal Hydride Supply	370	2.30	0.92	2.12	582
Hydrogen Temperature = 200°F Metal Hydride Supply	370	2.40	1.00	2.40	610

⁽¹⁾ W₃ = Weight of engine and transmission where engine weight includes emission controls, carburetor or equivalent mixing valve or direct injection valve system, hydrogen pump or compressor, intercooler, and plumbing. Weight is calculated as follows:

W₃ = A₃ + B₃ × cid = A₃ + B₃ × K × hp, where cid = engine displacement in cubic inches.

⁽²⁾ [] = Reference number.

W_{E3} = weight of thermal control provisions if needed to isolate energy storage system from vehicle. Assume proportional to tank volume.

W_{E4} = weight increment for tank storage volume ≈ 37 lb/ft³ of tank outside volume. Estimated using automobile dimensional data and weight estimates contained in draft Report of the Automotive Design Panel of the Task Force on Motor Vehicle Goals Beyond 1980, 15 October 1975.

E. 2. 4. 1 Evaluation of W_{E1}

W_{E1} = weight of hydrogen and storage material if used.

For liquid hydrogen:

W_{E1} = weight of hydrogen W_H in loaded tank

Weight of usable hydrogen considering avoidance of a dry tank, which would increase tank refill time and greatly increase hydrogen loss.

W_{HU} = 0.90 W_H for 1985 model year

= 0.95 W_H for 1990 and 2000 model years

For metal hydrides:

W_{E1} = weight of metal hydride W_{MH} including full load of hydrogen

Weight of usable hydrogen depends upon the flow rates demanded by the driving cycle and the possible need to burn a portion of the hydrogen to satisfy dissociation temperature and heat absorption requirements. Experimental vehicles using engine exhaust heated iron-titanium hydrides have had only 60 to 75 percent of their hydrogen charge usable at 50 mph. Assume that better system design will allow 80 to 90 percent of the loaded hydrogen to be removed from the hydride bed. For advanced, high-temperature hydrides, assume 15 percent of the hydrogen released from the bed is burned to generate supplemental heat to aid in hydride dissociation for normal running and for startup. The usable hydrogen weights are therefore:

For iron-titanium and similar low-temperature metal alloy hydrides:

$$\begin{aligned} W_{HU} &= 0.80 W_H \text{ for 1985 model year} \\ &= 0.90 W_H \text{ for 1990 and 2000 model years} \end{aligned}$$

For magnesium-nickel and similar high-temperature metal alloy hydrides:

$$\begin{aligned} W_{HU} &= 0.90 \times 0.85 W_H \\ &= 0.765 W_H \text{ for 1990 and 2000 model years} \end{aligned}$$

The total weight of the charged hydride W_{E1} is inversely proportional to the concentration of hydrogen

$$W_{E1} = \frac{W_H}{\%H_2}$$

For iron-titanium hydride represented by $\text{FeTiH}_{1.6}$, which can be recharged at high pressure in 15 to 30 min, the hydrogen concentration is about 1.5 percent by weight. Although magnesium hydride can attain a concentration of 7.7 percent hydrogen, its elevated dissociation temperature (290°C) makes it unsuitable for automotive use. A practical alloy of magnesium, nickel, and other elements with a dissociation temperature of about 200°C at 1 atm and reasonable characteristics of heat transfer, charging time, and stability is not expected to achieve more than a 5-percent hydrogen concentration (at high pressure in 15 to 30 min with water cooling of the bed).

For iron-titanium hydride:

$$W_{E1} = \frac{W_H}{0.015} = 66.67 W_H$$

$$W_{E1} = 66.67 \frac{W_{HU}}{0.80} = 83.34 W_{HU} \text{ for 1985 model year}$$

$$= 66.67 \frac{W_{HU}}{0.90} = 74.08 W_{HU} \text{ for 1990 and 2000 model years}$$

For an advanced magnesium-nickel alloy hydride:

$$W_{E1} = \frac{W_H}{0.05} = 20.0 W_H$$

$$= 20.0 \frac{W_{HU}}{0.765} = 26.14 W_{HU} \text{ for 1990 and 2000 model years}$$

E. 2. 4. 2 Evaluation of W_{E2}

W_{E2} = weight of tank and heat exchanger, integral piping, fill and vent valves, pressure and temperature transducers, and lines to engine injection system.

For liquid hydrogen;

In the range of 50 to 60 gal of liquid hydrogen, data are available on tank designs for different materials of construction. This is summarized in Table E-2:

TABLE E-2. LIQUID HYDROGEN TANK WEIGHT AND COST VERSUS MATERIALS OF CONSTRUCTION

Materials Outer/Inner	Tank Wt/Liquid Hydrogen Wt (lb/lb)	Production Cost Estimate ⁽¹⁾ (\$/lb) [E-3] ⁽²⁾
Alum/Alum ⁽³⁾	3.18	10-12
Stainless/Alum	7.33	10-12
Stainless/Stainless	13.56	10-12

(1) Cost estimates are for large quantities and may be difficult to achieve.

(2) [] = reference number.³

(3) Minnesota Valley Engineering Model VLH-50G spherical tank 50 gal of liquid hydrogen, OD = 34 in., ID = 28 in., volume ratio = 1.79:1.

Since aluminum alloys appear suitable for spin forming of spheres and spheroids that may package better into available vehicle volumes, assume that aluminum alloy tanks are used for model years 1985-2000 with negligible weight change.

Allow 30 lb for the weight of a water-to-liquid hydrogen heat exchanger, fill and vent valves, pressure relief valves, flow control valves, transducers, and lines leading from the tank to the engine injection system.

³Personal communication: H. Smaller, Aerospace Corporation, El Segundo, California (May 25, 1977).

$$W_{E2} = 30 + 3.2 \times W_H, \text{ lb}$$

For metal hydrides:

W_{E2} = Weight of the hydride tank, a hydride heat exchanger typically integral with the tank, hydrogen fill and vent valves, pressure and temperature transducers, plumbing between subsystem elements and between the storage subsystem and the engine. High-temperature hydrides would typically require additional items including a hydrogen circulator, an air pump, and a hydrogen burner unit and controls. The circulator and pump are assumed to be electrically driven. Start-up aids for the high-temperature hydrides would be either a small, low-temperature hydride canister, a high-pressure hydrogen bottle, or an electric resistance heater for a section of the hydride bed.

For the stainless steel tanks built by Billings Energy Corporation for its automotive applications of iron-titanium hydrides, the tank weights with integral heat exchange tubes were 39 to 69 percent of the weight of the hydride, disregarding structural supports for multiple tanks. Adding minimal instrumentation, valves and plumbing, it appears that near-term applications would require tank and hardware weight,

$$\begin{aligned} W_{E2} &= 0.45 W_{E1} \text{ for iron-titanium and similar low-temperature} \\ &\text{metal alloy hydrides} \\ &= 0.45 \times 66.67 W_H = 30 W_H \end{aligned}$$

The use of high charging pressures (≈ 500 psi for quick refill) and the likely need for periodic high-temperature reactivation of the hydride will probably preclude the use of lighter weight, lower cost aluminum alloy construction.

For the high-temperature magnesium-nickel alloy hydrides, stainless steel will be required by the high operating temperatures ($\geq 200^\circ\text{C}$)

and probably by similar hydride reactivation requirements. Tank design pressure will probably not be much less than for current iron-titanium systems (500 psi) due to the need for acceptable charging times. Assume that the combined weight of hydride tank and heat exchanger is proportional to the volume of hydride.

There is no well-characterized magnesium-nickel alloy hydride that satisfies all automotive requirements. A comparison of the composition of an alloy having a relatively low dissociation temperature (232°C) with an alloy of magnesium with 10-percent nickel by weight allows a rough projection of an increase in hydride bulk density from 56 lb/ft³ (Ref. E-4)⁴ to 70 lb/ft³. This assumes that the density of the material is equally reduced by hydriding and that the fractional void space between hydride particles is the same. The bulk density of the hypothetical high-temperature hydride is substantially lower than the 220 lb/ft³ reported by Brookhaven National Laboratory (BNL) (Ref. E-5)⁵ for FeTiH_{1.6}. It should be noted that the 220 lb/ft³ bulk density value appears high when the 5.47 g/cm³ for FeTiH₂ and 5.88 g/cm³ for FeTiH₁ (Ref. E-4) are considered. A void fraction of about 37 percent is implied.

$$W_{\text{tank \& heat exchanger}} = \frac{W_{E2}}{W_{E1}(\text{FeTi})} \times \frac{\rho(\text{FeTi})}{\rho(\text{adv})} \times W_{E1}(\text{adv})$$

$$= 0.45 \times \frac{220}{70} \times W_{E1}(\text{adv})$$

$$W_{E2} = 1.41 W_{E1} \text{ for high-temperature metal alloy hydrides}$$

$$= 1.41 (20 W_H) = 28.2 W_H$$

⁴J. J. Reilly and R. H. Wiswall, Jr., "Formation and Properties of Iron Titanium Hydride," Inorganic Chemistry, **13**, 218 (1974).

⁵J. J. Reilly, R. H. Wiswall, Jr., and C. H. Waide, Motor Vehicle Storage of Hydrogen Using Metal Hydrides, TEC-751001, Brookhaven National Laboratory, Upton, New York (October 1974).

It should be noted that for a given usable weight of hydrogen, the tank for an advanced hydride is heavier (and larger) than a tank for a low-temperature hydride:

$$\frac{W_{\text{tank (adv)}}}{W_{\text{tank (FeTi)}}} = \frac{1.41 W_{E1 \text{ (adv)}}}{0.45 W_{E1 \text{ (FeTi)}}} = \frac{1.41 \times 26.14 W_{\text{HU}}}{0.45 \times 74.08 W_{\text{HU}}} = 1.106$$

E. 2. 4. 3 Evaluation of W_{E3}

W_{E3} = weight of thermal control provisions if needed to isolate energy storage system from vehicle.

This requires a detailed analysis, impossible at this time. The normal temperature hydrides do not require such insulation. The cryogenic tank will have a carefully designed insulation system but will still require some isolation from vehicle radiative and conductive heat sources. One pound of insulating provisions per cubic foot of tank volume will be arbitrarily allowed. The uninsulated high-temperature hydride system can present a safety hazard and a substantial heat load in the vehicle compartment. An arbitrary allowance of 2 lb/ft³ of system volume will be made.

For liquid hydrogen (see discussion in Section E. 2. 4. 4):

$$W_{E3} = 1 \times V_{\text{outer}} = 1 \times 0.445 W_H = 0.45 W_H$$

For high-temperature hydrides (see discussion in Section E. 2. 4. 4):

$$W_{E3} = 2 \times 1.5 \times 0.476 W_H = 1.43 W_H$$

E. 2. 4. 4 Evaluation of W_{E4}

W_{E4} = weight increment for tank storage volume
 $\approx 37 \text{ lb/ft}^3$ of outside volume.

For liquid hydrogen:

With a vacuum jacket of 4 in. thickness for a 50-gal spherical tank, the outside-to-inside volume ratio is 1.79:1.

The inside volume will be assumed to be 10 percent greater than the liquid volume at a density of 4.42 lb/ft³.

$$V_{\text{outer}} = \frac{1.79 \times 1.10 \times W_H}{4.42} = 0.445 W_H, \text{ ft}^3$$

$$W_{E4} = 37 \times 0.445 W_H = 16.5 W_H$$

For metal hydrides:

The hydride tank volume is equal to the volume required by the bulk hydride divided by the hydride packaging density considering tank configuration, clearance between tubes, and tube thickness. Additional volume allowances may be necessary for possible separate start-up hydride tanks, burner assemblies, heat exchangers, and circulation fans and controls.

For iron-titanium hydride, the bulk density is about 220 lb/ft³, and the packaging density (η_{pd}), using exhaust heat as an energy source, is 60 to 65 percent.

$$V_{\text{tank}} = \frac{W_{EI}}{220 \eta_{pd}} = \frac{66.67 W_H}{220 \eta_{pd}}, \text{ ft}^3$$

For 1985 allow $\eta_{pd} = 0.65$ and for 1990 and 2000 allow 0.75

$$W_{E4} = \frac{37 \times 66.67 W_H}{220 (0.65)} = 17.3 W_H \text{ for 1985}$$

$$W_{E4} = \frac{37 \times 66.67 W_H}{220 (0.75)} = 15.0 W_H \text{ for 1990 and 2000}$$

For magnesium-nickel alloy and similar high-temperature metal hydrides, the bulk density is about 70 lb/ft³. Packaging density for the tank will probably be adversely affected by poor heat transfer characteristics of the hydride and the use of circulating hydrogen as the heat transfer fluid. Reduce η_{pd} to 0.60.

$$V_{\text{tank}} = \frac{W_{EI}}{70 \eta_{pd}} = \frac{20 W_H}{70 (0.60)} = 0.476 W_H, \text{ ft}^3$$

The combined volume of the start-up hydride tank, fuel circulator, hydrogen burner system, and three or four heat exchangers is power level-dependent and cannot be estimated with any precision at this time. The volume relative to the hydride tank depends on the vehicle design range. As a gross allowance, this volume will be assumed to be half the volume of the hydride tank.

$$W_{E4} = 37 \times 1.5 \times 0.476 W_H = 26.4 W_H$$

E. 2. 5 Summary of Energy Storage Dependent Weights

Table E-3 presents a summary of the component weights for each of the three hydrogen energy storage systems, as derived in the previous sections of this appendix.

TABLE E-3. SUMMARY OF HYDROGEN ENERGY STORAGE SYSTEM
DEPENDENT WEIGHTS

Storage System Weights	Liquid Hydrogen ⁽¹⁾		Iron-Titanium Hydride ⁽¹⁾		Advanced Magnesium-Nickel Hydride ⁽¹⁾
	1985	1990-2000	1985	1990-2000	1990-2000
W_{HU} , Usable Hydrogen Weight, lb	$0.9 W_H$	$0.95 W_H$	$0.80 W_H$	$0.90 W_H$	$0.765 W_H$
W_{E1} , Weight of Hydrogen-Containing Material, Including Hydrogen, lb	$1.0 W_H$	$1.0 W_H$	$66.67 W_H$	$66.67 W_H$	$20 W_H$
W_{E2} , Weight of Supply Tank, Heat Exchanger, Plumbing, Instrumentation, lb	$30 + 3.2 W_H$	$30 + 3.2 W_H$	$30 W_H$	$30 W_H$	$28.2 W_H$
W_{E3} , Weight of Thermal Isolation Provisions, lb	$0.45 W_H$	$0.45 W_H$	0	0	$1.43 W_H$
W_{E4} , Vehicle Weight Increment for Required Storage System Volume, lb	$16.5 W_H$	$16.5 W_H$	$17.3 W_H$	$15.0 W_H$	$26.4 W_H$
$W_5 = \Sigma W_E$, Energy Storage Dependent Weight, lb	$30 + 21.2 W_H$	$30 + 21.2 W_H$	$114.0 W_H$	$111.7 W_H$	$76.0 W_H$

(1) W_H = Hydrogen weight in a fully charged system.

APPENDIX F

UNIT CONVERSION FACTORS

To assist the reader in interpreting this report, which does not contain a consistent set of units throughout, the following tables of unit conversion factors are presented. They are somewhat abbreviated versions of the tables presented in the Jet Propulsion Laboratory report, Hydrogen Tomorrow, Demands and Technology Requirements, December 1975. Table F-1 provides factors for converting from the conventional English units most frequently used in this report to international system (SI) units. Conversion factors for various measures of energy to Btu's and Joules are presented in Table F-2. For selected measures of energy, the conversion factors are extended to barrels of crude and kilowatt-hours in Table F-3.

TABLE F-1. CONVERSION FACTORS FROM
CONVENTIONAL TO INTER-
NATIONAL SYSTEM OF UNITS

To Convert From:	To:	Multiply by
amperes/ft ²	A/m ²	10.7642
atmospheres	N/m ²	1.0132 x 10 ⁵
barrel	m ³	1.5898 x 10 ⁻¹
Btu/ft ²	J/m ²	1.1365 x 10 ⁴
Btu/ft ³	J/m ³	3.7288 x 10 ⁴
Btu/gal	J/m ³	2.7896 x 10 ⁵
Btu/hr	Watts	0.2931
Btu/hr-ft ² -°R	J/s-m ² -°K	1.73204
Btu/hr-ft ² -°R/in	J/s-m ² -°K	0.1443366
Btu/kw-hr	J/J	2.9329 x 10 ⁻⁴
Btu/lb _m	J/kg	2.3278 x 10 ³
Btu/mile	J/km	656.227
ft	m	0.3048
ft ²	m ²	9.290 x 10 ⁻²
ft ³	m ³	2.8316 x 10 ⁻²
ft/sec	m/s	3.048 x 10 ⁻¹
ft ² /min	m ² /s	1.5483 x 10 ⁻⁴
gallon	m ³	3.785 x 10 ⁻³
gram/mile	g/km	0.621504
inch	m	2.54 x 10 ⁻²
kw-hr/Btu	J/J	3.4095 x 10 ³
kw-sec/lb _m	J/g	2.202
kw-hr/lb _m	J/g	7.93668 x 10 ³
lb _m	kg	0.45359
lb _f	N	4.44822
lb _m /ft ³	kg/m ³	6.64152 x 10 ³
lb _m /sec	kg/s	4.5359 x 10 ⁻¹
lb _m /ft ²	N/m ²	47.8818
lb _f /in ² (psi)	N/m ²	6.89475 x 10 ³
mile	km	1.609
miles/gal	km/m ³	4.2509 x 10 ²
miles/hr	m/s	4.4704 x 10 ⁻¹
temperature (°C)	°K	t _K = t _C + 273.15
temperature (°F)	°K	t _K = (5/9)(t _F + 459.67)
temperature (°R)	°K	t _K = (5/9)t _R
ton (long)	kg	1.01604 x 10 ³
ton (short)	kg	9.0718 x 10 ²
ton-mile	kg-km	1.45965 x 10 ³
Watt-hr/lb _m	J/kg	7.9366 x 10 ³

TABLE F-2. CONVERSION FACTORS
FOR ENERGY UNITS
AND QUANTITIES

To Convert From:	To Btu's Multiply by	To Joules Multiply by
Btu (mean)	1.0	1.05587 x 10 ³
calories	3.9685 x 10 ⁻³	4.19002
kilocalories	3.9685	4.19002 x 10 ³
ergs	9.479 x 10 ⁻¹¹	1.0 x 10 ⁻⁷
electron volts	1.519 x 10 ⁻²²	1.6021917 x 10 ⁻¹⁹
joules	9.479 x 10 ⁻⁴	1.0
ft-lb	0.001285	1.356
kw-hr	3412.8	3.6 x 10 ⁶
kw-sec	0.948	1.0 x 10 ³
mw-hr	3.413 x 10 ⁶	3.6 x 10 ⁹
hp-hr	2545	2.684 x 10 ⁶
barrel crude oil	5.8 x 10 ⁶	6.1240 x 10 ⁹
barrel gasoline (motor fuel)	5.253 x 10 ⁶	5.5465 x 10 ⁹
barrel gasoline (aviation)	5.048 x 10 ⁶	5.3300 x 10 ⁹
gallon gasoline	1.25 x 10 ⁵	1.3198 x 10 ⁸
barrel residual fuel oil	6.29 x 10 ⁶	6.6414 x 10 ⁹
barrel distillate fuel oil	5.825 x 10 ⁶	6.1504 x 10 ⁹
barrel heavy fuel oil	6.287 x 10 ⁶	6.6383 x 10 ⁹
barrel diesel oil	5.806 x 10 ⁶	6.1304 x 10 ⁹
ton anthracite coal	25.4 x 10 ⁶	26.8 x 10 ⁹
ton bituminous	26.2 x 10 ⁶	27.7 x 10 ⁹
ton sub-bituminous	19.0 x 10 ⁶	20.1 x 10 ⁹
ton coal coke	24.8 x 10 ⁶	26.2 x 10 ⁹
ton coke breeze	20 x 10 ⁶	21.1 x 10 ⁹
ton lignite coal	13.4 x 10 ⁶	14.2 x 10 ⁹
avg. ton coal used in 1969 electric production	24.7 x 10 ⁶	26.1 x 10 ⁹
cu. ft. natural gas (dry)	1031	1.0915 x 10 ⁶
cu. ft. natural gas (wet)	1103	1.1646 x 10 ⁶
barrel liquefied natural gas (avg.)	4.1 x 10 ⁶	4.3291 x 10 ⁹
grams U ₂₃₅ fissioned	74.0 x 10 ⁶	78.1 x 10 ⁹
ton methanol	19.48 x 10 ⁶	20.57 x 10 ⁹
gallon methanol	64,700	6.8315 x 10 ⁷
lb. hydrogen (HHV)	61,084	6.4497 x 10 ⁷
ton hydrogen (HHV)	1.222 x 10 ⁸	1.2903 x 10 ¹¹
ft ³ hydrogen (gas)	325.1	3.433 x 10 ⁵
gal. hydrogen (liq.)	35,600	3.7589 x 10 ⁷
kw-yrs	29.9 x 10 ⁶	31.571 x 10 ⁹

TABLE F-3. ADDITIONAL CONVERSION FACTORS FOR ENERGY UNITS AND QUANTITIES

Converting from:	Multiply by:			
	To Barrels Crude(1)	To kWh	To Btu's	To Joules
Kilocalories	4.33×10^{-5}	0.0738	3.9685	4.19002×10^3
Kilowatt-hours	5.87×10^{-4}	-	3412.8	3.6×10^6
Barrels crude oil	-	1699.4	5.8×10^6	6.1240×10^9
Gallons gasoline	7.27×10^{-3}	36.6	1.25×10^5	1.3198×10^8
Tons coal (avg.)	4.3 - 4.5	7300 - 7600	$25 - 26 \times 10^6$	$26.4 - 27.4 \times 10^9$
Tons lignite coal	2.305	3926	13.4×10^6	14.2×10^9
ft ³ natural gas	$1.77 - 1.9 \times 10^{-4}$	0.302 - 0.322	1030 - 1100	$1.088 - 1.161 \times 10^6$
Barrels liquefied natural gas	0.705	1201	4.1×10^6	4.329×10^9
Tons hydrogen	0.2107	357.3	1.222×10^8	1.2903×10^{11}
ft ³ hydrogen	5.6015×10^{-5}	0.095	325.1	3.433×10^5
Barrels methanol	0.487	760	2.717×10^6	2.869×10^9
Grams uranium- 235 fissioned	12.7	21,682	74.0×10^6	78.1×10^9
Tons uranium ore (U ₃ O ₈)	96,300	1.64×10^8	5.6×10^{11}	5.91×10^{14}

(1) Based on heating value of crude and of the converted fuel unit.

APPENDIX G

VISITS AND CONTACTS

During the course of this study, the following organizations were visited or contacted by telephone.

<u>Organizations</u>	<u>Primary Contacts</u>
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Daimler-Benz AG Stuttgart, F. R. Germany	Dr. H. Buchner Dr. H. Säufferer
Energy Development Associates Madison Heights, Michigan	Mr. P. Carr
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Ford Motor Company Scientific Research Center Dearborn, Michigan	Dr. S. A. Weiner Mr. R. W. Minck Mr. L. E. Unnewehr

Organizations

General Research Corporation
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Gould, Inc.
Rolling Meadows, Illinois

Institute of Gas Technology
Chicago, Illinois

Jet Propulsion Laboratory
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Lawrence Livermore Laboratory
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NASA Langley Research Center
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NASA Lewis Research Center
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Oklahoma State University
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Primary Contacts

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GLOSSARY

A	Frontal Area
ac	alternating current
ADL	Arthur D. Little, Inc.
ANL	Argonne National Laboratory
BEC	Billings Energy Corporation
BNL	Brookhaven National Laboratory
BOM	Bureau of Mines
BTC	Before Top (Dead) Center
BTDC	crank angle Before Top Dead Center
CA	Crank Angle
CARB	California Air Resources Board
C_D	Coefficient of Aerodynamic Drag
CFI	Cylinder Fuel Injection
CFR	Cooperative Fuel Research
CO	Carbon Monoxide
CR	Compression Ratio
C_r	Coefficient of Rolling Resistance
CT	Current Technology
CVS	Constant Volume Sampling
DB	Daimler-Benz AG
dc	direct current

DI	Direct Injection of gaseous fuel into cylinders
DOD	Depth of Discharge
DOE	Department of Energy
EDA	Energy Development Associates
EGR	Exhaust Gas Recirculation
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ERDA	Energy Research and Development Administration - now DOE
EV	Electric Vehicle
FE	Fuel Economy
FTP	Federal Test Procedure
GE	General Electric Co.
GM	General Motors Corporation
GRC	General Research Corporation
GSHV	Gaseous Storage Hydrogen Vehicle
HC	Hydrocarbon
HEST	Hydrogen Energy Systems Technology
HHV	Higher Heating Value of combustion of fuel in air
HIT	Hydrogen Induction Technique
H ₂ O ₂	Hydrogen peroxide
HTGR	High-Temperature, Gas-Cooled Reactor
HV	Hydrogen Vehicle
HYTACTS	Hydrogen Technology Advanced Component Test System (Program at BNL)
ICE	Internal Combustion Engine

ICV	Internal Combustion engine Vehicle
IGT	Institute of Gas Technology
IMEP	Indicated Mean Effective Pressure
JPL	Jet Propulsion Laboratory
LNG	Liquefied Natural Gas
LRIT	Long-Range Improved Technology
LSHV	Liquid Storage Hydrogen Vehicle
LWR	Light Water Reactor
MBT	Minimum spark advance for Best Torque
MCH	Methylcyclohexane
MF	Mixture Formation
MIT	Massachusetts Institute of Technology
MVE	Minnesota Valley Engineering Company
NA	Naturally Aspirated
NASA	National Aeronautics and Space Administration
NBS	National Bureau of Standards
NMR	Nuclear Magnetic Resonance
NO _x	Oxides of Nitrogen
OEM	Original Equipment Manufacturer
OSHA	Occupational Safety and Health Administration
OSU	Oklahoma State University
OTEC	Ocean Thermal Energy Conversion
PAX	Passenger

PL 94-413	Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976
POX	Partial Oxidation Process
r	Compression or expansion ratio
R&D	Research and Development
RF	Energy Recovery Factor
SAE	Society of Automotive Engineers
SCR	Silicon-Controlled Rectifier
SEED	Student Engineered Economy Design
SIT	Stevens Institute of Technology
SLI	Starting, Lighting, and Ignition
SNG	Substitute Natural Gas
SO _x	Oxides of Sulfur
SPE	Solid Polymer Electrolyte
SRI	Stanford Research Institute
SRIT	Short-Range Improved Technology
S/V	Surface to Volume ratio
TDC	Top Dead Center piston position
TEC	Transportation Energy Conservation
THC	Total Hydrocarbons
UCLA	University of California, Los Angeles
UT	University of Tennessee
UVDC	Urban Vehicle Design Competition
VLCC	Very Large Crude Carrier
WT	Vehicle Test Weight

γ	Specific heat ratio
ΔH_F	Heat of Formation
η	Indicated thermal efficiency
η_B	Brake thermal efficiency
ϕ	Equivalence Ratio