

ELECTRIC AND HYBRID VEHICLES PROGRAM

**18th ANNUAL REPORT TO
CONGRESS FOR FISCAL YEAR 1994**



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**U.S. Department of Energy
Assistant Secretary, Energy Efficiency and Renewable Energy
Office of Transportation Technologies
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PREFACE

This eighteenth annual report serves to inform the United States Congress of the progress in Fiscal Year 1994 and the plans of the Department of Energy Electric and Hybrid Vehicles Research and Development Program. This document complies with the reporting requirements established under Section 14 of the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976, Public Law 94-413, as amended, 15 U.S.C. §2513. It also satisfies the reporting requirements of Section 615 of the Energy Policy Act of 1992, Public Law 102-486, 42 U.S.C. §13285. In addition, this report is intended to serve as a means of communication from the Department to all the public and private sector participants involved in making the program a success, and other interested parties.

The Department remains focused on the technologies that are critical to making electric and hybrid vehicles commercially viable and competitive with current production gasoline-fueled vehicles in performance, reliability, and affordability. During Fiscal Year 1994, significant progress was made toward fulfilling the intent of Congress. The Department and the United States Advanced Battery Consortium (a partnership of the three major domestic automobile manufacturers) continued to work together and to focus the efforts of battery developers on the battery technologies that are most likely to be commercialized in the near term. Progress was made in industry cost-shared contracts toward demonstrating the technical feasibility of fuel cells for passenger bus and light duty vehicle applications. Two industry teams which will develop hybrid vehicle propulsion technologies have been selected through competitive procurement and have initiated work, in Fiscal Year 1994. In addition, technical studies and program planning continue, as required by the Energy Policy Act of 1992, to achieve the goals of reducing the transportation sector dependence on imported oil, reducing the level of environmentally harmful emissions, and enhancing industrial productivity and competitiveness.

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1.0 INTRODUCTION

The transportation sector is the single largest user of petroleum in the United States; not only did it account for approximately 66 percent of all petroleum used last year, but more significantly, it used about 53 percent more oil than the country produced. The transportation sector is also a major contributor to air pollution. Extensive use of electric, hybrid, and fuel cell vehicles could lead to an overall reduction in petroleum fuels consumption for transportation and a corresponding reduction in on-road emission of environmentally harmful exhaust gases.

The Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 authorizes the Department of Energy to, among other things, "encourage and support accelerated research into, and development of electric and hybrid vehicle technologies." 15 U.S.C. §2501(b)(1). The Department established the Electric and Hybrid Vehicles Program to undertake, in cooperation with industry, research, development, testing, and evaluation activities to develop the technologies that would lead to the production and introduction of electric and hybrid vehicles in the Nation's transportation fleet. The Program is managed by the Electric and Hybrid Propulsion Division within the Office of Propulsion Systems. In Fiscal Year 1994, Congress provided an appropriation of \$74 million for the Program.

The current program structure and principal responsibilities of the organizational units are shown in Figure 1-1. The participants in electric and hybrid propulsion systems research and development, and their cost-sharing commitment, are listed in Table 1-1. Participants include major automotive companies, battery companies, component and propulsion system companies, universities, and electric vehicle users from the public and private sectors.

In Fiscal Year 1994, the Program continued to emphasize battery, fuel cell, and propulsion systems development. The Program also supported testing and evaluation of vehicles and components in laboratory and fleet operations. The battery program concentrated on technologies that could satisfy the mid- and long-term goals of the automobile manufacturers as determined by the United States Advanced Battery Consortium. Two major cost-shared contracts were placed with automotive industry teams for the development of hybrid propulsion systems that would double the fuel efficiency of conventional vehicles and satisfy the Environmental Protection Agency Tier II emissions standard.

The Energy Policy Act of 1992, in Title XX, Subtitle A, recognizes the role of electric vehicles in reducing the nation's dependence on imported oil. Section 2025 authorizes an expanded program of research and development of electric motor vehicles and associated equipment. Subtitle A of Title VI provides for a commercial demonstration program in electric vehicles. In Fiscal Year 1994, the comprehensive five-year program plan developed for carrying out the purposes of Section 2025 was completed.

This Annual Report describes the progress made in developing electric and hybrid vehicle technologies. The report provides a summary of Fiscal Year 1994 accomplishments, followed by detailed descriptions of program activities in advanced battery, fuel cell, and propulsion systems development. The results of testing and evaluation of new technology in fleet site operations and in laboratories are provided.

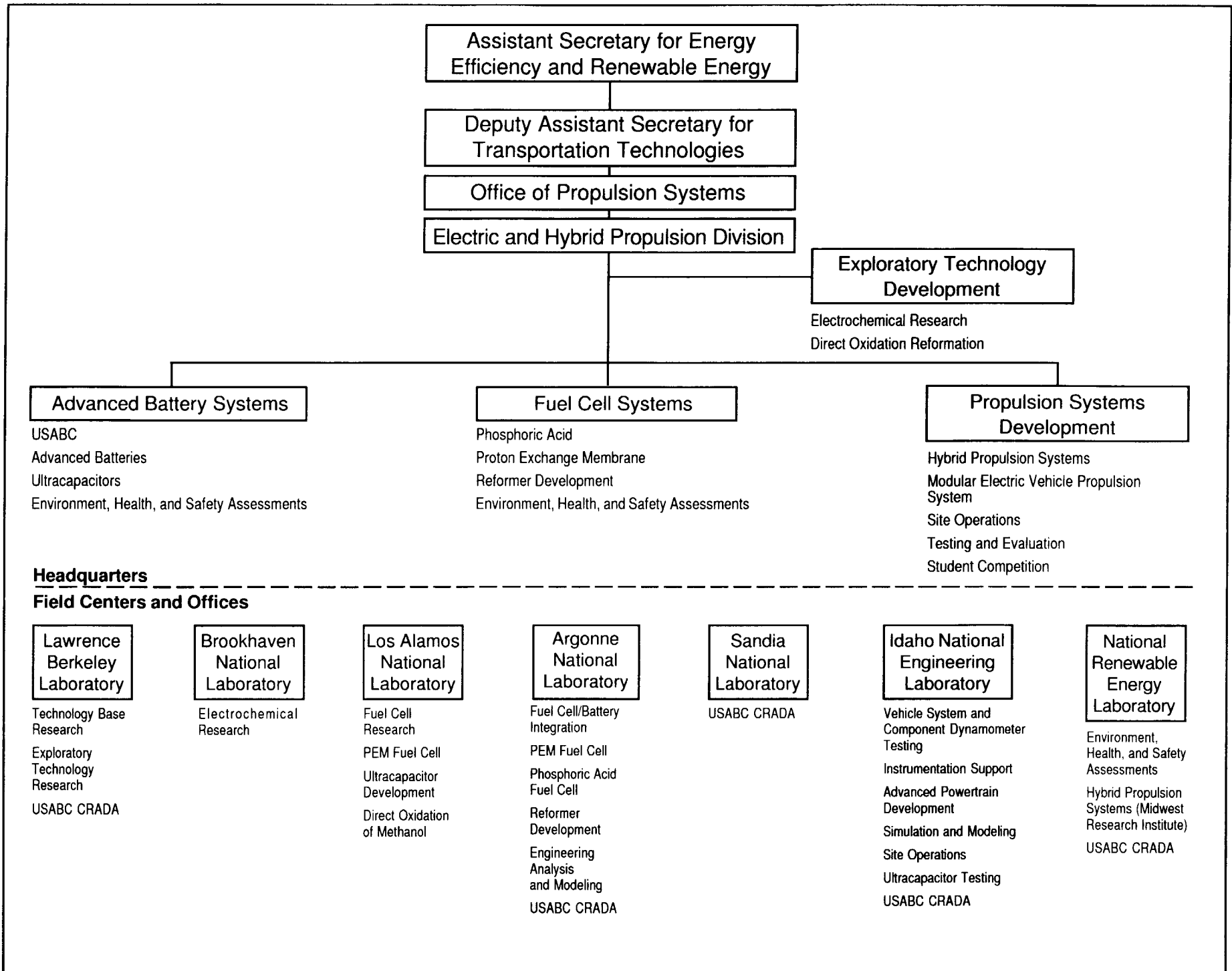


Figure 1-1: Electric and Hybrid Propulsion Division Program Structure

Table 1-1. Major Participants in the Electric and Hybrid Vehicles Program

Participant	Participant Cost Share of Contract,* percent
Automotive Companies	
Ford Motor Company (Fuel Cell)	20
General Motors/Allison (Fuel Cell)	20
United States Advanced Battery Consortium	50
General Motors (Hybrid)	50
Ford Motor Company (Hybrid)	50
Component and Propulsion System Companies	
H-Power	22
A.D. Little	17
Pentastar Electronics (Fuel Cell)	20
Battery Companies (participating through the United States Advanced Battery Consortium)	
Universities	
Georgetown University	14
Fleet Testing Site Operators ^{1/}	
Arizona Public Service Company	95
United States Navy	100
Southern California Edison	90
Los Angeles Dept. of Power and Water	100
Kansas State University	63
Orcas Power and Light Company	50
Platte River Power Authority	86
Pacific Gas and Electric Company	96
Potomac Electric Power Company	79
Public Service Gas and Electric Company	97
Texas A&M University	98
University of South Florida	95
York Technical College	94
1/ The variance in the cost-share percentage by site operators is due to the different activities and contractual arrangements with the site operators.	
* All contracted efforts are with fee waiver.	

2.0 FISCAL YEAR 1994 ACCOMPLISHMENTS

Significant Fiscal Year 1994 accomplishments of the Electric and Hybrid Vehicles Program include the following:

- Yardney Technical Products was awarded a new contract by the United States Advanced Battery Consortium for the development of low-cost nickel electrode technology. Low-cost electrode technology development is important for meeting the cost goals in the nickel/metal hydride battery programs
- The Consortium updated and issued a revised manual for advanced battery test procedures covering almost all aspects of electric vehicle battery testing, including improved tests for maximum power, and battery operation under extremes of temperature, shock, and vibration. Over 50 advanced batteries were delivered to the Consortium and subsequently tested. The Consortium's independent evaluation of contractor deliverables assures that milestones in the program are met.
- Maxwell Laboratories, under contract to the Department, developed the first ultracapacitor to demonstrate specific energy of greater than 5 watt-hours per kilogram at a power level of 500 watts. This goal was set by the Department in 1991 as the minimum performance level to consider ultracapacitor technology for use in electric vehicles.
- The Idaho National Engineering Laboratory developed a comprehensive set of test procedures for evaluating ultracapacitors for electric and hybrid vehicles. These tests will allow progress in ultracapacitor technology to be objectively measured.
- Under the Exploratory Battery Technology Program in support of the Consortium, PolyPlus Battery Company (in a subcontract from Lawrence Berkeley Laboratory) has successfully demonstrated the high performance potential of sodium/polymer/polydisulfide cell technology. If long cycle lifetimes can be achieved with these cells, they could offer a lower-cost alternative to lithium/polymer electrolyte cells.
- Lawrence Berkeley Laboratory has developed a new technique (known as Metal Plasma Immersion Ion Implantation) for implanting metals in nickel oxide electrodes. Initial results indicate that this process significantly improved the electrode capacity. This would lower the cost and improve the performance of all nickel battery technologies, including nickel/metal hydride.
- Los Alamos National Laboratory demonstrated that freeze-thaw cycling of proton exchange membrane fuel cells had no deleterious effect on performance. These results suggest that the direct application of a thin electrode to the membrane generates a bond which effectively prevents delamination under demanding changes in operating temperature. These results also suggest that fuel cell vehicles would be useable under a wide range of operating conditions, including extreme cold.

- H-Power Corporation completed the fabrication of the first U.S.-built fuel cell powered bus. The 30-foot long, 25-passenger bus uses a 50-kilowatt phosphoric acid fuel cell to supply all of the vehicle's energy needs, including wheelchair lifts and air conditioning. The fuel cell operates on methanol fuel and a fuel efficiency of over 40 percent has been demonstrated. Carbon monoxide and nitrogen oxide emissions levels are more than 30 times lower than the 1998 federal heavy-duty diesel emission standards, with virtually no hydrocarbon or particulate emissions.
- The General Motors Corporation completed a three-year, 20-percent cost-shared contract (Phase I) which successfully developed and tested a 10-kilowatt methanol-fueled proton exchange membrane fuel cell system. In addition, a vehicle conceptual design study was completed, selecting a minivan for initial demonstration of performance comparable to the internal combustion engine, but with over twice the energy efficiency and nearly zero emissions. A 30-month Phase II follow-on contract was awarded to General Motors towards building and testing a complete 60-kilowatt laboratory-scale propulsion system.
- Two teams headed by Ford Motor Company and Pentastar Electronics, Inc. (a Chrysler company) were awarded 20-percent cost-shared contracts for 30 months to develop propulsion systems for light-duty passenger vehicles based on proton exchange membrane fuel cell technology fueled directly by hydrogen carried on board the vehicle. Development of conceptual vehicle designs and hydrogen safety analyses are underway.
- Arthur D. Little, Inc. continued Phase II activities in a 30-month contract (17-percent cost-shared, also co-funded by the State of Illinois) to develop a prototype partial oxidation ethanol fuel processor. A bench-scale (approximately 7 kilowatt, equivalent) partial oxidation reformer was built and scaled up to 25 kilowatts.
- Argonne National Laboratory analyzed proton exchange membrane fuel cell systems for a variety of fuel, fuel storage, and fuel processing options. The highest full load system efficiencies (over 52 percent) were obtained for compressed hydrogen and from hydrogen stored in iron-titanium hydride systems. Methanol-fueled system efficiencies were 38 to 45 percent, while natural gas-fueled system efficiencies were about 41 percent.
- Argonne National Laboratory successfully tested a bench-scale methanol partial oxidation reformer designed for a 10-kilowatt fuel cell system. The reformer has demonstrated rapid cold start capability with liquid feed, high hydrogen content in product gas, and very good load-following capability. This reformer technology would allow fuel cell powered vehicles to operate from methanol, a liquid fuel with easy handling requirements.
- Two industry lead teams, headed by General Motors Corporation and the Ford Motor Company, were awarded five-year, 50-percent cost-shared contracts to design, construct, and test improved hybrid propulsion systems. The General Motors team evaluated several hybrid propulsion system technologies and has built a testbed vehicle

for future use as a rolling laboratory to test various components of the hybrid powertrain as they become available. This testbed vehicle will facilitate the evaluation of various component combinations and control strategy alternatives. After weighing all the analysis during Phase I of the program, it was decided that the team will pursue a series configuration electric hybrid.

- The Ford hybrid propulsion team initiated the Systems Study/ Definition Phase to define component characteristics for subsequent trade-off studies and developed an integrated hybrid propulsion simulation computer model. This model simulates the function of the major hybrid components during operation on various vehicle driving cycles and will facilitate the evaluation of various hybrid configurations, component combinations, and control strategies prior to large investments in hardware fabrication.
- A Cooperative Research and Development Agreement entitled "Electromechanical Batteries for Hybrid Vehicles" was signed between General Motors and Lawrence Livermore National Laboratory under the General Motors Hybrid Propulsion Systems Program. The effort will involve the design, fabrication, integration, and test of electromechanical batteries (flywheels) for hybrid vehicles.
- Phase II of the Modular Electric Vehicle Program was completed with the development of a modular 75-horsepower electric drivetrain that was incorporated into a testbed electric van. The vehicle, known as the Ford Ecostar, is being field tested at a number of sites across the country. This is the first time that Department-developed propulsion technology has been incorporated in a major automaker's prototype.
- The Site Operators procured 42 advanced design electric pickup trucks from Spartan Motors (with General Electric drivetrain) and U.S. Electricar (with Hughes Power Systems drivetrain) under cost-shared cooperative agreements with the Department. These vehicles will be field tested in Fiscal Year 1995 as part of the Site Operators Program.
- The 1994 Hybrid Electric Vehicle Challenge student engineering competition, co-sponsored by the Department and others, attracted over 800 student participants from 30 colleges and universities. The vehicles competed in three categories: Saturn vehicles converted to hybrids, Ford Escort conversions, and hybrids built from the ground up. The Challenge also contributed data for the development of a standard test procedure for hybrid vehicles.
- The California Air Resource Board and the Department have entered into a Memorandum of Understanding for testing electric vehicles at the Idaho National Engineering Laboratory. The data collection will serve to further the objective of the fixed percentage of zero-emission highway vehicles that California law mandates (with a 1998 deadline).
- The Department initiated activities with a confederation of electric utilities, known as "EV America" to critically examine the status of available electric vehicles for potential use in broader demonstrations of this technology.

- The Department continued to participate in the development of an infrastructure for electric vehicles through the Infrastructure Working Council and appropriate committees. The Council coordinates the activities of the electric utility industry, the automobile industry, and equipment suppliers towards development of common standards.
- The Department signed on June 30, 1994, a Memorandum of Understanding with the Advanced Research Projects Agency concerning the coordination of activities in three program areas, namely: Electric and Hybrid Vehicle Research and Development; Fuel Cell Vehicle Research and Development; and Electric and Hybrid Vehicle Deployment. The goal of the Memorandum is to avoid duplication of efforts and ensure the efficient use of government resources between the agencies. Detailed agreements will be developed in Fiscal Year 1995 to implement the Memorandum.
- The Notice of Proposed Rulemaking on Equivalent Petroleum-Based Fuel Economy for electric vehicles was published in the Federal Register in February 1994. The rulemaking delineates the procedure for calculating the electric vehicles' equivalent miles per gallon for application to manufacturer's corporate average fuel economy. Appropriate comments from the public hearing are being incorporated into the final rule which will be released during Fiscal Year 1995. This rulemaking provides an increased incentive to vehicle manufacturers to produce electric vehicles.

3.0 BATTERY SYSTEMS RESEARCH AND DEVELOPMENT

3.1 United States Advanced Battery Consortium

During Fiscal Year 1994, the United States Advanced Battery Consortium and the Department continued to work together to achieve the technical and cost objectives required for mid- and long-term battery systems. More specifically, the purpose of this cooperation is to develop for commercialization advanced battery systems that will provide increased range and improved performance for electric vehicles in the latter part of the 1990s.

In the spring of 1994, the Consortium participated in workshops and public hearings held by the California Air Resources Board concerning the technical status of advanced batteries for electric vehicles. The Consortium outlined the development process it was using and its forecast of the availability of advanced batteries for the mid term.

In particular, discussions focused on the status of the nickel-metal hydride batteries which are being developed under contract to the Consortium by Ovonic Battery Company and SAFT America. Cells, modules, and battery packs are being tested in laboratories and in vehicles. While each contract is at a different stage of development, neither company has fully met the mid-term criteria.

The Ovonic contract has begun the third phase of a four-phase effort. Battery performance in the first and second phases improved consistently and all deliverables were met on or ahead of schedule. Test results to date at Argonne National Laboratory have shown that this technology holds promise of meeting the mid-term performance criteria. Phase 2 modules are now under test at Argonne, including life and temperature testing to determine thermal management requirements. While these modules continue to cycle on the rigorous Dynamic Stress Test, the mid-term criterion for cycle life (600 cycles) has not yet been reached. The criteria for success are to maintain both energy and peak pulse power above 80-percent of their initial ratings (30-second pulse at two-thirds open circuit voltage and 80-percent depth-of-discharge). Based on Ovonic's technical progress, the consortium agreed to install full-size Phase 2 packs in vehicles prior to completion of Phase 3. These have now been delivered and integrated into vehicles.

Projections of battery selling price made by Ovonic, and independently by the Consortium, are currently in excess of the United States Advanced Battery Consortium mid-term goal of \$150 per kilowatt-hour. Ovonic has proposed additional development aimed at reducing materials and manufacturing costs to meet this goal. Overall, it will take more than two additional years before final verification testing can be started for this improved technology. Subsequent verification of cycle life will take about one additional year. This could result in eventual achievement of the price goal, with specific energy levels well above the mid-term criteria.

In parallel with this effort, General Motors recently announced an agreement with Ovonic to further develop, manufacture and commercialize the Ovonic nickel-metal hydride batteries for electric vehicles. The impact this agreement will have on the timing for volume

production and meeting the cost goal is not known at this time.

SAFT is also making excellent progress in their nickel-metal hydride development program. The program is structured on a number of hardware deliverable to measure progress against defined performance goals. Although the initial and interim goals are below mid-term targets, they plan to meet the mid-term goals in the final deliverables. The first SAFT 12-volt modules were delivered to the Sandia National Laboratories in July 1993. Performance and cycling tests are in progress using the Dynamic Stress Test profile but have not yet achieved the 600 cycles required by the Consortium. The second hardware deliverables were provided on schedule in January 1994. By the end of 1994, four 40-kilowatt-hours battery packs will have been delivered. These packs are expected to meet at least some of the mid-term goals. The final contract deliverables are scheduled for the end of 1995 and the first quarter of 1996. Testing of these full-sized packs in the laboratory and in vehicles will require up to 12 additional months to verify achievement of the cycle life goal.

Throughout the development, efforts will continue towards achieving the mid-term battery cost goal. Even if successful, a decision to commercialize this technology could not be made before mid-1997. Thereafter, production facilities would have to be set up and commissioned before significant production rates could be achieved.

The Battery Test Procedures Committee of the Consortium continued its work in test development, data reporting, and advanced planning. A revised version of the Electric Vehicle Battery Test Procedures Manual, containing updated versions of test procedures and data reporting formats, was published. First drafts of a Glossary of Terms and Detailed Test Procedures were completed and will be included in the next revision of the Battery Test Procedures Manual. All Consortium deliverable schedules, data distribution, and testing costs were planned and monitored. Initial drafts of the In-Vehicle Test Plan and Battery Safety Testing studies were completed.

Work continued in Fiscal Year 1994 under Cooperative Research and Development Agreements between the Consortium and national laboratories including Argonne National Laboratory, Idaho National Engineering Laboratory, Lawrence Berkeley National Laboratory, National Renewable Energy Laboratory, and Sandia National Laboratory.

3.2 Exploratory Technology Research

In Fiscal Year 1994, exploratory research activities managed by Lawrence Berkeley National Laboratory focused on identifying new rechargeable battery systems with higher performance and lower cycle-life costs than those now available, and conducting critical supporting and materials research for the batteries now under development by the U.S. Advanced Battery Consortium.

Work on rechargeable *lithium/polymer electrolyte* batteries addressed charge and discharge processes, and synthesis of polymer electrolyte materials. At Lawrence Berkeley, researchers have identified the important physical processes taking place in the charge and discharge of lithium/polymer electrolyte cells and have developed a mathematical model to understand the dynamic changes that occur. This model has been extended to examine the

behavior of the “Rocking Chair” configuration, which is based upon two electrodes which store lithium at different potentials. A thermal model has been developed which predicts the amount of heat that is generated during cycling of a lithium/polymer battery. The results demonstrate that thermal management may not be a serious problem for these batteries under low discharge rates. However, under high discharge rates, the temperature of a battery may increase significantly if the thickness of a battery exceeds a certain value.

At Case Western Reserve University, a project is underway to develop novel materials for polymer electrolytes. Researchers are attempting to synthesize sulfonated and phosphonated polybenzimidazole polymers. Northwestern University is involved in two projects: (a) synthesizing polymer electrolytes based on aluminosilicate-polyether hybrid electrolytes with improved low-temperature performance; and (b) applying theoretical studies involving molecular dynamics and simulations to understand the conduction process in polymer electrolytes. A new hybrid polymer electrolyte (polyether-bound lithium aluminosilicate-polyether) has been synthesized and will be tested shortly. Theoretical models are being developed to determine the influence of different parameters on the transport of lithium in polymer electrolytes.

The University of Dayton is conducting research to synthesize and characterize new polymer electrolytes that contain crown ethers which could have a fundamentally different mode of ion transport than those currently under investigation. The proposed systems are doped polymers with side chains that have crown ether groups which form a strong bond to lithium. It is hypothesized that these materials will create highly ordered structures, thereby forming paths through which ions can move easily. The synthesis of polymers involving a seven-step procedure has been initiated.

Rutgers University is investigating methods to optimize the synthesis of polymer electrolytes by sol-gel processing of alkali silicate components. Various lithia-silicate compositions have been prepared which were found to have ionic conductivities over the range from room temperature to 400°C that show some promise for test in lithium batteries.

Lawrence Berkeley Laboratory is also developing new electrochemical couples, and new versions of previously investigated couples, with the potential to meet or exceed the battery performance goals of the Consortium. These include the *sodium/polymer* and *zinc/nickel oxide* cells which could provide high performance at ambient or near-ambient temperatures.

A *sodium/polymer* cell consists of electrodes made of pure sodium (for some studies, a sodium-lead alloy was substituted) and sodium cobalt oxide, and a polymer electrolyte. Studies are underway to find an alternative to the costly sodium cobalt oxide. The most suitable family of low-cost metal oxides is the manganese oxides. Tests in sodium/polymer cells indicate that this material can operate over an acceptable voltage range with good performance. In a separate study, Brookhaven National Laboratory observed that adding metal oxides to manganese oxides improved the performance of these electrodes.

In their evaluation of the *zinc/nickel oxide* cell, researchers at Lawrence Berkeley found that the nickel oxide electrode limits the cell lifetime. It was previously believed that the reactions of zinc species with the nickel oxide electrode degrade its performance. In a

collaborative study, Brookhaven National Laboratory used advanced spectroscopic techniques to study nickel oxide electrodes that were cycled in zinc/nickel oxide cells at Lawrence Berkeley Laboratory. These measurements showed that a substantial amount of zinc is present in the nickel oxide electrodes, and that the zinc species were different in the electrodes obtained from three vendors. There was no evidence for reaction of cycled nickel oxide electrodes with zinc species. Lawrence Berkeley will transfer zinc/nickel oxide cell technology to the Energy Research Corporation under a Cooperative Research and Development Agreement.

Other electrochemical cells were also investigated in Fiscal Year 1994. Oak Ridge National Laboratory has fabricated cells that contain a thin, solid electrolyte of amorphous lithium phosphorus oxynitride and electrodes of lithium and manganese oxide. These cells can be cycled at low-current densities. Efforts are now underway to improve the performance at higher current densities by reducing the resistance of the cell. PolyPlus Battery Company has successfully demonstrated the high performance potential of sodium/polymer/polydisulfide cell technology. If long cycle lifetimes can be achieved with these cells, they would offer a lower-cost alternative to lithium/polymer-electrolyte cells.

Research projects are also focused on development of electrodes. The State University of New York (Binghamton) is synthesizing molybdenum oxides for positive electrodes in rechargeable lithium cells. Molybdenum oxides with a layered structure were produced which should allow for rapid diffusion of lithium ions. These materials were synthesized using the hydrothermal method. SRI International is investigating high-performance organosulfur electrodes, which show promise for use in sodium/polymer electrolyte cells. Electrodes and polymer electrolytes have been produced, and cells have been fabricated for cycle testing. Case Western used spectroscopic techniques and thermal analysis to study the lithium/organic electrolyte interface during cycling. The thermal studies with lithium exposed to propylene carbonate showed evidence of a reaction that produces lithium carbonate. Evidence was also found to indicate that lithium hydride may be formed.

A new thrust was initiated in-house at Lawrence Berkeley to identify the optimum properties of carbonaceous materials for use in electrodes to store lithium for rechargeable lithium cells. Analysis of existing data suggests that no unified theory is available which explains the relationship between the physical properties of carbon and the amount of lithium that can be stored. The electrochemical experiments are conducted in collaboration with Lawrence Livermore National Laboratory. Livermore evaluated the performance characteristics of commercially available lithium-ion cells manufactured by Sony Corporation using the cycling profile (Dynamic Stress Tests) developed by the U.S. Advanced Battery Consortium. Using this test protocol, between 375 and 480 cycles were obtained at complete cell discharge, depending on charging conditions.

Researchers are also investigating corrosion-resistant coatings for use in the corrosive environments of non-aqueous, alkali-sulfur, and molten-salt cells. The Illinois Institute of Technology has undertaken a theoretical study to improve the quality of the molybdenum carbide coatings obtained by plasma-enhanced chemical vapor deposition. The Environmental Research Institute of Michigan has prepared titanium-coated aluminum containment materials by sputter-deposition techniques. Materials prepared by these techniques were corrosion-

resistant for 500 hours in sodium sulfide environments typically used in alkali-sulfur cells.

3.3 Ultracapacitors

High power density ultracapacitors can be used to provide accelerating power and allow the more uniform or level load to be handled by traction batteries. For electric vehicles, power to sustain level loads are less than one third of peak power requirements. Therefore, ultracapacitors, in combination with batteries, can increase electric vehicle range by as much as 50 percent for some types of batteries and more than double the cycle life. The size (kilowatt-hours stored), and thus the cost of the battery system needed to meet vehicle range requirements could potentially be reduced. Ultracapacitors are being considered for regenerative braking energy storage in conjunction with hybrid propulsion systems. Research and development of ultracapacitor technology will continue to be coordinated with the hybrid propulsion systems development projects in Fiscal Year 1995. In addition, further ultracapacitor development is being considered under the United States Advanced Battery Consortium.

The ultracapacitor development program for electric and hybrid applications is outlined in Table 3-1. Near-term and advanced program goals have been defined for specific energy (5 and 15 watt-hours per kilogram) and specific power (500 and 1600 watts per kilogram). The Idaho National Engineering Laboratory is responsible for technical program management, technology assessment and testing. Several carbon-based and non-carbon-based technologies are being developed for capacitors with specific energies of 25 to 30 watt-hours per kilogram. Several devices were tested during Fiscal Year 1994.

Maxwell Laboratories Inc. was funded to develop bipolar carbon-based ultracapacitors with an energy density of at least 5 watt-hours per kilogram by 1995, which could be configured in a 100 kilogram unit to store 500 watt-hours and produce peak power of 50-kilowatts. Several ultracapacitor laboratory cell fixtures (see Figure 3-1) were delivered by Maxwell Laboratories Incorporated to the Idaho laboratory for testing. These 3-volt, 20-square centimeter bipolar cells (carbon-metal electrode configuration with organic electrolyte and capacitance of 15 Farads) achieve specific energies as high as 7 watt-hour per kilogram. They exhibit specific powers as high as 2.5 kilowatts per kilogram while maintaining specific energies of at least 5 watt-hours per kilogram. Results are based on constant power discharges and the weight of active materials only (electrodes, separator, electrolyte, and current collector plate). Although optimized cell packaging and high voltage cell stacks have not yet been realized, these results, along with other designs currently under development, indicate that technical goals are possible. Devices containing at least six bipolar cells (18-volt) of this design are currently being fabricated and will be delivered to the Idaho National Engineering Laboratory for performance testing in late 1994.

Los Alamos National Laboratory delivered three 0.75-volt, 10-Farad doped layered polymer capacitor cell fixtures containing Type I polymer to the Idaho National Engineering Laboratory in September 1994. These preliminary test cells achieved specific energies less than 2 watt-hours per kilogram and specific powers less than the near-term program goals of 500 watts per kilogram. Tests have demonstrated that these Type I materials can function as working capacitors and are attractive due to their potential for low-cost manufacturing.

Table 3-1. Summary of the Status of Ultracapacitor Technologies

Technology	Developer	Early Deliverables			Recent and Expected Deliverables			Projected Energy Density (Watt-hour per kilogram)
		Date	Description	Energy Density	Date	Description	Energy Density	
Composite Carbon Fiber	Maxwell/Auburn	7/93	Carbon/nickel/aqueous cells, 20 square centimeters (cm ²)	1.5 - 2.0	7/94	Carbon/nickel/aqueous 20-volt stack, 20 cm ²	1.5 - 2.0	3 to 4
					11/94	8 cell organic bipolar stack, 20 cm ²	8	10 to 12
					7/95	16 cell, 200 cm ² bipolar stack	8	
Aerogel Carbon	Lawrence Livermore	10/93	Aerogel carbon, aqueous cells, 80 cm ²	1 - 2	1/94	Aerogel carbon, organic cells, 80 cm ²	1 - 2	10 to 12
Mixed-oxide (ceramic)	Pinnacle Research Institute	11/93	Mixed-oxide, aqueous 8-volt stack, 80 cm ²	< 2	10/94	Mixed-oxide, aqueous, 28-volt stacks, 80 cm ²	2	5
					1/95	Mixed-oxide, aqueous, 75-volt stack	5	10
Foamed carbon particulate with binder	Sandia Nat'l Lab	11/93	Foamed carbon with binder, aqueous, 1-volt cells	2 - 3				3
Doped polymer on carbon paper	Los Alamos	9/94	Doped polymer, organic (Type I) 1-volt, cell	2 (5 based on active polymer material)	9/96	Type III, 20-volts, 20 cm ²	5	5
Z-axis carbon	Federal Fabrics	11/94	Z-axis carbon, aqueous, 20 cm ² , 1-volt cells	< 2	12/94	Z-axis carbon, aqueous, 20 cm ² , 20-volt stack	6 - 8	10
					6/95	Z-axis carbon, organic, 20 cm ² , 50-volt bipolar	20 - 25	30
Nano-structure multi-layer	Lawrence Livermore	12/94	Single film TiO ₂ , 1 μ 400-volt, 50 cm ² , very low loss (less than 0.1%)		6/94	Multi-layer, TiO ₂ , 1 μ, 400 V, 50 cm ² , very low loss (less than 0.1%)	2 - 3	3

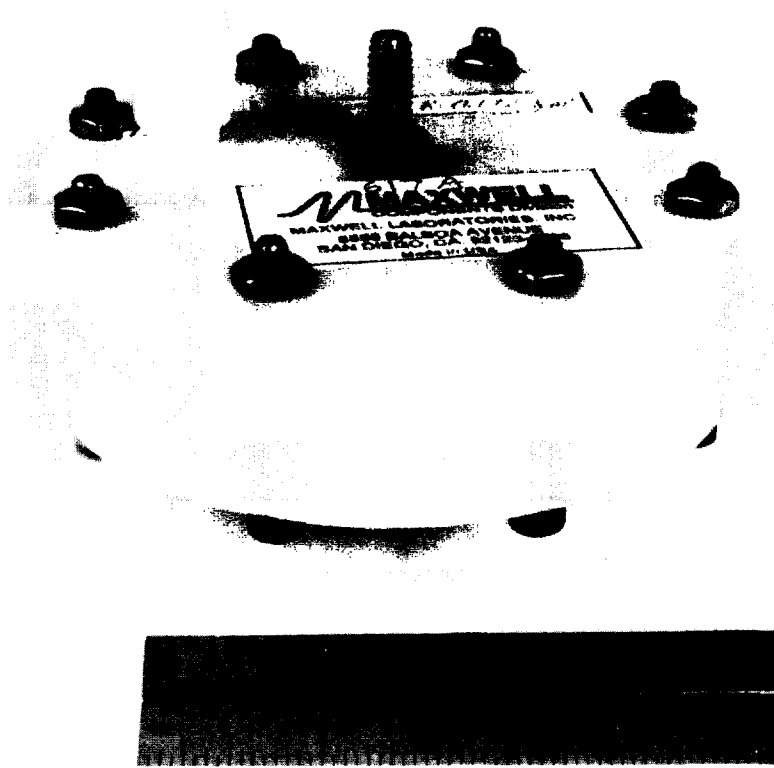


Figure 3-1. Maxwell Laboratories ultracapacitor cell fixture tested at the Idaho National Engineering Laboratory

Development of Type II and III Los Alamos materials with improved specific energy and specific power is on-going, and deliverables for further testing are expected in Fiscal Year 1995.

General Electric Corporate Research and Development in Schenectady, New York, performed a study of the electronics needed to interface an ultracapacitor unit with the battery in an electric vehicle driveline. The interface unit (see Figure 3-2) was designed to control the charge and discharge of the capacitors such that the battery is load-leveled to discharge at the average power required by the vehicle. In addition, the interface electronics unit could uncouple the battery/capacitor voltage from that of the motor/inverter permitting a 100-volt battery/capacitor unit to power a 350-volt motor/inverter drive system. The results of the study indicate that a high efficiency interface unit utilizing soft-switching can be built with the size, weight, and cost comparable to that of the electronics in the Modular Electric Vehicle Program vehicle. The Idaho National Engineering Laboratory Report, "Ultracapacitor/Battery Interface Electronics for Electric Vehicle Drivelines," (EGG-EP-11039), published in October 1993, summarized Phase I results. In Phase II, General Electric will build and deliver hardware for bench testing the design at the Idaho laboratory in late Fiscal Year 1995.

The University of Wisconsin produced porous, conducting ceramic electrodes which were delivered and tested at Idaho. The electrodes are 2-square centimeter, 1-micron thick spin-coated layers of manganese, nickel, and titanium oxides on metal substrates. Preliminary results for the nickel oxide electrodes indicate that this material functions as a capacitor. The capacitance of these research cells was estimated at 0.009 Farads.



Figure 3-2. Ultracapacitor/battery setup using the electronics interface unit

The Pinnacle Research Institute in Los Gatos, California, delivered a 28-volt, 0.825-Farad bipolar ultracapacitor containing mixed metal oxides to the Idaho National Engineering Laboratory at the end of Fiscal Year 1994. Although preliminary calculations indicate that this device will fall short of the Department's near-term specific energy goals, Pinnacle has shown the ability to produce functioning high voltage, bipolar cell stacks incorporating innovative construction techniques.

An "Electric Vehicle Capacitor Test Procedures Manual," (DOE/ID-104-91) was completed by the Idaho National Engineering Laboratory and JME, Incorporated to provide consistent test methods for evaluating the performance of electrochemical capacitors intended for use in electric and hybrid vehicle drivelines. Consistent testing guidelines were needed to compare one technical approach or capacitor product configuration with another. The standardized test methods and reporting can identify critical performance deficiencies, thereby providing direction for subsequent developments.

4.0 FUEL CELL SYSTEMS RESEARCH AND DEVELOPMENT

The Department prepared a comprehensive ten-year National Program Plan for research and development of fuel cells as an alternative to internal combustion engines for vehicle propulsion. The transportation industry, universities, national laboratories, government agencies, regulatory bodies, and alternative fuels-proponents all provided significant input to the formulation of this plan. The plan addresses the development of various types of fuel cells and fuel cell propulsion systems for light-duty and heavy-duty vehicles; fuels processing and on-board storage; technology assessment and systems analysis, strategic planning and quality metrics; and information transfer and public outreach. This plan is currently being reviewed by several program managers from Energy headquarters and the national laboratories, as well as other agencies funding fuel cell-related research and development.

The Department's Chicago Field Office administers cost-shared contracts with industry for fuel cell development. Argonne National Laboratory provides technical management and support for these fuel cell activities.

4.1 Light-Duty Vehicle Propulsion Systems

Proton Exchange Membrane Fuel Cell with On-Board Hydrogen Storage

In Fiscal Year 1994, the Department awarded two 20-percent cost-shared contracts to teams headed by Ford Motor Company and Pentastar Electronics, Inc. (a Chrysler company) to develop fuel cell propulsion systems for light-duty passenger vehicles. The propulsion systems will be based on proton exchange membrane fuel cell technology fueled directly by hydrogen carried on board the vehicle. On-board storage of hydrogen could simplify the fuel cell power system by eliminating the fuel processor and would permit an early demonstration of fuel cells in light-duty vehicles. If this concept proves feasible, stationary fuel reformers (or electrolyzers where appropriate) would supply hydrogen for refueling vehicles much like refueling operations at gasoline service stations.

Ford and its subcontractor team will carry out: (a) the conceptual design of a light-duty passenger vehicle powered by a proton exchange membrane fuel cell system; (b) research and development of on-board hydrogen storage technologies; and (c) the design, fabrication, and laboratory demonstration of a complete, integrated 50-kilowatt propulsion system. Subcontractors on the Ford (Dearborn, Michigan) team include: International Fuel Cells of South Windsor, Connecticut; Energy Partners of West Palm Beach, Florida; H-Power Corp. of Belleville, New Jersey; Mechanical Technology, Inc. of Latham, New York; Tecogen of Waltham, Massachusetts; Directed Technologies, Inc. of Arlington, Virginia; Airco Gases of Murray Hill, New Jersey; Air Products & Chemicals, Inc. of Allentown, Pennsylvania; and Praxair, Inc. of Tonawanda, New York.

The Pentastar (Huntsville, Alabama) team includes: Chrysler Liberty of Madison Heights, Michigan; and an AlliedSignal team led by AlliedSignal Aerospace Systems and Equipment of Torrance, California and supported by AlliedSignal Automotive of Southfield, Michigan and AlliedSignal Research and Technology of Morristown, New Jersey. The

Pentastar/Chrysler/AlliedSignal team is taking a design-to-cost approach to their development activities. For the fuel cell's polymer electrolyte, lower cost alternatives are being developed rather than the traditional perfluorinated sulfonic acid membranes such as Nafion™. Potentially lower cost alternatives for the machined graphite bipolar plate are also being explored. The Pentastar/Chrysler/ AlliedSignal team will also carry out a passenger vehicle conceptual design, conducting research and development of on-board hydrogen storage technologies and laboratory demonstration of an integrated 30-kilowatt power source system. A preliminary conceptual design is shown in Figure 4-1.

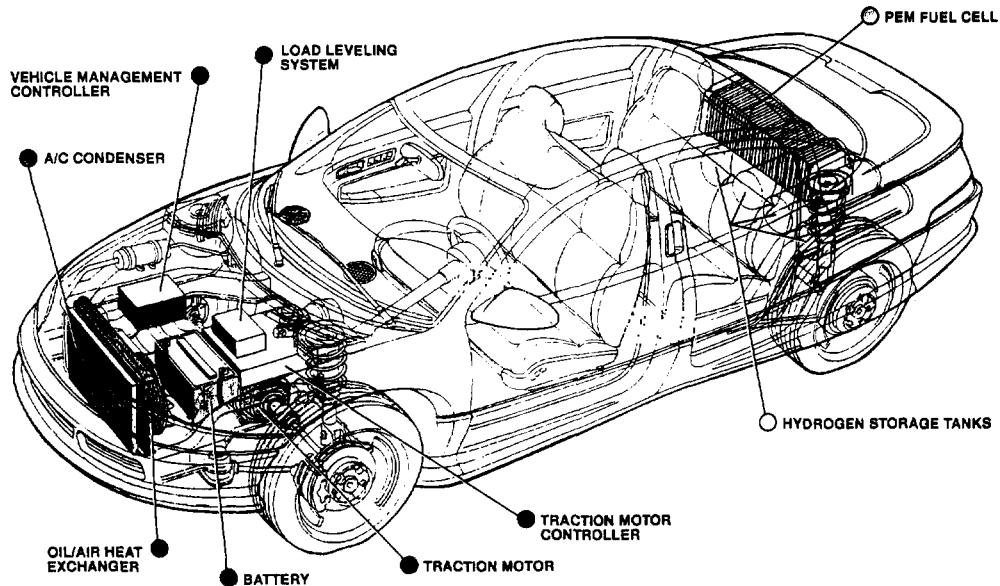


Figure 4-1. Conceptual hydrogen proton exchange membrane fuel cell vehicle

Methanol-Fueled Proton Exchange Membrane Fuel Cell

General Motors has completed a Phase I contract (20-percent cost-shared) that successfully developed and tested a 10-kilowatt methanol-fueled proton exchange membrane fuel cell system. In a conceptual design study for a minivan, the performance of fuel cell technology was shown to be comparable to the internal combustion engine, but with over twice the energy efficiency and nearly zero emissions. In Fiscal Year 1994, the Department awarded a 30-month Phase II follow-on contract to General Motors to continue the development and testing of a complete 60-kilowatt laboratory propulsion system. The General Motors effort includes AC Delco Division (formed by the merging of AC Rochester and Delco Remy divisions) and Harrison Radiator Division. Key subcontractors on the General Motors Phase II team are DuPont, Dow Chemical, Los Alamos National Laboratory, Ballard Power Systems, and Allison Engine Company.

4.2 Heavy-Duty Vehicle Propulsion Systems

The size and weight constraints that tend to limit the application of fuel cells for light-duty vehicles are not as severe for heavy-duty applications. Although the number of heavy-duty vehicles is considerably smaller than the number of light-duty vehicles, the energy savings impact of fuel cell propulsion in this market is significant because of the greater number of miles traveled per vehicle. The Department is working to develop fuel cell technology for heavy-duty applications with their Phosphoric Acid Fuel Cell Bus and Fuel Cell Powered Locomotive activities. A fuel cell transit bus is providing early experience with fuel cell-powered heavy-duty applications. Expanding the use of fuel cells to trucks and locomotives can provide significant economic, energy, and environmental benefits.

Phosphoric Acid Fuel Cell Bus

H-Power Corporation of Belleville, New Jersey completed the third year of a cost-shared contract to design and build three fuel cell-powered urban transit buses. Key subcontractors on the H-Power team are Transportation Manufacturing Corporation, Bus Manufacturing USA Inc., Booz-Allen & Hamilton, Fuji Electric, and Soleq Corporation. The goal is to establish fuel cell technology as a viable alternative to the diesel engine for heavy duty applications.

During Fiscal Year 1994, H-Power completed the fabrication of the first U.S.-built fuel cell powered bus. Public demonstration of the bus was conducted in April 1994 and formal performance tests and evaluations were initiated. The 30-foot long bus provides seating for 25 passengers, typical for a bus of that overall length. The bus fully meets all applicable standards for transit buses. It offers air conditioning and it meets the requirements of the Americans with Disabilities Act by providing a wheelchair lift and on-board accommodations for two wheelchairs.

The fuel cell bus uses a 50-kilowatt phosphoric acid fuel cell to supply all of the vehicle's energy needs. Tests of the fuel cell system confirmed that it operated on methanol fuel at an efficiency of over 40 percent; fuel economy tests over standard transit bus duty cycles are in progress at the Aberdeen Proving Grounds in Maryland. The bus has shown carbon monoxide and nitrogen oxide emissions levels that are more than 30-times lower than the 1998 Federal heavy-duty diesel emission standards, and has virtually no hydrocarbon or particulate emissions. Test and evaluation of bus performance under real operating conditions will also be conducted.

Fuel Cell Powered Locomotive

The Department of Energy has entered into a multi-phased cooperative program with the South Coast Air Quality Management District and other California agencies to study fuel cell powered locomotives. The objective is to show that fuel cell-powered locomotives can meet railroad industry performance requirements comparable or superior to conventional diesel locomotives with dramatically reduced environmental emissions and increased efficiency. During Fiscal Year 1994, a study conducted by the Jet Propulsion Laboratory (with South Coast funding) established the feasibility, benefits, and operational requirements

of fuel cell locomotives. A solicitation was prepared for the first phase of a multi-year program designed to demonstrate the technical and commercial viability of fuel cell-powered locomotives. The solicitation package is currently undergoing internal review.

Development contracts for Phase I will be awarded in 1995. Phase I, an 18-month design phase, is expected to involve one or two contracting teams led by locomotive manufacturers. Contingent on availability of funding, Phase I will lead to the development of a preliminary design for a 1-megawatt (1,350-horsepower) fuel cell test locomotive and the conceptual design of a 2.25 to 4.5-megawatt (3,000 to 6,000-horsepower) commercial locomotive. At the end of the Phase I design study, a contractor team will be selected for Phase II to build and test a 1-megawatt test locomotive over a range of duty cycles to obtain performance and cost data. Phase II is expected to take three years to complete. Phase III, the development of a commercial prototype locomotive, is expected to take an additional three years to complete, with one or more prototype locomotives built by the year 2002. These prototype locomotives will provide the basis for future commercialization of fuel cell locomotives by the U.S. railroad industry.

4.3 Research and Development

A Program Research and Development Announcement for advanced fuel cells for transportation applications was prepared and is currently undergoing internal review. Work that will be funded through this solicitation is expected to lead to significant cost reductions and improved performance in current fuel cell technology and to the development of advanced fuel cells and related components for light-duty transportation applications. This solicitation seeks innovative research in the following areas: (a) cost reduction through new and novel manufacturing techniques and significantly improved performance and reliability of current proton exchange membrane fuel cells; (b) development of fuel cells able to operate directly on methanol, thereby eliminating the need for external fuel reforming; (c) development of solid oxide fuel cells that operate at lower temperatures than current technology permits, thereby eliminating the need for a separate, external fuel reformer and improving the prospects for transportation applications of the technology; and (d) improved components for the balance-of-plant, such as high efficiency compressor/expanders, power electronics, and special exhaust fuel stream burners for fuel cell vehicles. Proposals will be solicited in Fiscal Year 1995.

Fuels Processing and Hydrogen Storage

On-board storage of hydrogen results in the simplest fuel cell vehicle propulsion system, although hydrogen's low energy density requires a large storage volume to achieve adequate range. With on-board reforming, fuel cell-powered vehicles can carry liquid fuels in tanks similar to those in today's cars. Fuel reformers can extract hydrogen from fuels such as methanol, ethanol, and natural gas, and provide the same range capability as today's cars. However, most reformers developed to date have been designed for stationary applications where size, weight, and dynamic response capabilities are not as critical as in most transportation applications. Methanol is the fuel specified in the Department of Energy's fuel cell bus and the General Motors' light-duty passenger vehicle development programs since it

can be derived from non-petroleum sources, is easy to transport, and can be converted to hydrogen at relatively low temperatures. Other fuels are of interest and are being considered.

During Fiscal Year 1994, Arthur D. Little, Inc. of Cambridge, Massachusetts continued Phase II activities in a 30-month contract (17-percent cost-shared and also co-funded by the State of Illinois) to develop a prototype partial oxidation ethanol fuel processor. A bench-scale (approximately 7-kilowatt, equivalent) partial oxidation reformer has been built and scaled up to 25-kilowatts. In subsequent phases of the program, the fuel processor will be integrated with the Department's 25-kilowatt brassboard fuel cell system and, eventually, into one of the Department's fuel cell vehicles (likely a transit bus).

Argonne has built a simple, compact, 5 to 10 kilowatt partial oxidation methanol reformer (see Figure 4-2). Liquid methanol (or a methanol/water mixture) and air are injected into the reformer which contains a copper zinc oxide catalyst on a rugged, light-weight, honeycomb support. The product gas consists of a mixture of hydrogen, carbon dioxide, nitrogen, and carbon monoxide. This reformer has shown rapid cold start capability, producing 15 percent hydrogen in less than 1 minute. Steady-state operation yields 36 to 40 percent hydrogen in the raw reformat, which corresponds to 51 to 54 percent hydrogen after further processing to convert the carbon monoxide and any remaining methanol in a water-gas shift reactor. First tests of transient operation have shown essentially invariant product gas composition following step changes in the methanol and air feed rates. Further tests are being conducted to determine the feasible range of operating conditions and performance over simulated driving cycles.

4.4 Exploratory Technology Development

Much of the exploratory fuel cell technology development managed by Lawrence Berkeley Laboratory, in collaboration with other national laboratories, was directed at improving proton exchange membrane fuel cells and on identifying electrode/electrolyte combinations that lead to a high-performance direct-methanol fuel cell. This type of fuel cell would be smaller and much less complex, compared to the reformed-methanol (hydrogen) fuel cell now under consideration.

One of the key technical issues with this fuel cell is the efficient operation of the polymer membrane. Los Alamos National Laboratory was awarded several U.S. Patents for describing the developments in membrane catalyst layers for fuel cells (No. 5,211,984, issued May 18, 1993; No. 5,234,777, issued August 10, 1993) and for the use of the thermoplastic form of the ionomer (No. 5,234,777, issued August 10, 1993). The first licensing agreement has been signed with a U.S. industrial company to utilize Los Alamos technology for membrane/electrode assemblies in proton exchange membrane fuel cells.

Los Alamos has investigated the use of platinum-ruthenium electrodes and their tolerance to operate effectively in the presence of common gases, namely carbon monoxide and carbon dioxide. The study showed that the advantage of platinum-ruthenium electrode is not to enhance the oxidation of carbon monoxide, but rather to minimize the extent of the carbon dioxide reduction process(es). Exposing the polymer electrolyte membrane fuel cell to freezing and room temperatures demonstrated no deleterious effect on performance. These

results suggest that the direct application of a thin electrode to the membrane generates a very good bond that effectively prevents delamination under demanding changes in operating temperature. Los Alamos developed a new design for distributing the reactant gases that provided higher performance than in cells with the earlier designs. Also, researchers observed that modifying the structure of the electrodes dramatically improved the performance of a direct methanol fuel cell.



Figure 4-2. Argonne methanol reformer test stand

Lawrence Berkeley Laboratory utilized spectroscopic techniques to study the composition of polycrystalline platinum-ruthenium alloys that were used to electrochemically oxidize methanol. When these alloys are heated, the amount of platinum on the surface becomes different from the amount in the solid. This change in the surface composition has significant implications on the effectiveness of these alloys for electrochemically reacting methanol. Lawrence Berkeley observed that the rate for reacting methanol on these alloys increases when the amount of platinum on the surface decreases from 90 percent (reaction at 25°C) to about 70 percent (reaction at 60°C). This change is attributed to the change in the interaction of methanol with the surface sites and with temperature. Lawrence Berkeley is also exploring the use of nuclear magnetic resonance to obtain information about chemical species that poison platinum-containing materials used for electrochemically reacting methanol.

Brookhaven National Laboratory utilized advanced spectroscopy techniques involving X-rays to study how the presence of small amounts of lead on platinum changes the rate at

which small organic molecules react on the platinum surface. The results suggest that the enhanced rate of the reaction is attributed to the layer that forms as a result of the presence of lead, and not to a process involving oxygen, which often plays a role when small organic molecules react electrochemically on a platinum surface.

4.5 Vehicle Systems Analyses

Argonne National Laboratory is analyzing a comprehensive set of options for polymer electrolyte fuel cell systems which include systems based on hydrogen, methanol, and natural gas as the on-board fuels. For on-board hydrogen, fuel storage options include compressed gas, magnesium hydride, iron-titanium hydride, and sponge iron (which generates hydrogen by reacting with steam). Only compressed gas storage was considered for natural gas. Hydrogen can be used directly in the fuel cell, but methanol and natural gas must first be reformed to hydrogen. For the latter two fuels, both steam and partial-oxidation reforming were considered. Table 4-1 summarizes the various fuel, fuel storage, and fuel processing options analyzed; the energy content of the fuels; and the calculated system (based on the on-board fuel) and "global" (based on the natural gas used to produce hydrogen and methanol) efficiencies.

Table 4-1. Argonne National Laboratory Systems Modeling Activity Summary

Fuel/Storage	Fuel Energy Density		Reforming	System Efficiency, percent	
	megajoules per kilogram	megajoules per cubic meter		On-board	Global
H ₂ , 200 atmospheres	142.8	2,320	None Needed	52.3	44.5
H ₂ , Mg Hydride	10.8	18,849		32.3	27.5
H ₂ , Fe-Ti Hydride	2.7	17,564		52.6	44.7
H ₂ , Sponge Iron	4.8	35,252		42.9	—
Methanol, liquid	22.7	16,662	Steam	44.8	30.5
			Partial Oxidation	40.2	27.3
Natural Gas, 200 atmospheres	55.5	7,240	Steam	41.1	41.1
			Partial Oxidation	40.9	40.9

The different systems can be compared on the basis of fuel storage, fuel processing, and balance-of-plant considerations. Of the three fuels considered, methanol has the highest

energy density, while compressed hydrogen, at a pressure of 200 atmospheres, has the lowest. Methanol is also the most attractive from the standpoint of refueling. The polymer electrolyte fuel cell systems use a variety of components -- pumps, compressors, fans, turbines, burners, heat exchangers, and catalytic reactors. This hardware requirement is the least extensive for the compressed hydrogen on-board system, and the most extensive for the steam-reformed natural gas system.

The Argonne analyses show that polymer electrolyte fuel cell systems for transportation can have on-board system efficiencies of about 52 percent with hydrogen, 45 percent with methanol, and 41 percent with natural gas fuels. Based on natural gas as the primary fuel source, the corresponding global efficiencies are approximately 44, 31, and 41 percent, respectively. These efficiencies do not take into account the energy used in the distribution and retailing of the fuel, nor the energy consumed in vehicle refueling. Further, because these are efficiencies at the design load (full load), system operation at part-load is expected to yield higher efficiencies. Continuing studies will analyze the performance of these systems over standardized automotive driving cycles.

5.0 PROPULSION SYSTEMS RESEARCH AND DEVELOPMENT

In Fiscal Year 1994, the Department supported various activities to improve the commercial viability and customer acceptance of electric vehicles, such as: a) development of a hybrid propulsion system that would have the energy and environmental benefits of an electric propulsion system with the range and drivability of a heat engine; b) integration of subsystems and components into modularized electric propulsion systems that match vehicle requirements; and c) field testing and evaluation of electric vehicle technologies, and prototype and limited production electric vehicles.

5.1 Hybrid Propulsion Systems Program

The range, performance and market acceptance of electric vehicles are currently limited by the lack of suitable battery technology. A hybrid vehicle using a combination of electric and internal combustion engine systems would offer the extended range and rapid refueling that consumers expect from conventional vehicles, as well as energy and environmental benefits of an electric vehicle. In the long-term, hybrid vehicles would help improve the consumer acceptance of electric vehicles. However, technological advancements are necessary to bring hybrid vehicles up to the level of performance, quality, safety, and value of vehicles powered by internal combustion engines.

The Hybrid Propulsion Systems Program is specifically aimed at assisting the United States auto industry in developing and demonstrating the commercial viability of hybrid propulsion systems. More specifically, the objective is to develop a near-term passenger vehicle that exhibits the following characteristics:

- has double the fuel efficiency of current vehicles;
- meets Environmental Protection Agency Tier II emission standards;
- competes with conventional vehicles on performance, range, safety, and cost;
- can operate on alternative fuels; and
- has significant consumer acceptance.

The Department has competitively selected two industry-led teams (headed by General Motors Corporation and the Ford Motor Company) to design, construct, and test hybrid propulsion systems over a five year period. These teams are funded under 50-percent cost-shared contracts managed by the Midwest Research Institute for the Department. At the conclusion of the projects, the prototype hybrid propulsion systems will be at the stage where a decision can be made by the automotive industry whether to mass produce and market hybrid vehicles. Table 5-1 shows the subcontractors included in the teams of General Motors and Ford.

The **General Motors Team** made substantial progress during Fiscal Year 1994 with the completion of the Concept Definition Phase. A wide range of hybrid propulsion system technologies were evaluated for their potential to meet program goals without compromising customer's expectations for value, performance, safety, and convenience. After weighing the considerable modeling and analysis results, it was decided that the program's mainstream

propulsion system will be a series configuration electric hybrid. This early decision will help to focus the program on developing those ancillary power units, motors, batteries, and control architectures most suitable to that configuration.

A hybrid technology test bed vehicle was built as a rolling laboratory for testing and evaluating various hybrid powertrain components. This vehicle permits components to be easily removed and replaced without the expense of integrating them into a production configuration. The test bed vehicle will also be used to refine the system control architecture and to better understand the issues and complexity of managing multiple energy sources.

A customer clinic on hybrid technology was held in Los Angeles to assess the public's attitudes and preferences regarding hybrid vehicles. Different hybrid vehicle attributes were defined and matched against a price trade-off. The information gathered through this exercise will be used to guide program decisionmaking and product design.

Table 5-1. Hybrid Propulsion System Development Program Lower-tier Subcontractors

General Motors Team	Ford Motor Company Team
Allison Engine Company Corning, Incorporated Kyocera Ceramics Norton Advanced Ceramics Goodyear Tire Lawrence Livermore National Lab Stirling Thermal Motor Company Pacific Scientific AeroVironment, Incorporated Consolidated Edison Company, NY Exxon Research & Engineering Company University of Idaho Onan Corporation The Analytical Sciences Corporation	Allied Signal Onan Corporation Sierra Research Pinnacle Research GE-Corp Research Division United Technologies Unique Mobility Energy Partners Directed Technologies Automotive Support Group Johnson Controls Mechanical Technology, Inc. A.D. Little GNB Industrial Battery Chevron Research

The **Ford Team** initiated the Systems Study/Definition Phase in Fiscal Year 1994. Each of the team members submitted preliminary performance parameters and operational and physical characteristics for the subsystem or component they are developing. These data will be utilized in the Ford corporate vehicle simulation program to evaluate and compare various hybrid configurations, component alternatives, perform trade-off studies, and explore different operating strategies. Data has also been collected describing several real world driving cycles which will be used to size components and develop detailed performance specifications.

Progress has been made in the modeling and preliminary design of several advanced technology components which could offer enhanced hybrid vehicle performance. These critical components include the flywheel, high power density batteries, wheel motors, and the turbo-alternator. Major issues for each of these components are size, weight, efficiency, response time, reliability, and cost. Increased resources will be directed later at infusing these attributes at the system level with a focus on manufacturability and assembly issues.

In cooperation with the two system development contracts, the Department is placing further emphasis on the development of technologies that are considered critical to the success of hybrid propulsion systems. These "enabling" technologies fall under three general categories: energy storage, electric propulsion, and power units. Technology development efforts will focus on performance enhancements as well as cost reduction. Improvements in any of these technologies will also benefit electric vehicle development.

Many existing government programs are developing similar technologies for other applications. Negotiations with the sponsoring agencies are proceeding in order to include hybrid propulsion system requirements in their programs. This approach will allow the Department to leverage its resources and avoid duplication of efforts. The Department completed a revision of the Hybrid Propulsion System Program Plan. The revised plan includes the General Motors and Ford system development projects and discusses the initiation of a coordinated multiagency program for the development of "enabling" hybrid propulsion technologies.

5.2 Modular Electric Vehicle Program

The Department has a cost-shared contract with Ford Motor Company (with subcontract to General Electric) for the development of a modular electric powertrain subsystem that could be produced from a common design. This powertrain would be accommodated in a wide range of electric vehicles -- from small passenger cars to front- and rear-wheel drive full-size vans. Because of economics of mass production, modularization of the electric powertrain across a variety of models and sizes would result in reduced cost and allow for early market entry of electric vehicles.

In January 1994, Phase II of this project concluded with the development of a modular (75-horsepower) electric drivetrain that was incorporated into a Ford Ecostar testbed electric van. The vehicle (see Figure 5-1) was delivered to the Idaho National Engineering Laboratory for engineering evaluation and field testing. Data was not collected in Fiscal Year 1994 because the Ecostar was involved in a head-on collision with another vehicle on a public street during the course of engineering evaluation at Idaho. However, the sodium/sulfur battery remained intact and undamaged, although the electric van suffered substantial damage to the chassis and running gear. Evaluation of a replacement vehicle will commence during the first quarter of next Fiscal Year.

The final review of the Ford/General Electric effort was held in Washington, D.C. on March 15, 1994. At that time, Ford had successfully fabricated more than 100 drivetrains of the same size (75-horsepower) which were integrated in Ford Ecostar electric vans. These

vans will undergo extensive field testing and engineering evaluation at various locations throughout the United States and overseas starting in Fiscal Year 1995.



Figure 5-1. Ford Econoline with modular electric powertrain for testing, data collection, and public demonstration in California

5.3 Site Operator Program

The 13 participants in the Site Operator Program are located in various regions of the United States, allowing operation, testing, and evaluation of electric vehicles in a wide range of climate, weather conditions, and terrain. Electric vehicles are used as delivery vans and trucks, commuter vehicles, and in mixed categories of transportation; others are used primarily for demonstrations to increase public awareness of these vehicles. Most of the problems encountered with these vehicles are associated with their batteries. Improvements are needed in battery chemistry, design, manufacturing techniques, and charging and maintenance practices. Improved and dependable control and drive components are also needed. The contractor's cost-shared percentages for this program are listed in Table 1-1.

The program continues to promote public exposure to electric vehicles. The annual "Solar and Electric 500 Race," sponsored by Arizona Public Service, attracted about 75 entries and national attention. Approximately 35 to 40 local and regional high schools participated with entries and local, regional, and national corporate sponsors provided support to the participating high schools. The Site Operator Program participants also displayed their vehicles at energy conferences, technical symposiums, and public participation "ride and drives" across the nation.

Program management activities continued in a variety of areas including: management of Site Operator activities, presentations on the Site Operator Program, participation in activities of other electric vehicle groups (i.e., the Electric Power Research Institute and the Electric Vehicles Association of the Americas), publishing technical and progress reports, and supporting the development of components and infrastructure. The Program was represented on three of the Electric Power Research Institute's National Electric Vehicle Infrastructure Working Committees and participated in the Electric Vehicles Association of Americas working groups on data collection and public awareness.

Purchase orders for a total of 42 pickup conversions have been placed with U.S. Electricar and Spartan Motors. The Spartan Motors conversions utilize a General Electric drivetrain, and the U.S. Electricar vehicles feature a Hughes drivetrain. The Site Operator Program supported EV America in the development of specifications for solicitation of vehicles they will purchase to achieve their program goals. Site Operator Program support of EV America continues through technical assistance in the testing and selection of vehicles proposed by vendors in response to solicitations.

Arizona Public Service currently operates nine electric vehicles, primarily in the Phoenix area. Seven of these are new demonstration vehicles: three EVcorts, one Solectria, one Solar car, and two G-Vans made by Griffon. Much of the vehicle use is for demonstration, often under loan or lease arrangements. Technical information is coordinated with Southern California Edison, the U.S. Department of Energy, the Idaho National Engineering Laboratory, and the Electric Power Research Institute. For public education, the Electric Vehicle Information Center at Arizona Public Service's Corporate Headquarters in Phoenix contains displays depicting the history and environmental benefits of electric vehicles and demonstrations of the operation and efficiency of electric vehicles. Arizona Public Service also sponsored the 1994 Solar and Electric 500 Race, which included nearly 75 entries, and supports electric vehicle clubs in Phoenix and Tucson with technical information and presentations. As a result, Arizona Public Service has contact with more than 100 electric vehicle owners in the state. They also used their Saturn electric race car and the Brawner Motorsport EX-11 electric "Indy" racer to promote electric vehicles throughout the United States.

Kansas State University, in conjunction with the Kansas Electric Utilities Research Program, a joint venture of six major electric utilities in the State, is taking a leading role in introducing electric vehicles in Kansas. Several industrial organizations in the State also provide technical and financial support to the Program. Three electric vehicles (a G-Van, and two EVcorts) are at this site. Western Resources, working in cooperation with Kansas State and Eagle Picher, are conducting research and testing of advanced battery technology in a G-Van.

Los Angeles Department of Water and Power operates eleven electric vehicles, including a hybrid minivan, a Uniq (from Unique Mobility, Englewood, Colorado), which is being tested and evaluated as a candidate fleet vehicle. The Los Angeles Department of Water and Power is a participant in the CALSTART Electric Bus/Mass Transit Program.

Orcas Power and Light Company operates a Solectria Force and a converted Ford Escort on the islands of San Juan County, Washington, where short driving distances and lower speed limits make the area particularly well suited to current electric vehicles. Orcas Power and Light Company has installed curbside charging stations, developed by Kansas State University. To date, these charging stations have been mainly used for demonstration purposes; however, the San Juan County Department of Public Works has made provisions for an electric vehicle charge station in the specification for a major road project on Orcas Island.

Pacific Gas and Electric Company operates three G-vans in California's Bay Area. Five Ford Ecostar vans have been ordered and will be used for testing, data collection, and public demonstrations.

In addition to testing and evaluation, Pacific Gas and Electric actively promotes many aspects of electric vehicle infrastructure development, commercialization, and related issues. For example, they are collaborating with other public utilities and the Electric Power Research Institute to establish a test protocol for human exposure to electromagnetic fields, and has applied to the California Public Utilities Commission for approval of more favorable billing rates for electric vehicle charging systems. Pacific Gas and Electric is also working with automakers, utilities, code specialists, and other organizations to establish a standard, safe, and reliable electric vehicle charging infrastructure. To further assist in the development and commercialization of electric vehicles, Pacific Gas and Electric has agreed to participate in the General Motors Corporation Preview customer evaluation program for the Impact IV passenger electric vehicle.

Platte River Power Authority operates two Soleq EVcort electric vehicles. They completed a project to develop a "smart" controller for charging electric vehicle batteries that allows the user to input charging requirements such as cycle completion time and state-of-charge at the end of the charging cycle. The controller determines charge initiation time and charge rate based on user input, battery pack state-of-charge, and the utility rate in effect at the required time. The smart controller minimizes impact on the utility's peak demand, maintains user convenience, and minimizes charging cost.

Platte River Power Authority tested thermal management techniques for winter battery operation, including charging in a heated environment and vehicle preheat from wall-plug power. These increased passenger comfort, as well as increasing the driving range.

Potomac Electric Power Company, a Washington, D.C. utility, operates three electric vehicles, primarily in fleet service.

Public Service Electric and Gas Company in Newark, New Jersey, is evaluating eight General Motors Corporation G-Vans and three Chrysler TEVans. The main thrust of the Public Service Electric and Gas Company efforts are evaluation of electric vehicles in daily use and normal fleet requirements.

Southern California Edison Company currently operates and maintains a fleet of 24 electric vehicles consisting of 15 Conceptor Industries G-Vans, and 9 other electric vehicles. In 1993, they purchased 2 Solectria Forces, a Shuttle Bus, a converted Ford Ranger pickup, and a converted Ford Tempo. Cumulative miles to date are more than 240,000. They are also exploring additional electric vehicle purchases and leases.

As part of Southern California Edison's Infrastructure Program, two G-Vans are on loan to Federal Express, one G-Van is in service with Miller Brewing Company, and a fourth with the City of Fountain Valley, California. They are also working with Ford and the U.S. Postal Service to lease six Ecostars to be placed into service with the Post Office, and two school buses are being converted in a cooperative effort with CALSTART. The six Ecostars and two buses will become part of the Site Operator Program at Southern California Edison.

Vehicle and component testing not only serves to identify technical advances and problems, but also provides essential input to planning and operating the electric utility system. An example, is the measurement of the distortion and power factor shift attributable to electric vehicle chargers.

Texas A&M University conducts its Site Operator Program activities in College Station, Texas, at its Center for Electrochemical Systems and Hydrogen Research, and in conjunction with the South Central Electric Vehicle Consortium, a group that includes Texas A&M, nine utilities, and other organizations. Currently, the Consortium operates 25 passenger and cargo electric vehicles, and 2 zinc-bromine battery-powered race cars. A Texas A&M G-Van is currently being used as a demonstration vehicle in Houston by the Electric Power Research Institute, and another in Austin by the Lower Colorado River Authority. Limited driving range has been the major problem with all the G-Vans.

The Texas A&M University electric car race team supported their University of California counterparts in building an electric car. The vehicle, converted from a Geo Prism, and powered by a zinc-bromine battery and alternating-current drive system, placed third in the 1994 Solar and Electric 500 stock car race (co-sponsored by Arizona Public Service and the Department of Energy) held in Phoenix, Arizona.

The South Central Electric Vehicle Consortium, based at Texas A&M University, supports the Program, and serves as a clearinghouse for information exchange between electric vehicle fleet operators in Texas and Oklahoma.

University of South Florida maintains a fleet of two G-Vans, six Chevrolet S-10 conversions, and one Mitsubishi Mirage conversion. One of the six S-10s is operated by the Pinellas County Air Quality Office and another by the privately owned Bruderly Engineering Associates of Gainesville. Performance data collection is simplified by the Mobile Data Acquisition System developed by the University. The system automatically monitors and stores main battery pack voltage, current, temperature, electric vehicle velocity, cab temperature, and ambient temperature, all relevant for optimum performance in the Florida climate. An Automatic Data Retrieval System receives Mobile Data Acquisition System data via cellular or land-line telephones for processing and analysis by University computers. This

system will be used in the Site Operator User Task Force vehicles for enhanced data collection.

The University of South Florida operates a photovoltaic charging system. Four source circuits accommodate direct charging of the S-10 pickup batteries. An automatic photovoltaic data acquisition system acquires data from the arrays to analyze overall performance and effectiveness.

The U.S. Navy maintains a total of 66 electric vehicles in daily use and participates in the Site Operator Program at no cost to the U.S. Department of Energy. Several types of electric vehicles are operated on Naval bases in climates ranging from frigid to tropical. The Navy is the advisor to the Department of Defense on electric vehicle applications, and has contributed much information on their use and technology.

York Technical College, at Rock Hill, South Carolina, operates 11 electric vehicles. The school's enthusiasm for electric vehicle technology is demonstrated by its growing Electric Vehicle Program and its pursuit of public awareness. York has been, and continues to be, deeply involved in developing a curriculum for training electric vehicle technicians. York has worked with General Motors, CALSTART, and other organizations to define and implement the program, the first of its type in the country. York interfaces regularly with local electric utilities, other Program participants, municipalities, the South Carolina State Energy Office, regional secondary schools and colleges, and the Clean Air Transport Association. Vehicles from the York fleet are being used by Duke Power, the City of Rock Hill, and Palmetto Electric Company. York's electric vehicles were publicly displayed and demonstrated numerous times during the year, many in collaboration with the Duke Power Company, and more are scheduled, including electric vehicles at the 1995 Olympics in Atlanta, Georgia.

Sandia National Laboratory at Albuquerque, New Mexico, although no longer a participant in the Site Operator Program, continues its electric vehicle work and shares information with the Program. Sandia has operated, on a daily basis, seven Ford Escort Electricas since 1981 and four other electric vehicles since 1987. A twelfth Electrica (1983 model) was obtained from Public Service Company of New Mexico and placed into service.

5.4 Engineering Evaluation and Testing

Dynamometer and Laboratory Tests

Dynamometer and laboratory tests evaluate the performance of electric vehicle systems and components under repeatable and well-defined operating conditions that simulate actual electric and electric/hybrid vehicle operation and environments. The objectives of the testing and evaluation are to: (a) subject batteries to the actual electrical loads of high technology electric vehicles in testbed vehicles on a dynamometer; (b) evaluate advanced drive systems in electric and electric/hybrid vehicles on the track, road, and dynamometer; (c) test and characterize auxiliary systems, such as battery chargers, state-of-charge indicators, and battery monitoring and thermal management systems in a realistic environment; and (d) test advanced

batteries by electrically loading them with complex driving cycle power profiles in a controlled laboratory environment over a range of operating temperatures from -20° to +80°C.

At the Idaho National Engineering Laboratory, dynamometer and battery tests are performed routinely on electric vehicles using standard driving profiles such as the Society of Automotive Engineers electric vehicle driving cycles (SAE J227a and SAE J1634). Special tests have been performed in the laboratory and on the test track to provide direct comparisons of alternating current and direct current powertrains, measure regenerative braking performance, evaluate air-conditioning concepts, evaluate interior noise levels, and measure electromagnetic emissions.

Electric Vehicle Testing for California Air Resources Board

California legislation now mandates a fixed percentage of zero-emission highway vehicles, with a 1998 deadline for full implementation. The California Air Resources Board entered into a Memorandum of Understanding with the U.S. Department of Energy for electric vehicle testing to collect data to further that objective. This Memorandum is implemented through a Cooperative Research and Development Agreement with the Idaho National Engineering Laboratory. The Agreement protects from public release all data developed under this effort.

During the Fiscal Year 1994, testing was initiated on advanced electric vehicles. The test vehicles included the ELX of AC Propulsion, Incorporated, the Solectria Force (see Figure 5-2), and a prototype Honda electric Civic. Most of the testing was conducted in the Vehicle Dynamometer Laboratory at the Idaho National Engineering Laboratory facility where on-road testing was accomplished using the laboratory's Versatile Data Acquisition System in the vehicle. In most instances, the dynamometer used coastdown and road-load data taken with the System. Measurements were made of battery voltage, current, and power for various driving modes for each of the vehicles. The driving modes included constant speeds between 40 and 96 kilometers per hour, the Federal Urban Driving Schedule and Highway Fuel Economy Driving cycles. Maximum effort acceleration tests were also performed.

The test data were used to calculate the energy consumption (watt hours per kilometer) and the driveline efficiency (from the battery terminals to the wheels) for each of the vehicles for the various driving modes. The data were also used to determine the characteristics (capacity and charge/discharge behavior at different rates) of the batteries in the vehicles. The vehicles were tested using a variety of battery types: sealed lead/acid, nickel/cadmium, sodium/sulfur, and nickel/metal-hydride. An abbreviated summary of these test results is presented in Table 5-2. Some of the vehicles tested were very efficient, having driveline efficiencies between 80 and 90 percent for most driving modes. Most of the vehicles exhibited good acceleration characteristics, with the ELX having a 0 to 96 kilometers per hour acceleration time of under 10 seconds. For all the vehicles, comparisons were made between the empirical data and calculated values obtained using the Idaho-developed SIMPLEV vehicle simulation program. Good agreement was found in all cases, with the differences between the laboratory data and predictions being generally less than 5 percent.



Figure 5-2. Solectria Force vehicle tested at the Idaho National Engineering Laboratory

Table 5-2. California Air Resources Board/Idaho National Engineering Laboratory summary test results

Driving Cycle	AC Propulsion ELX	Solectria GT
FUDS ¹ (net, watt-hours per kilometer)	101	109
Highway (net, watt-hours per kilometer)	97	122
LA 92 (net, watt-hours per kilometer)	127	137
All Electric (FUDS ¹ + HWFET ²) (net, watt-hours per kilometer)	100	113
¹ Federal Urban Driving Schedule cycle ² Highway Fuel Economy Driving cycle		

Test Procedure Evaluation

A cooperative effort between the Department and the Environmental Protection Agency was initiated this Fiscal Year to evaluate a test procedure promoted by the Society of Automotive Engineers for measuring the energy efficiency and driving range of an electric vehicle. Dynamometer tests involved the use of Environmental Protection Agency Urban

Driving Schedule and the Highway Fuel Economy Test. A key evaluation point of interest is the potential variation in test results at different laboratories.

Since the purpose is to evaluate the test procedure and not the vehicle, the approach controls the items which would be expected to produce test-to-test variations but does not control items which would normally vary with implementation of the procedure. The laboratories selected (Idaho National Engineering Laboratory, Environmental Protection Agency, Ford Motor Company, Southwest Research Institute, and the California Air Resources Board) to participate in this project represent a cross-section of the types of laboratories expected to rely on this procedure in the future.

Controlled variables include the vehicle, instrumentation, and the data acquisition system. An EVcort electric vehicle was chosen as the test vehicle because of its proven consistency and reliability. Instrumentation and the data acquisition system supplied by the Idaho National Engineering Laboratory is common to all tests at all test sites.

Tests conducted at four of the five selected test sites on five different dynamometers were completed in Fiscal Year 1994. Results of the tests completed thus far indicate that the direct-current energy consumption measured at each test site compare favorably. However, large differences in system alternating-current energy consumption were noted. This disparity is largely attributed to variations in battery behavior and differences in alternating-current electrical service available at each of the sites. Details of the test results from the participating laboratories, including critiques of the test procedure implementation, will be reported by the Idaho laboratory at the completion of the test program.

Systems Modeling

The computer simulation code, SIMPLEV, developed by the Idaho National Engineering Laboratory, was significantly improved during Fiscal Year 1994 and released as Version 3.1. Minor improvements in Version 3.0 were made as a result of the needs of users to predict the vehicle performance of state-of-the-art electric, series and parallel hybrid, and ultracapacitor/battery powered vehicles. And like previous versions, 3.1 can be run on any IBM compatible personal computer. The following are the most significant features that have been added and are contained in SIMPLEV Version 3.1.

- Output displays have been significantly upgraded. The user may choose between three display modes (text, 320 × 200 graphics, and 640 × 480 graphics display modes).
- Ability to model parallel hybrid and ultracapacitor hybrid propulsion systems has been added.
- A separate utility was created to allow the user to build and/or edit a file containing all of the necessary inputs to the simulation, and then run the simulation in "batch" mode using this file.
- Context sensitive information and "help" text has been included. The Ctrl-h key combination at any point during the simulation displays a list of special

keys and their use. The user may also add additional information or customized notes to the help text as desired.

- Periods of vehicle coasting may be specified during the driving cycle.
- Road grade and vehicle direction may be given as a function of distance and driving profiles can be defined as a function of time or distance.
- Wind speed and direction as a function of time may be specified.

SIMPLEV has been licensed to more than 70 users including automobile companies, battery companies, component suppliers, and colleges and universities. The code has also been distributed to other government agencies.

5.5 Student Competitions

The 1994 Hybrid Electric Vehicle Challenge

The Hybrid Electric Vehicle Challenge is an annual student engineering competition cosponsored by the U.S. Department of Energy, the Society of Automotive Engineers, Natural Resources Canada, and the "Big Three" automakers. It provides future engineers with opportunities to design, build, and test "real-world" hybrid electric vehicles. Students from a variety of disciplines including engineering, computer science, business, and communications work together in vehicle development teams. The teams develop innovative and environmentally responsible vehicles that combine electric and thermal power to improve mileage and reduce emissions while maintaining performance comparable to conventional vehicles. Safety, energy efficiency, and the use of alternative fuels are the cornerstones of the Hybrid Electric Vehicle Challenge. This competition provides a wealth of technical data from innovative and advanced designs that complement and enhance industry's research and development efforts.

The 1994 Hybrid Electric Vehicle Challenge was held in Southfield, Michigan from June 14-21. Over 800 students representing 38 colleges and universities came from across North America to the campus of Lawrence Technological University to participate in this event. The hybrid electric vehicles were divided into three classes: Saturn vehicles converted to hybrids, Ford Escort conversions, and hybrids built from the ground-up. Competitive categories included designs and capabilities in acceleration, long-range and urban-type driving cycles, energy economy, and low emissions. Some of the vehicles also used alternative fuels such as ethanol and methanol. The overall winners of the 1994 Challenge were the University of Maryland, Saturn conversion class; Weber State College, Ford Escort conversions; and the University of California, Davis, Ground-Up class.

Computer software simulations and data collection are key derivatives of the annual Hybrid Electric Vehicle Challenge. The data collected from the 1994 Challenge was used to validate simulation code (simulation results were compared to actual performance data). Parametric runs are currently being performed using the simulators to determine the sensitivity of hybrid performance to various vehicle and component specifications. The

simulators were also used to predict performance of the industry hybrid electric vehicles under challenging driving conditions, such as extended mountain climbs. Future work includes developing an object-oriented hybrid vehicle simulator to which emissions prediction will be added after extensive laboratory and field testing.

The Hybrid Electric Vehicle Challenge is also contributing data for the development of a standard test procedure for hybrid vehicles. The National Renewable Energy Laboratory and the Society of Automotive Engineers are working together to develop this procedure. The procedure, which is currently in the evaluation and refinement stage, will be presented to the Environmental Protection Agency and other regulatory organizations for their adoption. Three of the vehicles that participated in the 1994 Challenge are being tested against the procedure as part of the evaluation process.

6.0 OTHER ACTIVITIES

6.1 The Energy Policy Act of 1992 and the Electric and Hybrid Vehicles Program

Deployment Activities

Section 2025 (f) of the Energy Policy Act requires the Department to undertake activities that will accelerate deployment of advanced battery technologies for electric vehicles. The United States Advanced Battery Consortium has formed a Commercialization Task Force, comprised of senior members of the Consortium's Management Committee, to examine new possibilities for industry and government to cooperate on deployment issues. The Task Force has considered ways for the Federal government to participate in a potential Phase II of the Consortium, which could involve commercialization activities. However, the current program emphasizes research and development.

Also required under Section 2025(f) are inventories and assessments of advanced battery and electric vehicle technology and commercial capability. As an internal effort, the United States Advanced Battery Consortium is also conducting mid- and long-term assessments of the technologies under development. Because of the competitive nature of this program, these assessments are protected from disclosure as 'Protected Battery Information'. Protection is provided up to a period of five years beyond the completion of the project.

In Fiscal Year 1994, the Department worked with a private non-profit organization called the Electric Vehicle Market Development Group in Washington, D.C. to set up an acceptance trial for electric vehicles. This work on this program will continue through Fiscal Year 1995.

Encouraging Purchase and Use of Electric Vehicles

In response to Section 615(b) of the Energy Policy Act, the U.S. Department of Energy initiated a study of electric vehicle costs and methods to reduce those costs. The study, as specified, is to report on methods for encouraging the purchase and use of electric motor vehicles. Specific objectives are to:

- Assess the potential cost of purchasing and maintaining electric vehicles, including the initial cost of the batteries and the cost of replacement batteries,
- Identify methods for reducing, subsidizing, or sharing such costs, and
- Recommend legislative and administrative measures to encourage the purchase and use of electric vehicles.

This study will continue through Fiscal Year 1995.

Demonstration Projects

In Fiscal Year 1994, no funds were appropriated for demonstration projects under Subtitle A -- Electric Motor Vehicle Commercial Demonstration Program of the Energy Policy Act of 1992. No activities were conducted under this subtitle.

6.2 Interagency Coordination

Coordination on Electric and Hybrid Vehicle Technologies

The Interagency Coordination Task Force for Electric and Hybrid Vehicle Technologies continued to coordinate and integrate the programs and policies of Federal agencies that research, develop, test, and promote electric and hybrid vehicles and associated technologies.

A Memorandum of Understanding was entered into by the Department of Energy with the Department of Defense Advanced Research Projects Agency in June 1994 to document a commitment to support common interests and objectives in the research, development, and demonstration of transportation, fuel cell, natural gas, and coal technologies for military and public benefit.

The Partnership for a New Generation of Vehicles

On September 30, 1993, the United States government and the United States Council for Automotive Research (representing Chrysler, Ford, and General Motors) formed an historic new partnership called the Partnership for a New Generation of Vehicles. This partnership is aimed at strengthening U.S. competitiveness by developing technologies that could lead to near-term improvements in auto manufacturing, mid-term improvements in the fuel efficiency of conventional vehicles, and the long-term development of a new generation of vehicles with up to three times the fuel efficiency but possess the same performance/operational attributes as comparable production vehicles, and meet the Environmental Protection Agency's Tier II emissions standards.

Several technologies being developed by the Electric and Hybrid Vehicles Program have been recognized as both relevant and important to the Partnership. Successful development of hybrid propulsion systems that could double the fuel economy of conventional vehicles is an important step in achieving the Partnership's long term goal of achieving triple fuel efficiency. Also, fuel cells continue to be a viable long term technology candidate that could offer improved fuel efficiency and minimal environmental emissions. High power batteries and ultracapacitors for energy recovery and storage are also important in improving the overall energy utilization by the vehicle.

In Fiscal Year 1994, the Electric and Hybrid Vehicles Program coordinated with the Partnership to ensure that technologies currently under development could contribute positively to the successful development of the new generation of vehicles by industry.

6.3 Database Development

The Idaho National Engineering Laboratory continued development of personal computer-based databases, and developed telephone and Ethernet computer network capability linking the Idaho laboratories and Electric and Hybrid Vehicle Program staff. This computer network also provides off-site user access to the databases.

Electric and Hybrid Vehicle Battery Test Database

During Fiscal Year 1994 the Idaho National Engineering Laboratory continued the development of its Electric and Hybrid Vehicle Battery Test Database and utilized the database as a mechanism to transfer test results to the customer, via Internet, in a more timely manner. To achieve this, three computer software technologies were developed. First, a computer automated data qualification system was acquired and modified for electric vehicle testing applications, under a contract with the Advanced Modeling Techniques Corporation of Idaho Falls, Idaho. The software, called the Advanced Data Validation and Verification System, assures the quality of test data, in an automated manner, using multi-variate statistical modeling technology. The software is now used in the Idaho Electric and Hybrid Vehicle Battery Test Laboratory and will be implemented in the Vehicle Test Laboratory early in Fiscal Year 1995. A second software allows a customer to remotely access the Battery Test Database, view the data, and ultimately download the test results, utilizing either the Internet or a telephone modem. A computer server provides security for proprietary data files, in order to prevent access by unauthorized users. Thus, for a typical battery test, the test results can now be quality assured, stored and protected in secure database computer files, and transmitted to the customer via Internet in an automated and timely manner.

Also during Fiscal Year 1994, additional users representing the United States Advanced Battery Consortium, the Advanced Research Projects Agency, and all participants in the Department of Energy Site Operator Program registered for network access to the Idaho National Engineering Laboratory Electric and Hybrid Vehicle databases. Access to these databases was also requested by the Electric Vehicle Research Network, an affiliate of the Electric Power Research Institute.

Site Operator Database

The Site Operator Database is a record of Site Operator Program activities, and contains information on the operators, vehicles, and vehicle operation and maintenance records. During Fiscal Year 1994, entry of the complete set of data from Site Operator participants was completed. Thus, the Site Operator operations and maintenance data from about 1988 to present is now available for Internet or telephone modem access by the electric vehicle community.

The database was extensively modified to accommodate a more comprehensive set of data that is being added to include vehicle/battery performance data, vehicle and component reliability data, and site weather data. This more comprehensive data will be acquired by in-vehicle data acquisition units, which are designed and produced by the University of South Florida. This will provide extensive and accurate vehicle and battery performance data

collection both as the vehicles are driven and as the batteries are charged. The data acquisition units are being installed in 30 of the 42 new vehicles purchased by the Site Operator Program for delivery during Fiscal Year 1995. More comprehensive vehicle and component reliability data will be acquired by implementing a uniform maintenance program that will be part of the normal vehicle fleet management system in operation at each site. This ensures that the same maintenance data is made available to both the Site Operator Program and the site fleet managers, thereby creating a more reliable process. Weather data will also be acquired utilizing the in-vehicle Mobile Data Acquisition System units and measuring vehicle battery, cab, and ambient temperatures.

To maximize the capability to handle this large amount of data, a computer server has been proposed that is accessible by the public, and therefore, accessible by remote sites within the Site Operator Program. The "Public Access Server" will then be utilized as a central data gathering point with the capability to assure quality of the data and the capability to provide a database system for query and analyses of field test data for the electric and hybrid vehicle community. The Advanced Data Validation and Verification System, which is being implemented in the Idaho National Engineering Laboratory Electric and Hybrid Vehicle Battery and Vehicle Test Laboratories, will be utilized to assure quality of the detailed data.

6.4 Electric Vehicle Readiness

Ad Hoc Electric Vehicle Battery Readiness Working Group

An *ad hoc* government/industry working group was organized to identify environmental, health, and safety issues associated with the shipment, in-vehicle use, and recycling/disposal of advanced batteries for electric vehicles. The working group (consisting primarily of representatives from battery developers, automobile manufactures, Federal agencies, and national laboratories) serves as an informal forum in which regulatory requirements are identified, and potential action plans are discussed.

The working group is comprised of three sub-working groups which review the most important regulatory issues on shipping, recycling, and in-vehicle safety. The sub-working group on shipping provides organizational and technical support, as needed, to facilitate the collection of information for regulatory applications. The sub-working group on in-vehicle safety reviews and discusses the implications of hazards associated with batteries in electric vehicle propulsion, and reviews proposed rules on Federal Motor Vehicle Safety Standards. The sub-working group on recycling and disposal assesses the technical, regulatory, and institutional issues involved in recycling advanced batteries. They also assess the feasibility of recycling as an alternative to disposal to avoid regulation under the Resource Conservation and Recovery Act.

In Fiscal Year 1994, two meetings were held by the *ad hoc* working group in Washington, D.C. Topics discussed on January 20-21, 1994 were coordinating efforts with other electric vehicle groups such as the Health and Safety Committee of the Electric Power Research Institute Infrastructure Working Council, Advanced Lead Acid Battery Consortium, Solar Electric Racing Association, and the United States Advanced Battery Consortium. Activities in the sub-working groups were presented including battery risk assessment, battery

safety issues identification, battery handling and charging procedures, and presentation of a video on EV emergency response for in-vehicle safety. Presentations were given on nickel/metal hydride battery and lithium battery component recycling, and on nickel/supply recycling issues. A strategy was developed in response to a German proposal on shipping sodium/beta batteries, and short- and long-term options for lithium battery shipping were discussed.

In the second meeting held in August 1994, action items, included: a) the review of developments on an international sodium/beta battery shipping initiative; b) the identification of electric vehicle safety issues in a government/industry "brainstorming process;" c) the development of a comprehensive battery safety issue matrix; and d) an abstract review for three papers accepted to the 12th Electric Vehicle Symposium. Other activities included presentations in the in-vehicle safety sub-working group on ground fault circuit interruption, Navy lithium battery safety testing, and a continuation of work on the battery safety issue matrix. An overview was presented on the DOE Office of Industrial Technologies recycling program, two presentations were given on sodium/beta and nickel/metal chloride battery recycling (the former of which was recently patented), and an industry report on lithium battery recycling was reviewed. Finally, regulatory issues were reviewed for shipping of lithium-polymer and lithium/iron sulfide batteries, and a presentation given on a lithium battery shipping assessment. A report was given on a special industry/government meeting held on April 15, 1994, to initiate dialogue between industrial developers and the Department of Transportation to discuss factors that could form the basis of regulatory exemptions for cell and battery shipment.

Infrastructure Development

During Fiscal Year 1994 the Department worked cooperatively with the Electric Power Research Institute's National Electric Vehicle Infrastructure Working Council. Headquarters and national laboratory personnel participated in the Steering Council and the current standing committees on Health & Safety, Load Management, Distribution & Power Quality, and Data Interface. Activities of the standing committees are managed and coordinated through the voting members of the Infrastructure Steering Council. The Council now has six utility company members (Alabama Power Company, Allegheny Power Systems, Salt River Project, Southern California Edison, Detroit Edison, and Pacific Gas & Electric) and three automobile (General Motors, Ford, and Toyota) voting members along with non-voting Ex Officio representatives/members (Electric Vehicle Association of the Americas, Electric Power Research Institute, and the Department of Energy).

The Electric and Hybrid Propulsion Division personnel also served on the International Energy Agency's Executive Committee for the Implementing Agreement for Electric Vehicle Technologies and Programmes. This committee manages the efforts of member nations currently working on the development of six Annexes. These Annexes are: I - Information Exchange on Electric Vehicle Technologies and Programmes; II - Assessment of Electric Vehicle Impacts on Energy, the Environment, and Transportation; III - Development of Electric Vehicle Technical and Testing Methods; IV - Support for Design of Internationally Compatible Electric Vehicle Infrastructure; V - Exploratory Research on Advanced Batteries and Capacitors for Electric Vehicles; and VI - Design of Light-Weight Vehicles. The United

States, through the Department of Energy, is currently supporting the United Kingdom Operating Agent organization efforts for Annex IV.

The Department also participated in other infrastructure related meetings organized by the Department of Defense Advanced Research Projects Agency, private industry (utilities and car companies), and private policy organizations, all working toward the furtherance of "clean transportation" alternatives. Examples of these activities are attending the Virginia Power Electroexpo' 94, triennial Electric & Hybrid Vehicle Technology Program Regional Consortia meetings sponsored by the Advanced Research Projects Agency to maintain cognizance and understanding of programs to avoid duplicative efforts, and the presentation of invited papers at the Northeast Sustainable Energy Association's Solar and Electric Vehicles 1994 Conference in Providence, Rhode Island.

Other activities included participation in the development of a strategy, called "Critical Path to the Electric Vehicle Infrastructure - Getting There From Here," and attendance at the Electric Transportation Coalition meetings held in Washington D.C. An infrastructure strategy chart was prepared by Cecil & Rizvi under the sponsorship of General Motors with the Edison Electric Institute and the Department along with eight nationwide major utilities with interests in electric vehicles. The strategy development is a continuing effort following "The Electric Vehicle and the American Community: A National Planning and Design Competition" which was also sponsored by the Department in 1993. The Electric Transportation Coalition meetings afford a convenient and important forum for the Department of Energy, Department of Defense/Advanced Research Projects Agency, electric vehicle/car companies, utilities, and members of Congress and their staff to hear about and ask questions concerning aspects of electric vehicle infrastructure needs and evolving electric vehicle performance levels being afforded by improved battery characteristics and energy management systems.

6.5 Environmental, Health, and Safety Studies

Environmental Impact of Battery Systems

In Fiscal Year 1994, the National Renewable Energy Laboratory completed an assessment of the environmental, health, and safety issues related to lithium/solid polymer electrolyte batteries, because of the added safety issues that these systems are anticipated to have in comparison to lithium batteries with non-solid polymer electrolytes. This solid polymer electrolyte has been proposed to alleviate some of the problems encountered in organic liquid electrolyte designs, such as reaction with the lithium negative electrode, gas venting, and the need for sophisticated seals to contain the liquids.

Human exposure to lithium/solid polymer electrolyte system materials is possible during use, as well as during the manufacture and recycling of batteries, and hence, the toxicity and potential carcinogenicity of lithium battery materials were analyzed. In addition, Occupational Safety and Health standards for the different cell materials were reviewed. For the materials analyzed, there did not appear to be any serious toxicity issues. As new cell materials are evaluated for lithium solid polymer electrolyte batteries, their toxicity should be evaluated.

Existing facilities that dispose of lithium batteries (non-solid polymer electrolyte type) were reviewed. These facilities all use hydrolysis as a method for deactivating the lithium in the batteries. At present, it is not economical for these facilities to recycle the lithium. Because lithium batteries for electric vehicles will not contain very much lithium (in the range of 5 kilograms for a 25-kilowatt-hour electric vehicle battery), it may not be economical to recycle the lithium from solid polymer electrolyte systems. However, the bulk of an electric vehicle lithium battery will be composed of metals (e.g., stainless steel) and plastics, and many of these materials may be recycled.

Even though the exact chemistries and associated constituents of lithium/polymer cells and batteries under development are not completely known, transport provisions could be assessed under currently existing "LITHIUM BATTERY" associated transport regulations. As such, any hazardous material other than lithium or lithium alloy that may be present in the battery or cell need not be specifically taken into account in order to determine the requirements applicable to the device. In addition, the quantity of lithium or lithium alloy present in a battery or cell is a critical factor when considering shipping requirements. It is anticipated that most, if not all, electric vehicle batteries and cells will contain quantities of lithium or lithium alloy exceeding the limitations specified in the domestic and international regulations. Therefore, special written approvals will be necessary from the respective transport regulatory authorities with jurisdiction.

A second assessment was conducted by Arthur D. Little (with the National Renewable Energy Laboratory as a technical monitor) to examine possible recycling processes for nickel metal hydride batteries for two sample compositions (named, AB₂ and AB₅ systems). The actual battery compositions were estimated based on published compositions of battery alloys. (Actual compositions of current designs were requested from representatives of major battery developers, but no information was released.) Three possible recycling processes were evaluated to determine possible routes for recovering battery materials. The processes were based on similar processes used commercially, currently, or in the past, to recover the major components found within nickel/cadmium batteries or for the recovery of nickel from waste materials. Focus was on recovering the major constituent materials in the nickel metal hydride batteries, nickel and iron. Vanadium recovery from the AB₂ system and rare-earth metals recovery from the AB₅ system were investigated. In addition, polypropylene is also recovered in each process. A report was published by the National Renewable Energy Laboratory entitled "Feasibility Study for the Recycling of Nickel Metal Hydride Electric Vehicle Batteries," (January 1995).

6.6 Energy Storage for Hybrid-Electric Vehicles

A study performed by the Idaho National Engineering Laboratory during Fiscal Year 1993 established preliminary performance, life and cost targets for energy storage units for hybrid-electric vehicle drivelines. In Fiscal Year 1994, Idaho enhanced its SIMPLEV computer simulation code to model various hybrid propulsion systems, including parallel hybrid and ultracapacitor load-levelled configurations. This permitted some additional refinement of requirements for hybrid energy storage devices both through modeling and discussions with industry interests, including the U.S. auto manufacturers and the U.S. Council for Automotive Research.

Based on vehicle system requirements, it was necessary to consider at least two hybrid operating modes to envelope storage system requirements. These have been designated as "dual mode" (where the hybrid storage device may need to supply all of the propulsion power under some conditions) and "power assist mode" (where the storage device provides only supplemental power) for acceleration and limited hill climbing capability. A preliminary set of requirements for these two modes has been proposed as shown Table 6-1.

During Fiscal Year 1994, a set of test procedures specifically for ultracapacitors was defined to measure their performance from early laboratory stages to subsystem scale-up. A general test profile and one or more test cycles are being developed to verify the performance and life of all types of hybrid energy storage devices against the requirements in Table 6-1. This test method evolves from, and is partly based on, a refinement of the battery testing procedures defined for the U.S. Advanced Battery Consortium. It is being done synergistically with the definition of vehicle-level performance tests by the Society of Automotive Engineers. Trial use of these test cycles will begin in Fiscal Year 1995 as part of a high power battery evaluation project involving the Idaho National Engineering Laboratory and a number of battery developers.

6.7 Supporting Analyses and Assessments of Transportation Fuel Cells

Analyses and assessments of critical technical, market, and policy issues related to the use of fuel cells in transportation are conducted to provide a rationale for the choice of research program elements, to assist in overall program planning, definition and direction, and to coordinate public outreach and information transfer. These activities are also needed to help integrate the transportation fuel cell program with major federal initiatives to improve the nation's economic productivity, international competitiveness, and environmental quality.

Table 6-1. Requirements for a Hybrid Energy Storage Device

Requirement for Hybrid Energy Storage Device	Dual Mode	Power Assist
Maximum Power (kilowatt)	80	60
Energy Storage (kilowatt -hour)	10+	2-3
Maximum Weight (kilogram)	100	60
Maximum Volume (Liter)	120	40
Life (cycles)	>2000	>100,000
Cost (\$ per kilowatt -hour)	<130	<250

In Fiscal Year 1994, the draft environmental assessment was revised to address the potential impacts of research and development activities outlined in the new program plan for

fuel cells in transportation. Also, a draft of the first of a series of reports on environmental, health, and safety issues related to phosphoric acid fuel cell buses was prepared. This report (which is still under peer review) shows that the phosphoric acid fuel cell bus is as safe as its diesel-powered counterpart while providing substantial reductions in air emissions and noise. Subsequent reports will address issues with other fuel cell technologies in transportation applications.

A key issue is linking the development of fuel cell technology with that of advanced manufacturing technology. In Fiscal Year 1994, strategic planning focused on capital, plant and equipment, and labor (including education and training) requirements, for the design, production, and servicing of fuel cell vehicles.

The potential energy savings and emissions reductions of light-duty fuel cell vehicles was assessed. Assumptions for new fuel cell vehicle market penetration and potential benefits are described in the report entitled "Fuel Savings and Emissions Reductions from Light-Duty Fuel Cell Vehicles" (TP-463-6257, April 1994). Benefits are due to the higher fuel efficiency of the fuel cell vehicle, which are significant even though the price of methanol and hydrogen from natural gas are projected to be higher than that of reformulated gasoline. The deployment of fuel cell vehicles will also mean a shift from petroleum-based fuels and a reduced demand for crude oil. The environmental benefits result from reductions of emissions of pollutants that affect local air quality such as non-methane organic gases, nitrogen oxides, and carbon monoxide, as well as carbon dioxide (CO₂) because of its important role in global climate change. Although tailpipe emissions are the primary component of transportation emissions, air emissions associated with producing and distributing fuel are not small. The estimate of environmental benefits accounts for the total fuel cycle of emissions that includes both vehicular *and* upstream emissions from fuel production and distribution.

7.0 INCENTIVES

The major incentive-related activities of the Electric and Hybrid Vehicles Program include proposed revisions to the Corporate Average Fuel Economy regulations and the implementation of the Energy Policy Act of 1992, which offers new incentives for electric and alternative fuel vehicle commercialization and development.

Corporate Average Fuel Economy Regulations

The Department has proposed to revise 10 CFR Part 474 (Equivalent Petroleum-Based Fuel Economy Calculation) to provide an improved means of calculating the corporate average-equivalent fuel economy for electric vehicles. The proposed method incorporates by reference the latest industry test procedure for measuring energy consumption of electric vehicles. In addition, the economic factors in the original rule which required annual updating would be eliminated in favor of fixed indices that are valid through the end of the century. Off peak charging would be assumed and the national average electric generating efficiency, fuel mix, and fuel depletion rates would be taken into account. The proposed methodology provides a simpler calculation procedure and results in a greater incentive to the automotive industry to manufacture and market electric vehicles. The incentive comes in the form of much higher corporate average fuel economy values for electric vehicles.

In early Fiscal Year 1994, a Notice of Proposed Rulemaking for the revised procedure was published in the Federal Register. The final rule is expected to be published in Fiscal Year 1995.

Energy Policy Act of 1992

The Energy Policy Act of 1992, Public Law 102-486 includes both tax incentives and research, development, and demonstration authorizations for electric vehicles. Section 1913 of the Act provides a 10-percent tax credit (up to \$4,000) for electric vehicles. Title VI of the Act authorizes electric and electric hybrid vehicle demonstrations between 1993 and 2002, as well as electric vehicle infrastructure development between 1993 and 1997. Section 2025 of the Act authorizes electric vehicle and equipment research and development between 1993 and 1998. To date, no funds have been appropriated for implementation of Title VI.

8.0 USE OF FOREIGN COMPONENTS

Section 14(2) of Public Law 94-413, 15 U.S.C. §2513(2), requires the Department to include in its Annual Report to Congress a statement of the extent to which imported automobile chassis or components are being used, or are desirable, for the production of vehicles under Section 7, 15 U.S.C. §2506, and of the extent to which restrictions imposed by law or regulation upon the importation or use of such chassis or components are impeding the achievement of the purpose of this chapter. No further vehicle purchases are being made under the provisions of Section 7 of the Act.

9.0 RECOMMENDATIONS FOR INITIATIVES

The Department of Energy has no recommendations for new legislative initiatives at this time.

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