DOE/EE-0003

16th Annual Report to Congress for Fiscal Year 1992

Electric and Hybrid Vehicles Program

August 1993

U.S. Department of Energy
Assistant Secretary, Energy Efficiency and Renewable Energy
Office of Transportation Technologies
Washington, DC 20585

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Preface

This sixteenth annual report informs the U.S. Congress of the progress and plans of the Department of Energy Electric and Hybrid Vehicles Research and Development Program. This document compiies with the reporting requirements established in section 14 of the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976 (Public Law 94-413 as amended by Public Law 95-238 and Public Law 96-185), 15 U.S.C. §§2501 *et seq.* In addition, this report is intended to serve as a communication link between the Department and all of the public and private interests involved in making the program a success.

During Fiscal Year 1992, significant progress was made toward fulfilling the intent of Congress in passing the Act. Underway are research and development of advanced batteries for the near-term introduction of electric vehicles in the U.S. transportation sector under a Cooperative Agreement between the Department of Energy (DOE) and the United States Advanced Battery Consortium (USABC). The USABC is a partnership formed in January 1991 by the three major domestic automobile manufacturers. It was later joined by the electric utility industry as represented by the Electric Power Research Institute. The Cooperative Agreement between DOE and USABC is for a 50/50 cost-shared program to support research and development efforts of advanced battery developers and companies. This agreement represents a major milestone in Government/industry cooperation to develop technologies for public use in commercial products.

Research and development efforts continue to show steady progress as well in advancing technologies for electric vehicles, fuel cells, and propulsion systems. Site operators are successfully demonstrating the practicability of electric vehicles and providing valuable technical feedback. The results of the ongoing activities will provide industry with technology options for vehicles that will be more economically competitive and more likely to gain public and environmental acceptance. With the passage of the Energy Policy Act of 1992 (Public Law 102-486), it is expected that the DOE Electric and Hybrid Vehicle Program activities may be expanded.

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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 consume about 64 percent of all petroleum used last year, but more significantly, it used 38 percent more oil than the country produced. This heavy reliance on petroleum fuels has also made transportation a major contributor to air pollution. In comparison, only 5 percent of electricity was generated from petroleum; the balance was generated using other energy resources including renewables. Electric vehicles (EV) offer a way for the transportation sector to meet a portion of its energy demand with electricity, thereby reducing the sector's heavy dependence on petroleum fuels.

The Department of Energy (DOE) Electric and Hybrid Vehicles (EHV) Program, in cooperation with industry, is conducting research, development, testing, and evaluation activities to encourage the use of electricity as an alternative fuel for transportation. The program's goals are the development of the technology that will lead to the production and introduction of low- and zero-emission electric and hybrid vehicles into the Nation's transportation fleet and substitute domestic sources of energy for petroleum-based fuels.

Public Law 94-413, the Electric and Hybrid Vehicle Research, Development, and Demonstration Act of 1976, authorizes the Department of Energy to, inter alia, "encourage and support accelerated research into, and development of electric and hybrid vehicle technologies" 15 U.S.C. §2501(b)(1). Congress provided an appropriation of $43.0 million for the EHV Program in Fiscal Year (FY) 1992.

The Program is managed by the Electric and Hybrid Propulsion Division within the DOE Office of Propulsion Systems. The current program structure and principal responsibilities of the organizational units are shown in Figure 1. The participants in EHV research and development, listed in Table 1, include major automotive companies, battery companies, component and propulsion system companies, universities, and electric vehicle users from the public and private sectors. Table 1 also provides the cost-sharing commitment of the participants.

In FY 1992, the Electric and Hybrid Vehicles Program continued to emphasize battery, fuel cell, and propulsion systems development. The program also supports the testing and evaluation of vehicles and components in laboratory and fleet operations. The battery program concentrates on those technologies that could satisfy the mid- and long-term goals of the automobile manufacturers as determined by the United States Advanced Battery Consortium (USABC).

This report describes the progress achieved in developing electric and hybrid vehicle technologies, beginning with highlights of recent accomplishments in FY 1992. Detailed descriptions are provided of program activities during FY 1992 in the areas of battery, fuel cell, and propulsion system development, and testing and evaluation of new technology in fleet site operations and in laboratories. This Annual Report also contains a status report on incentives and use of foreign components, as well as a list of publications resulting from the DOE program.

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

Automotive Companies	Cost Share of Contract*
Ford Motor Company	20%
General Motors/Allison	20%
United States Advanced Battery Consortium	50%
Component and Propulsion System Companies	
Delco/GM	50%
General Electric	20%
H-Power	25%
Battery Companies	
Beta Power, Inc.	30%
Chloride Silent Power	19%
Saft America, Inc.	20%
Westinghouse Electric Corporation	22%
Universities	
Georgetown University	14%
Fleet Testing Site Operators 1/	
Arizona Public Service	93%
United States Navy	100%
Southern California Edison	96%
Los Angeles Dept. of Power & Water	100%
Kansas State University	78%
Orcas Power & Light	50%
Platte River	58%
Pacific Gas & Electric	97%
Potomac Electric Power Co.	86%
Public Service Gas & Electric	87%
Texas A&M	88%
University of South Florida	84%
York Technical College	68%

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.

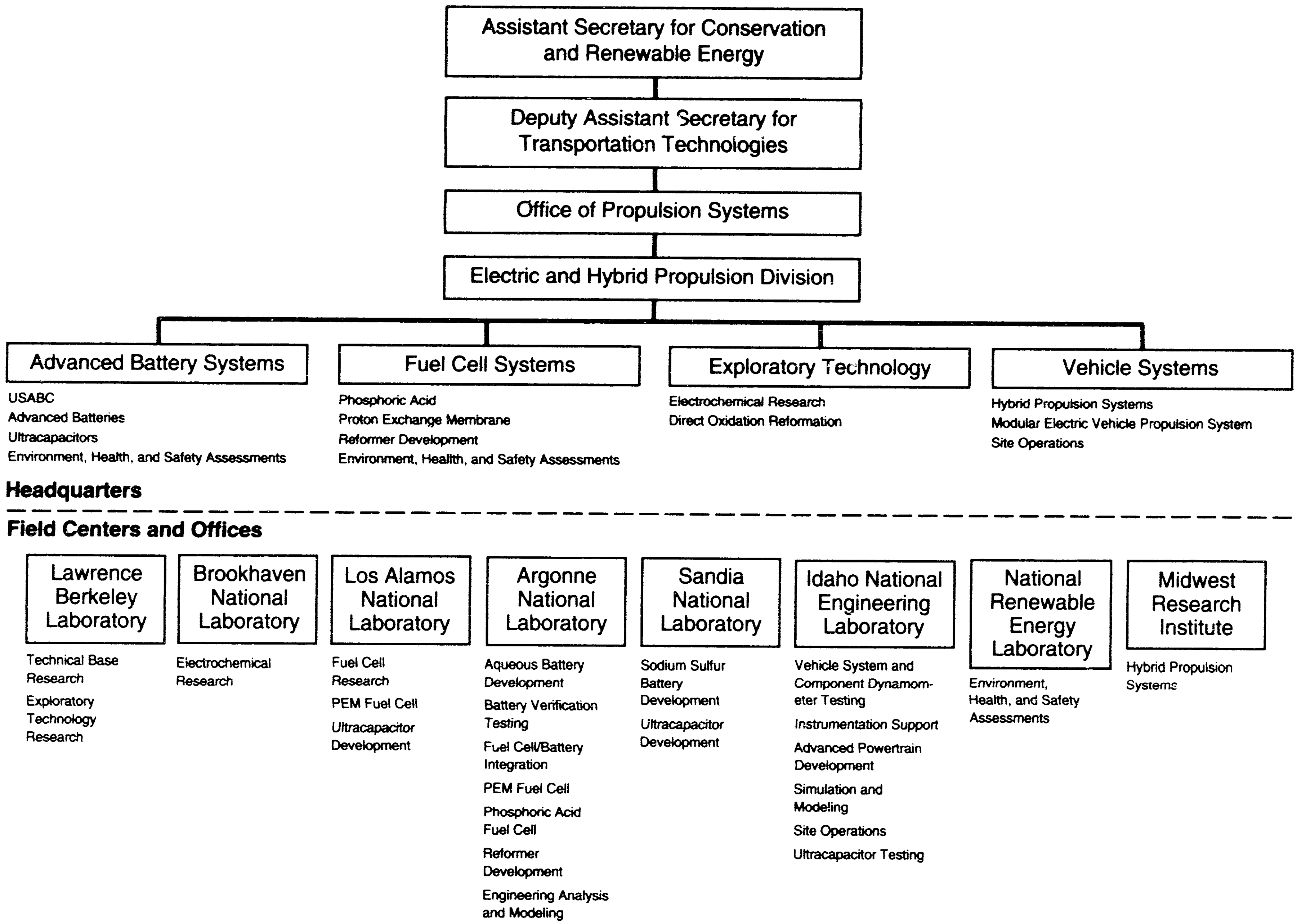

Figure 1. EHP Program Structure.

2.0 FY 1992 ACCOMPLISHMENTS

The highlights of significant FY 1992 accomplishments in each of the Electric and Hybrid Propulsion Systems Program areas are as follows:

- The USABC announced several battery development subcontracts during FY 1992 (and early FY 1993). These include the Ovonic Battery Company for development of nickel metal hydride battery; the W.R. Grace Consortium for development of lithium polymer battery; and SAFT America, Inc., for development of lithium iron disulfide battery. Cooperative Research and Development Agreements (CRADA) were signed with two National Laboratories, National Renewable Energy Laboratory and Lawrence Berkeley Laboratory. Three other CRADAs, with Argonne National Laboratory, Idaho National Engineering Laboratory, and Sandia National Laboratory have been announced.
- Chloride Silent Power Limited completed the design and development of a second-generation sodium/sulfur battery in a DOE contract that was ongoing prior to the formation of the USABC. This battery will have a reduced weight compared to an earlier first-generation battery and will be suitable for underfloor mounting in the Ford/DOE ETX-II vehicles. Although the intent of the contract was to perform the evaluation in the vehicle, adequate funds were not available to fabricate a full voltage battery. Instead, a 100-volt, 24-kW·h (90 W·h/kg) battery will be delivered to Argonne National Laboratory for performance and life characterization. Final assembly and commissioning are scheduled for November 1992.
- During FY 1992, Beta Power completed an ongoing DOE contract for the conceptual designs of high-performance, sodium/sulfur batteries for four U.S. electric vans. A battery using the common van cell would have nearly 3 times the energy capacity, yet weigh 40 percent less. In addition, a similar cell and battery design effort was completed for an advanced passenger car application. A battery using a cell specifically designed for the passenger car would provide 50 percent more energy in a package 2.4-feet shorter and 50 percent lighter. If there is further development of this technology, it will be conducted through the USABC.
- The Idaho National Engineering Laboratory tested several lead-acid batteries to provide Site Operators with data on batteries available for their current electric vehicle fleets. Life cycle testing of two Sonnenschein sealed lead-acid batteries and two flooded lead-acid batteries were completed. The batteries tested completed 382 charge/discharge cycles under simulated vehicle driving conditions before the battery energy degraded to the end-of-life criteria of 80 percent of the pre-test measurement. Post-test analysis of the batteries included physical and chemical analyses in order to determine the mechanisms involved which contributed to the battery failure.
- A contract was placed with Dreisbach Electromotive, Inc., for the fabrication of zinc-air battery technology in 12 volt, 240-A·h modules, to be tested by the USABC. Phase I of this effort, completed in FY 1992, resulted in the development of a subsystem for managing several functions, such as controlling the ancillary systems, necessary to operate this battery system.
- The development of high-specific energy capacitors for load leveling electric vehicles continues to show significant progress. Tests performed at the Idaho National Engineering Laboratory on available capacitors indicated that spiral-wound, carbon based devices are capable of an energy density of 2 W·h/kg and 500,000 charge/discharge cycles. A Sandia-fabricated double-layer capacitor the size of a common "D" cell exhibits a total capacitance in excess of 1000 Farads (F). The carbon electrode exhibits a volumetric capacitance in excess of approximately 130 F/cm^3, and the energy density of the laboratory device is approximately 1.4 W·h/kg. A contract was placed with Maxwell Laboratories and Auburn University to develop bipolar, carbon based ultracapacitors with an energy density of at least 5 W·h/kg by 1995 which could be configured in a 100 kg unit to store 500 W·h of energy.
- H-Power Corporation completed the first year of a three-year contract to design and build three fuel-cell-powered urban transit buses. At the end of FY 1992, H-Power had completed the major subsystem designs and had begun fabrication of the bus

structure and the 50-kW phosphoric acid fuel cell system. The first test bed bus will be delivered in FY 1993.

• General Motors Corporation (Allison Gas Turbine Division) completed the second year of a 32-month R&D contract (20 percent cost-shared) to develop the proton-exchange-membrane (PEM) fuel cell as a complete power source system for transportation applications. Improvements in membranes and electrodes were developed, state-of-the-art 5-kW PEM fuel cell stacks were built and tested, and significant progress was attained in the methanol fuel processing and control technologies required for a complete system.

• The Department of Energy initiated a 30-month contract (11.5 percent cost-shared) in May 1992 with Arthur D. Little, Inc., to develop the capability for reforming methanol, ethanol, or natural gas into hydrogen for use in transportation fuel cell systems and to develop advanced systems for on-board hydrogen storage. This project will not only provide fuel flexibility for fuel-cell-powered vehicles, but will also reduce system size and cost, reduce start-up time, and increase transient response capability.

• Catalyst development work at Argonne National Laboratory has identified a highly promising catalyst formulation for the partial oxidation reforming of methanol and another potential catalyst formulation for the steam reforming of ethanol. Further work to characterize the stability and performance of these and other suitable catalysts is continuing.

• The Second Generation Single-Shaft Electric Propulsion (ETX-II) System test bed vehicle developed under contract with Ford Motor Company and General Electric Company was tested at the Idaho National Engineering Laboratory. The vehicle system included a sodium-sulfur battery and yielded a range of more than 180 km at 88 km/h.

• The Ford Modular Electric Vehicle Program (MEVP) has successfully fabricated nearly a dozen 75-hp electric vehicle drivetrains. These systems are being used in various phases of the program's engineering evaluation effort. The 75-hp drivetrain will be utilized in Ford's Ecostar electric vehicle field demonstration program. The MEVP is the final phase of the DOE/Ford/GE cost-shared electric powertrain development program that began with the ETX-I contract in 1984.

• The Idaho National Engineering Laboratory has developed test procedures for evaluating the energy consumption (electricity and liquid fuel) of, and emissions from, hybrid vehicles when they are driven on the Federal Urban and Highway driving cycles.

• The electric vehicle computer simulation program, SIMPLEV, developed by the Idaho National Engineering Laboratory, was distributed for use in six government-sponsored programs and licensed to the following 20 organizations:

- Jordan College Energy Institute
- University of California, Department of Information and Computer Science
- Cornell University, School of Mechanical and Aerospace Engineering
- Seattle University, Department of Mechanical Engineering
- Chrysler Corporation, Electric Vehicle Program
- Cal Poly State University, Department of Mechanical Engineering
- Concordia University
- Wayne State University, Electrical and Computer Engineering Department
- York Institute of Technology
- New York Institute of Technology
- University of Alberta, Department of Mechanical Engineering
- Texas Tech University, Mechanical Engineering Department
- Regents of the University of California, Electrical and Computer Engineering
- Pentastar Electronics, Inc.
- General Electric Corporate Research and Development
- Electrochemical Systems and Hydrogen Research
- NEVCOR, Inc.
- University of Ottawa, Electrochemical Science and Technology Center
- Colorado School of Mines, Engineering Department
- IMRA America

• The Idaho National Engineering Laboratory expanded its efforts in the management of the Site Operator Program to establish and coordinate interorganizational activities and increase public awareness of electric vehicles. The Site Operator Program currently includes 13 participants representing a wide variety of operating environments in which over 3 million miles of electric vehicle operation have been accumulated.

Over the years since the beginning of the Electric and Hybrid Vehicle Program, various electric vehicles have been designed and tested by DOE. Further use of these test vehicles has been the focus of a DOE outreach program. The ETV-1 (electric car) and the ETX-II (electric van) have been transferred as surplus to the DOE American Museum of Science and Energy at Oak Ridge, TN. These vehicles are now on display and will soon be part of a museum futuristic home theme (Figure 2). The ETV-1-2 (the second electric test car) has been surplused to the York Technical College in Rockhill, SC, for the purpose of student activity to refurbish the car for training and demonstration (Figure 3). The ETV-2 (electric and flywheel) test vehicle is housed at Wayne State University in Detroit, MI, where it will be used for engineering design classes (Figure 4). The HTV-1 (hybrid test vehicle) has been surplused to the University of Maryland in College Park, MD, where students will be studying the theory and operation of the hybrid vehicle. If feasible, the vehicle would be brought back to operational condition and improvements would be made to the subsystems (Figure 5).

Figure 2. ETV-1 and ETX-II electric vehicles at the DOE American Museum of Science and Energy at Oak Ridge, TN.

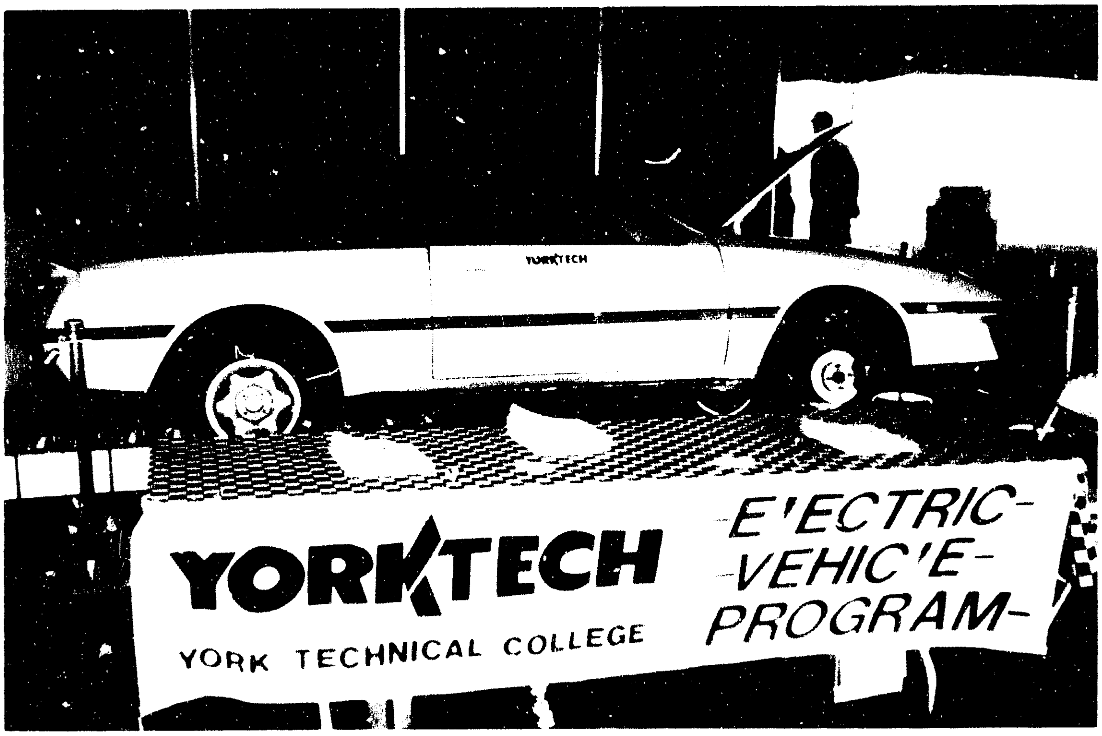

Figure 3. ETV-1-2 at the York Technical College in Rockhill, SC.

Figure 4. Garrett AiResearch ETV-2 at Wayne State University, Detroit, MI.

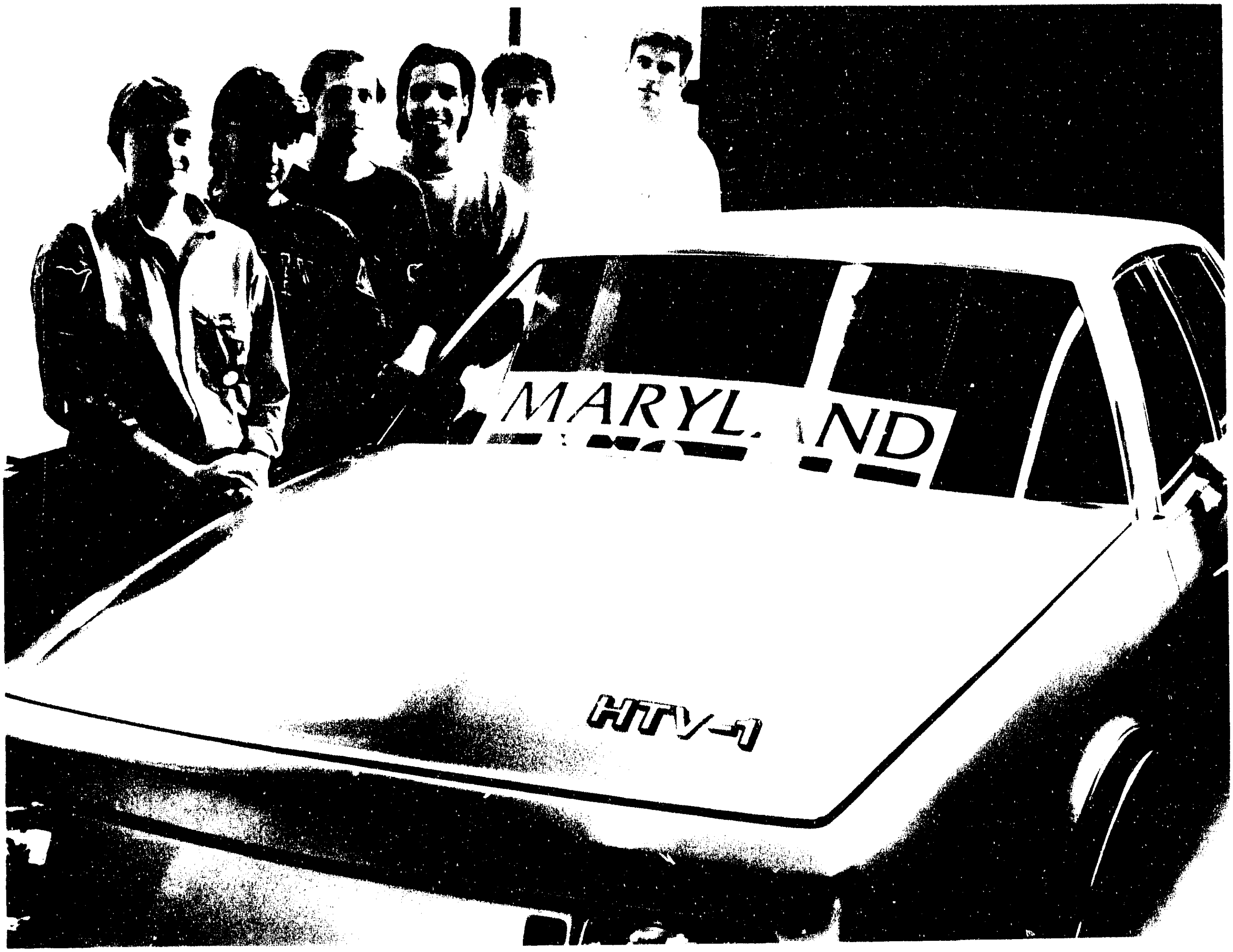

Figure 5. HTV-1 studied at the University of Maryland.

3.0 BATTERY SYSTEMS R&D

Since signing the Cooperative Agreement in early FY 1992, the USABC and DOE have worked together in selecting the advanced battery systems for R&D to meet the USABC goals. DOE Advanced Battery Systems R&D efforts were refocused; projects supported prior to the formation of the USABC were gradually phased out, and new projects were initiated under the cooperative agreement with the USABC. This section describes activities of the USABC and DOE exploratory technology battery development, testing of advanced batteries as well as currently available batteries, and development of high specific energy ultracapacitors.

3.1 United States Advanced Battery Consortium

The USABC was formed on January 30, 1991, as a partnership of Chrysler, Ford, and General Motors. The purpose of the USABC is to work with advanced battery developers and companies that will conduct research and development on advanced batteries for electric vehicles. The USABC signed a cooperative agreement with the Department of Energy in early FY 1992, for a 50/50 cost-shared program of advanced battery research and development. The formation of the USABC and its relationship with the Government represent a significant milestone in Government-industry cooperation in the development of technologies for public use in commercial products.

In FY 1992, the USABC focused on selecting potential subcontractors and negotiating suitable agreements for the development of advanced batteries. The USABC also negotiated a series of CRADAs with several DOE National Laboratories during this period. The following agreements were concluded:

- Subcontract to Ovonics Battery Company for nickel metal hydride battery development - May 4, 1992;
- CRADA with National Renewable Energy Laboratory to develop advanced insulation for high temperature batteries - June 10, 1992;
- CRADA with Lawrence Berkeley Laboratory for lithium polymer battery technology development - June 15, 1992;
- Subcontract to W.R. Grace Consortium for lithium polymer battery development - announced October 29, 1992;
- Subcontract to SAFT America for development of lithium iron disulfide batteries - announced October 29, 1992;
- CRADAs with Argonne National Laboratory for development of lithium iron disulfide battery technology and testing of advanced batteries - announced October 29, 1992;
- CRADA with Idaho National Engineering Laboratory for testing of advanced batteries - announced October 29, 1992;
- CRADA with Sandia National Laboratory for development of lithium polymer battery technology and battery reclamation - announced October 29, 1992.

The USABC continues to negotiate with other potential developers of advanced battery technology and to monitor the status of development of other advanced technologies through purchase of prototype or commercially available cells, modules, or batteries for independent test and evaluation. In order to better respond to numerous external requests for information about its operations, the USABC published a short paper describing key aspects of its program, including the organization's purpose, structure, and general business objectives. The battery technology and subcontractor selection process were also described in some detail.

As the USABC program developed, common technical needs were addressed, such as integrating the advanced batteries with each partner's electric vehicles and assuring that the laboratory testing of prototype batteries would be realistic. Each partner was asked to carefully define the needs of his vehicle for one or more specific battery configurations. The detailed definitions included consideration of the battery's allowable size and weight, operating voltage, peak power requirements, and other interfaces with vehicle systems. Sufficient details were provided so that the battery development contractors could engineer their specific technologies for the vehicle requirements.

The USABC development program calls for extensive testing of prototype cell, modules, and batteries from the development contractors. To assure that the program for battery testing is comprehensive and uniform, the USABC has set up a working group to address testing issues. The Battery Test Procedures Working Group consists of USABC and National Laboratory staff members. It has reviewed the existing testing methodologies developed by the National Laboratories, including methods for characterizing cells, modules, and batteries, as well as methods of subjecting them to realistic driving cycle discharges. The group has utilized the existing testing methods as a starting point and has proceeded to identify new testing methods to address calendar life and the high power peaks imposed on battery systems by the new generation of electric vehicle drive trains.

The USABC has also reviewed its own development criteria for mid-term batteries. Reassessment of the criteria originally defined in early 1991 resulted in no significant changes. The USABC remains concerned about the potential for advanced batteries to meet the high power requirements demanded by the automotive customer. There is also concern about the ability of batteries to rapidly recharge. These factors are both reflected in the revised goals set in Tables 2 and 3.

Finally, the USABC continues to consider the operational safety and reclamation of advanced batteries of significant importance. USABC members participate in DOE Electric Vehicle Battery Readiness Working Groups.

Table 2. USABC Advanced Battery Technology Primary Criteria

Primary Criteria	Mid-Term Goals	Comments
Power Density W/l	250	
Specific Power (Charge) W/kg (80% DOD/30 sec)	150* (*200 desired)	
Specific Power (Recharge) W/kg (20% DOD/10 sec)	75	
Energy Density W·h/l	135	Eventually measure on SFUDS
Specific Energy W·h/kg	80* (*100 desired)	Eventually measure on SFUDS
Power/Energy Ratio	1.5-2.5	Eventually tailor to OEM Vehicle
Life (Years)	5	Pack life
Cycle Life (Cycles) (80% DOD)	600	Pack level cycles (Implies higher cycle life for cells)
Power & Capacity Degradation (% of rated spec)	20%	Defines end of cycle or calendar life
Ultimate Price ($/kW·h) (10,000 units @ 40 kW·h)	<$150	Includes recycling and warranty cost. Needs further platform review
Operating Environment	-30 to 65°C	
Normal Recharge Time	<6 hours	
Fast Recharge Time	50% of capacity in<30 minutes	New market driven requirement. Will need new test procedures
Continuous Discharge in 1 hour (No Failure)	75% (of rated energy capacity)	Needs to be harmonized with fast recharge requirement. Impacts on thermal management.

Table 3. USABC Advanced Battery Technology Secondary Criteria

Secondary Criteria	Mid-Term Goals
Efficiency C/3 Discharge 6 hr Charge	75%
Self-Discharge	<15% in 48 hours
Maintenance	No Maintenance Service by Qualified Personnel Only
Thermal Loss (for high temperature batteries)	3.2 W/kW·h 15% of Capacity 48 Hour Period
Abuse Resistance	Tolerant
SPECIFIED BY CONTRACTOR Recyclability - 100% Packaging Constraints Environmental Compliance (manufacturing process, transport, in use and recycling) Safety Overcharge/Overdischarge Tolerance Vibration Tolerance	

3.2 Advanced Battery R&D

During FY 1992, a transition was made in the advanced battery program. Projects funded by DOE prior to the formation of the USABC were gradually phased out. The FY 1992 activities for these completed projects are described in the following sections.

Sodium/Sulfur Battery

In FY 1992, three ongoing sodium/sulfur development and evaluation activities were effectively completed; namely, the final phase of design and fabrication of an electric vehicle battery possible with state-of-the-art cell technology; the design of a common, high-performance sodium/sulfur cell for U.S. electric van batteries; and characterization of the effect of the latest Chloride Silent Power Limited (CSPL) innovations on PB-cells on battery performance, service life, and safety.

The first sodium/sulfur activity involves development of an electric vehicle battery possible with today's cell technology that was developed under a complementary, DOE-supported, core-technology program. In September 1986, a cost-shared contract was placed by Sandia National Laboratories with CSPL to advance the sodium/sulfur technology specific to EV applications. This program was modified in 1987 and again in 1990 to specify that two sodium/sulfur batteries be designed, fabricated, and qualified that are suitable for evaluation in the ETX-II experimental electric vehicle. Total DOE funding for this 5-year activity is approximately $2.7M.

Characterization testing of the first-generation battery was completed in February 1992 at the Idaho National Engineering Laboratory. The battery was originally heated in October 1989 at Ford Motor and satisfied its energy and power performance requirements. However, because of its size, it was located in the cargo bay of the vehicle. Overall, the battery was at operating temperature for 21 months, but only logged approximately 60 cycles. In February, when the capacity of the battery had decreased from its initial 300 A·h to 230 A·h, testing was terminated. For reference, a peer group from the ETX-II cell population was also tested continuously at Argonne National Laboratory. This 120-cell bank at Argonne completed about 500 Simplified Federal Urban Driving Schedule (SFUDS)-based electrical cycles before suffering a significant loss in capacity.

Development of improved mechanical and electrical systems for the second-generation battery was completed along with a detailed design. Part of the development of a suitable mechanical system involved qualifying the various cell and battery components with respect to vibration resistance. The small CSPL-manufactured test battery shown in Figure 6 (containing 120 PB cells arranged in two 8-volt banks) was used to qualify the response of the ETX-IIs battery components to vibration. The actual second-generation battery will have a reduced weight compared to the first-generation battery and will be suitable for underfloor mounting and evaluation in the Ford ETX-II vehicles. The battery will utilize the latest CSPL-PB cells that contain an improved seal material. The service life of the battery is expected to be at least 2 years and 500 cycles. Although the intent was to perform the evaluation in the actual vehicle, funding limitations prevented the fabrication of a full voltage battery. Instead, a 100-volt, 24-kW·h battery will be delivered to Argonne for performance and life characterization. The expected initial energy and power densities for this battery are: 90 W·h/kg, 135 W·h/l, 125 W/kg, and 185 W/l. Final fabrication and delivery of the battery to Argonne will be completed in January 1993.

The design of common, high-performance sodium/sulfur cells and batteries for electric vans was also completed in FY 1992. This work, performed under a 30 percent cost-shared contract with Beta Power, Inc., defined the mid-term capabilities of the sodium-sulfur technology. A task was also included to consider purpose-built, passenger vehicles. The period of performance for this $460K contract was 18 months.

A conceptual cell design formulated in FY 1991 exceeded original program goals with high energy (250 W·h/kg and 420 W·h/l) and power (600 W/kg and 1010 W/l) densities. During FY 1992, conceptual battery designs were defined for the G-Van, TeVan, and ETX-II vehicles using this cell. The same internal battery module configuration is employed, consisting of 15, 3-cell series strings connected in parallel. In all cases, the batteries satisfied the required performance with much smaller size and weight than is possible with the current sodium/sulfur technology.

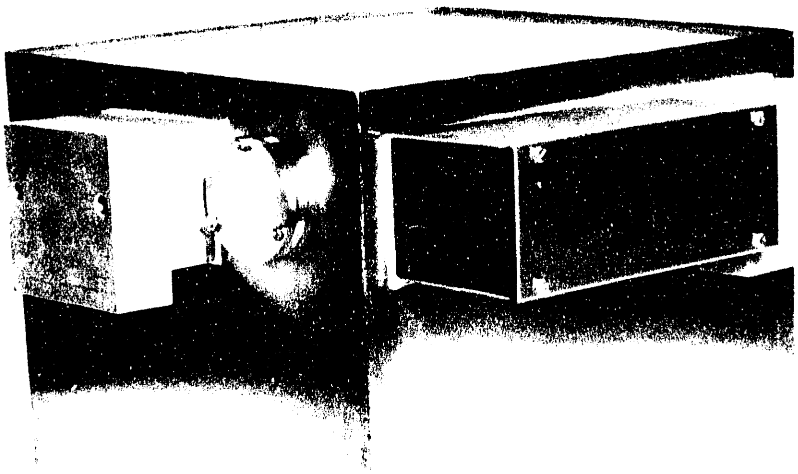

Figure 6. Sodium/sulfur battery used in vibration testing.

The specifications for General Motor's Impact were selected as the basis for producing challenging passenger car battery requirements. Two batteries were designed, one using the van cell and the other using a small diameter cell with much higher peak power to energy ratio (4:1). The first battery with the van cell would just fit into the Impact's battery tunnel, but would provide 36 kW·h of energy compared with 13.7 kW·h for the lead-acid battery. The battery weight would decrease from 396 kg to 235 kg. The battery utilizing the small-diameter cell designed would provide 20 kW·h, but would reduce the battery length by 2.4 feet. The battery weight would be reduced to 180 kg.

The final FY 1992 sodium/sulfur task involved the characterization of the effect of cell size on performance, service life, and safety; and the latest CSPL innovations on PB-cell service life. This work is being performed under a 45 percent cost-shared contract with CSPL that extends to June 1993. Important preliminary conclusions reached to date include the following: (1) the service life of the larger XPB cells (30 A·h) and modules is markedly more erratic and poorer than that for corresponding PB cells and modules (10 A·h); (2) direct air cooling of cells is complex and not satisfactory; (3) CSPL's new improved ceramic seal is yielding improved service life and freeze/thaw durability; and (4) a cell containing a sulfur electrode fabricated with graded graphite felt has better low-temperature performance, but inferior rechargeability at nominal operating temperatures, compared with cells containing CSPL's standard electrode configuration. However, tests of 12 PB cells at Sandia show that cell life is only about 80 weeks, far short of current program goals.

Lithium-Aluminum/Iron Sulfide Battery

In FY 1992, DOE provided limited support for the phasing out of a project to develop prismatic lithium-aluminum/iron sulfide batteries by SAFT America, Inc., and continued a low-level R&D project on the development of bipolar lithium-aluminum/iron sulfide batteries at Argonne. The project at SAFT was initiated in April 1990 under a 3-year, $4.2 million cost-shared contract to develop full-size EV batteries. Argonne participation in the prismatic battery development effort includes technology transfer, R&D support, independent evaluation of contract deliverables, and technical management of the SAFT project, while DOE-Chicago provides contract administration.

During the FY 1992 phase-out of the project, SAFT fabricated and tested baseline and improved technology cells. SAFT also completed tests on a thermal simulator that was used to develop improved components and component configurations for the thermal management system. Baseline cells, cycle tested using a C/3 power profile, exhibited >200 W·h/l energy density, while accumulating >365 cycles. However, the baseline cells lacked power, especially beyond 60-percent depth-of-discharge (DOD). Significant improvements in the power density and overcharge tolerance capability were demonstrated in the improved technology cells. On SFUDS cycles, the improved cells delivered 55 percent more usable capacity than the baseline cells, due to improved power capabilities at deeper DOD.

In its low-level R&D project on bipolar lithium-aluminum/iron sulfide batteries, Argonne focused its FY 1992 efforts on scaling up cells and multiple-cell stacks to the 13-cm diameter size. Peripheral seal design and processing refinements formed a major part of the overall scale-up effort. Bipolar Li-Al/FeS and Li-Al/FeS_2 cells and 4-cell stacks (as illustrated in Figure 7) were built and tested during FY 1992. Bipolar 13-cm diameter Li-Al/FeS cells deliver 130 W·h/kg at a 25 W/kg discharge rate, with a peak power capability of 240 W/kg at 80-percent DOD. Bipolar Li-Al/FeS_2 cells deliver 180 W·h/kg at a 30 W/kg discharge rate, with a peak power capability of 400 W/kg at 80-percent DOD.

3.3 Exploratory Technology Development

Although the USABC is taking the lead in identifying and developing the most promising advanced battery technologies, given the many technical challenges, their successful commercialization is not assured. Exploratory technology development is needed to maintain a base of scientific and technical expertise in electrochemical processes and engineering that USABC battery developers can tap into to resolve basic problems and for new ideas/approaches.

The DOE exploratory technology development activities in FY 1992 included research on electrochemical phenomena that limit the performance and lifetime of rechargeable batteries, developing new materials and cell components, and discovering new electrochemical cells with superior performance and durability for possible development by the USABC. Battery technologies addressed include Li/Polymer,

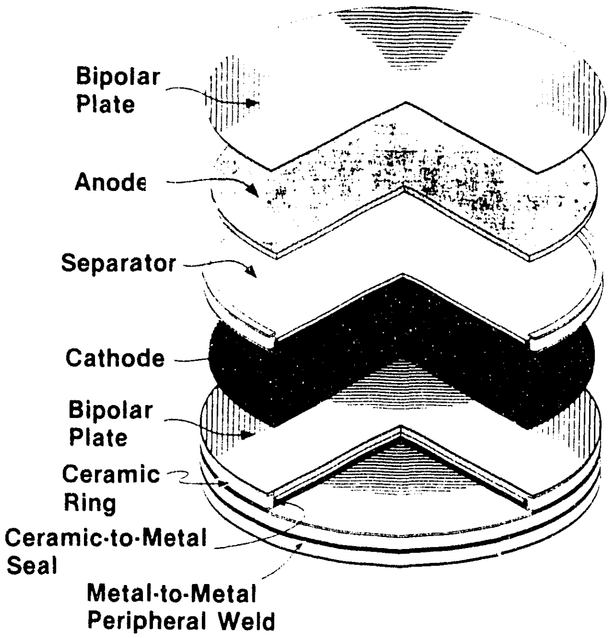

Figure 7. Exploded view of four-cell bipolar lithium-aluminum/iron sulfide stack.

Na/S, and Li/FeS_x (all of which are of current interest to the USABC) and zinc batteries.

In FY 1992, the Argonne facility for studying micro-reference electrodes for lithium/polymer cells was completed, and a facility for the fabrication of polymer electrolyte and positive electrode materials is nearing completion. Reference electrodes are invaluable tools for battery R&D because they provide a means for performance analysis of electrodes in working cells and batteries, thereby suggesting effective ways to improve the overall performance of the battery system. The ultra-thin cell components of advanced lithium/polymer electrolyte cells places stringent requirements on the dimensions of the reference electrode. Also, the special assembly configurations of the lithium/polymer battery will require investigation of the placement of the reference electrode to ensure that it is functioning properly for the electrode and cell performance evaluations. Work on lithium and lithium-aluminum alloy reference electrodes was initiated and results indicate that they are very stable in this system. A nickel/nickel salt reference electrode of the second kind was examined and found to be unstable, which is likely the result of the nickel salt being soluble in the electrolyte. Further work needs to be done to examine the effect of miniaturization on the lithium and lithium-aluminum reference electrodes, as well as to examine other types of reference electrodes.

The University of Pennsylvania was funded through the DOE Lawrence Berkeley Laboratory to investigate polymeric electrolytes formed by radiation-polymerization of various oligomers that contain different compositions of plasticizer (ethylene carbonate, EC, and propylene carbonate, PC) and 1 M $LiAsF_6$. Polymeric electrolytes with ≥ 50 percent weight PC in mixtures with EC appear to exhibit acceptable electrochemical (reversible Li redox process) and physicochemical properties (ionic conductivity >8 x 10^{-4} at room temperature, glass-transition temperature of –94°C, amorphous structure from –90° C to 150° C) for use in rechargeable Li cells. SRI International has developed a Li-ion conducting PEO-type polymer in which oxygen is replaced by sulfur. The best-performing polymer electrolyte, obtained from sulfur-substituted PEO (16.7 percent S) and tetraethylorthosilicate with a plasticizer, exhibited a conductivity of 7.5 x 10^{-4} ohm^{-1} cm^{-1} in a Li/Li cell. Case Western Reserve University has used *in situ* spectroscopic techniques and thermal analysis to study the Li/organic electrolyte and Li/poly (ethyleneoxide) interfaces. Interactions between Li and tetrahydrofuran, and the formation of Li-O and Li-CO_3 species, were detected. Preliminary cyclic voltammetry studies of Au in contact with $LiClO_4$-poly(ethylene oxide) electrolyte at 55° C showed evidence for underpotential deposition of Li.

Lawrence Berkeley also funded work at Johns Hopkins University and Jackson State University to investigate electrochemical phenomena in nonaqueous electrolytes of interest for rechargeable Li cells. Hopkins observed that iron and 1018 carbon steel display an extensive and stable passive region in $LiAsF_6$/dimethoxyethane (DME). In a nominally dry $LiAsF_6$/DME solution (<100-ppm H_2O), the breakdown potentials of iron and carbon steel are 1300 mV (vs. saturated calomel electrode, SCE) and 1050 mV, respectively. The adsorption of DME and the formation of carbon-based polymer film are believed to be responsible for passivation. Jackson State evaluated the electrochemical properties of C_{60} fullerene as an electrode material that may be useful in rechargeable Li cells. The cyclic voltammograms of C_{60} in $LiClO_4$/polyethylene glycol 400 dimethyl ether (PEG400DME) indicated five redox peaks which suggested the formation of C_{60}^{-}, C_{60}^{2-}, C_{60}^{3-}, C_{60}^{4-}, and C_{60}^{5-}. These anions dissolve in PEG400DME.

Lawrence Berkeley initiated research to develop Na/polymer cells that contain thin electrodes of Na and metal oxide and a polymer membrane that is capable of conducting Na^{+} ions, i.e., sodium/poly(ethylene) oxide/metal oxide electrode (Na/PEO/MO_x). These cells are expected to operate at lower temperatures than typically used with Li/polymer cells. Furthermore, the simple cell design is expected to be easily fabricated using existing thin-film technology. Preliminary half-cell experiments at 90°C with Na/$PEO_8CF_3SO_3$ (PEO-NaTf) demonstrated several cycles at either 0.25 or 0.5 mA/cm^2. Figure 8 shows the voltage transient during constant-current discharge (with periodic excursions to open circuit) at 0.5 mA/cm^2 of a Na/PEO/Na cell. Although there was some instability in the first cycle, the voltage stabilized subsequently. This may be interpreted to mean that Na initially reacts with PEO to form a conductive and protective interface layer. This is analogous to the behavior seen in Li cells with liquid or polymer electrolytes.

Several projects are underway to improve the components used in alkali/sulfur cells, such as superior alternatives to the high-temperature sulfur-polysulfide electrode, and more corrosion-resistant coatings for Na/S cells. Lawrence investigated the influence of phosphorus on the sulfur electrode of Na/S cells by equilibrium open-circuit potential measurements. Mixtures with P/S molar ratios from 0.143 to 0.60 and Na mole fractions from 0.0 to 0.4 were studied at 350°C and 400°C. The Na/P_xS_y cells showed significantly higher cell voltages than Na/S cells, which is a strong indication that phosphorus may be a beneficial additive to the sulfur electrode. The plots of electromotive force vs. Na^{+}-ion mole fraction in Figure 9 indicate that multiple crossings of phase boundaries occur during cell discharge.

Illinois Institute of Technology (IIT) is optimizing the quality of electrodeposited Mo_2C coatings to obtain long-term endurance, and the Environmental Research Institute of Michigan (ERIM) is evaluating TiN-coated containment materials, in Na/S cells. IIT observed that complete removal of moisture from the electrolysis bath is necessary to obtain a reproducible, high quality coating. Coatings of an even better quality were obtained with a bath containing non-Li alkali molybdates and carbonates. ERIM is extending the preliminary studies at Ford Motor Company which indicated that sputter-coated TiN on Al was resistant to attack in a polysulfide melt during the 72-hour test. A reactive-sputtering system is being assembled at

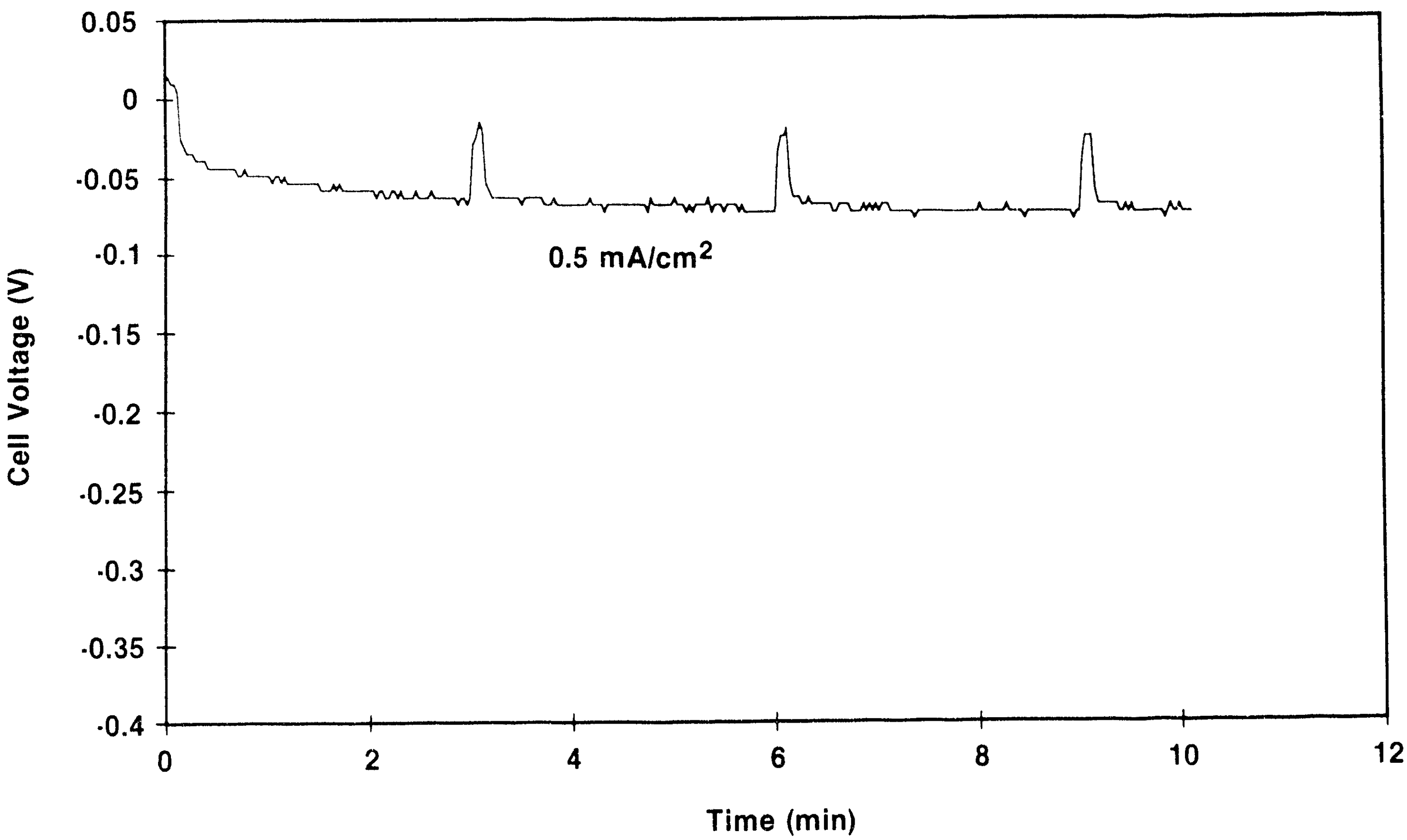

Figure 8. Discharge of Na/PEO-NaTf/Na cell at 0.5 mA/cm^2.

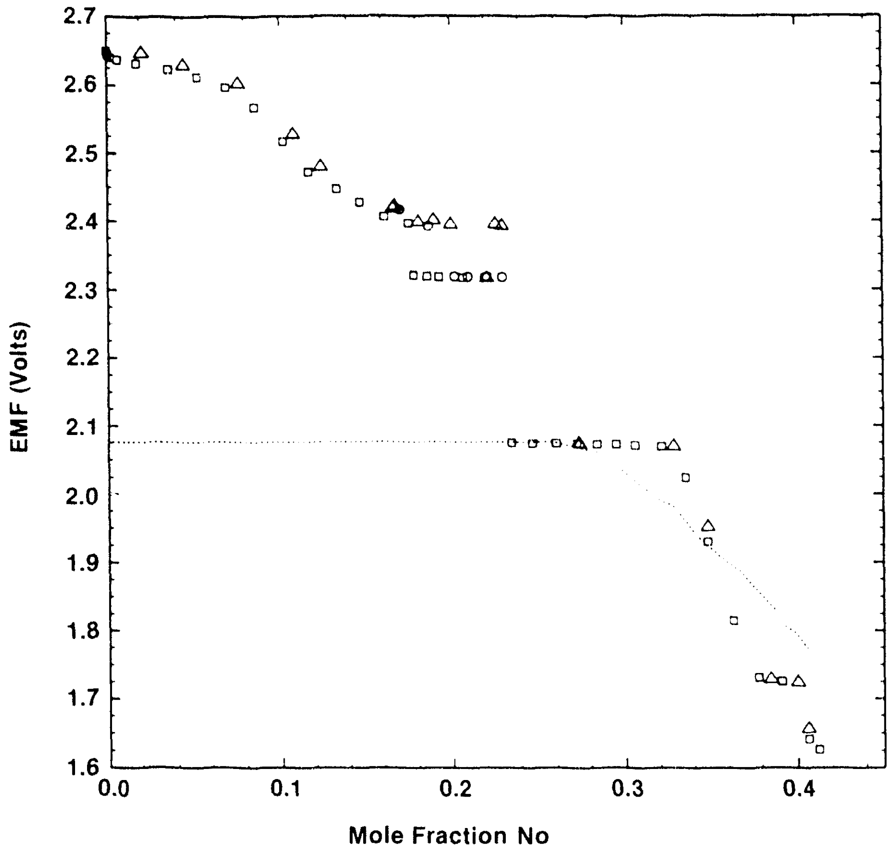

Figure 9. Plots of cell potential vs. Na mole fraction in P-S melt in a Na/P-S cell.

ERIM to duplicate the quality of the coatings obtained at Ford and to evaluate the corrosion-resistant properties of TiN for extended periods in polysulfide melts.

Sodium/nickel chloride batteries offer the potential for a safe battery system with excellent reliability to serve as a power source for both electric vans and passenger vehicles. DOE supports research at Argonne to generate the scientific and technical base required to develop advanced sodium/nickel chloride batteries that meet the USABC long-term objectives (200 W·h/kg and 400 W/kg). During FY 1992, efforts have been focused on optimizing the performance of the nickel chloride electrode through the use of appropriate chemical additives and pore forming materials, as well as characterizing the nickel chloride electrode under EV SFUDS or power dynamic operating conditions. These studies indicate that the Argonne-developed chemical additives produce the following results: enhance the specific energy of the cell by 40 percent and the power by over 200 percent; permit the sodium/nickel chloride cell operating temperature to be varied from 160° C to 370° C; reduce cell recharge time from 5 hours to 1 hour; and significantly improve the sodium/nickel chloride cell life by reducing the solubility of the nickel chloride cathode material in the electrolyte.

In FY 1992, Lawrence Berkeley Laboratory demonstrated that for Zn/KOH/NiOOH cells a moderately alkaline electrolyte is very effective for extending the cycle life of the cells. A 1.35-A·h sealed, starved-electrolyte cell containing alkaline-fluoride-carbonate electrolyte (3.2 M KOH - 1.8 M KF - 1.8 M K_2CO_3) retained 80 percent of its original charge after approximately 400 deep-discharge cycles and reached 570 cycles before its capacity fell below 60 percent. The cell is shown in Figure 10. A pressure transducer is attached to the cell, and the electrodes and current-collecting tabs are visible inside the cell. Lawrence Berkeley received a 1992 R&D-100 Award for the development of this promising technology. Scale up of Zn/KOH/NiOOH cells to 20 A·h (electrodes of approximately 15 x 15 cm) is underway, and the new electrolytes are being evaluated in these larger cells. Lawrence Berkeley issued an RFP to transfer the

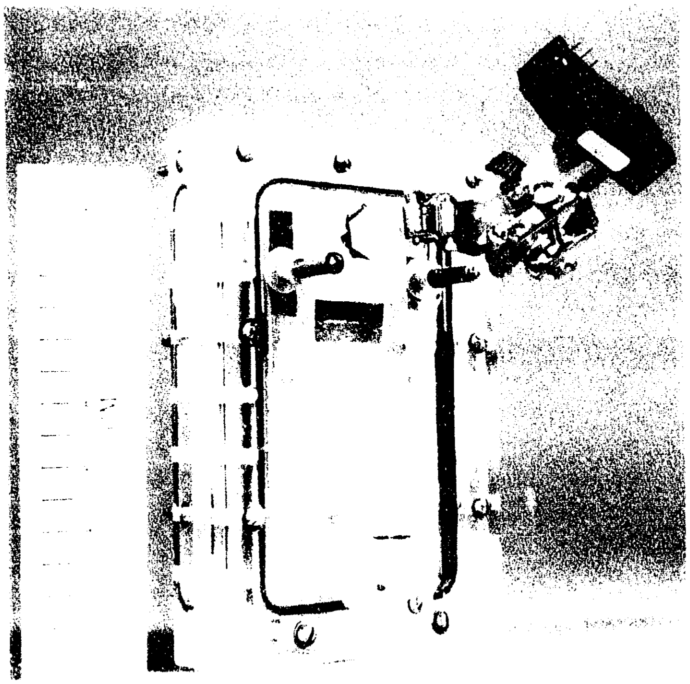

Figure 10. Sealed zinc/nickel oxide cell which has attained 575 deep-discharge cycles using novel alkaline-fluoride-carbonate electrolytes.

technology to an industrial battery developer, which is expected to develop Zn/NiOOH cells using the new electrolyte and electrode formulations.

Exploratory development of zinc/air batteries continued in FY 1992. A new 22 percent cost-shared contract was placed with Westinghouse Electric Corporation to advance the zinc/air technology by developing a prototype design of an EV battery and fabricating battery modules for proof-of-concept evaluations. The goal is to develop the technology to the level that the USABC mid-term vehicle requirements are met. The period of performance is 26 months. Total DOE funding for this contract is $1.466M with initial FY 1992 funding of $400K. FY 1993 deliverables will include four state-of-the-art cells and one improved cell or module. In FY 1994, submodules and modules will be delivered. All deliverables will be evaluated using USABC test procedures.

In concert with the United States Advanced Battery Consortium, a contract for the development of zinc-air batteries for electric vehicle propulsion was let with Dreisbach Electromotive, Inc., (DEMI). Under this effort, DEMI will develop a number of 12-V, 240-A·h, rated battery modules for test and evaluation at the Idaho National Engineering Laboratory Battery Test Laboratory. Approximately half of the delivered batteries will be of a hybrid battery configuration, utilizing nickel-cadmium batteries to increase the electrical power which can be delivered by the system. During FY 1992, efforts concentrated in developing a suitable battery manager for the zinc-air cells which performs several functions such as scrubbing CO_2 from the air going into the battery and controlling the ancillary battery systems. This battery manager has been successfully demonstrated during Phase I of the program. Phase II commenced in FY 1992 to build the deliverable battery modules. It is anticipated that these batteries will be completed and tested in FY 1993.

Department of Energy projects are underway at Case Western Reserve University and Eltech Research Corporation to develop more stable oxygen electrodes for rechargeable Zn/air cells. Case Western has observed that the catalytic activity for the reduction of O_2 at cobalt tetrasulfonated phthalocyanine (CoTsPc) adsorbed on ordinary pyrolytic graphite (OPG) in alkaline solution is enhanced by approximately 60 mV in the presence of alcohols. Further, the presence of methanol has no short-term deleterious effect on the kinetics for O_2 reduction on CoTsPc/OPG, which also exhibits negligible catalytic activity for methanol oxidation. Eltech is investigating the viability of graphitized carbon blacks and metal oxides as electrocatalyst supports in bifunctional air electrodes for electrically rechargeable Zn/air cells. Graphitized carbon blacks of Monarch 120 and Shawinigan acetylene black, and the metal oxides of $NiCo_2O_4$, Co_3O_4, $Pb_2Ru_2O_7$ and $Pb_2Ir_2O_7$, have been prepared.

Lawrence Berkeley Laboratory is investigating various configurations of Zn/air cells and their performance under standardized cycling regimes. Experiments were initiated to adapt the mechanically rechargeable Zn/air cell invented at Lawrence Berkeley, which employed a reticulated Zn electrode structure to operate under natural convection, for electrically rechargeable cell configurations. A laser-Doppler velocimeter was modified to measure the electrolyte velocity and the expected signal was obtained. An algorithm was developed to model the convective diffusion of the electrolyte in the porous electrode structure. Lawrence Berkeley is evaluating commercial bifunctional air electrodes in Zn/air cells, as well as developing improved bifunctional air electrodes from metal oxide electrocatalysts. A bifunctional air electrode (BF-8) from Electromedia, Inc.,

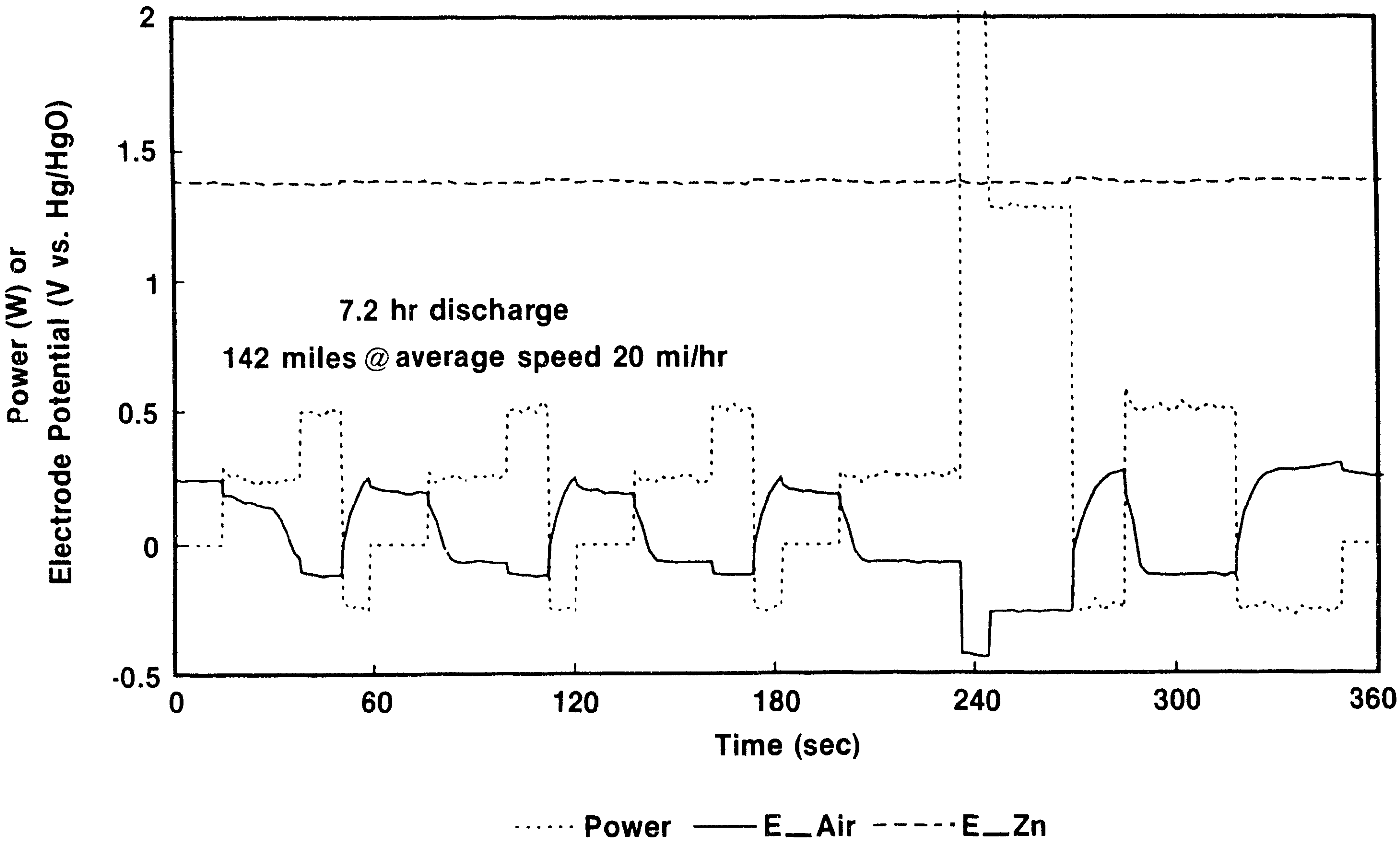

Figure 11. Discharge #6 of a 1.8 A·h Zn/air cell at SFUDS repitition #40.

was cycled at constant-current rates and the SFUDS in a Zn/air cell (see Figure 11) with an electrolyte of 45 percent weight KOH and 40 g Zn^{2+}/l. Approximately 25 cycles were achieved, regardless of the discharge rates.

3.4 Battery Testing

Battery testing was conducted during FY 1992 on a variety of advanced and near-term batteries. Argonne and Sandia performed tests on advanced batteries to provide a measure of progress towards the USABC goals. The Idaho tested near-term lead acid batteries to provide Site Operators with information on batteries available for use in their electric vehicles.

Laboratory experimental evaluations and post-experimental examinations are conducted at the National Laboratories to assess the suitability of various battery technologies for EV propulsion. Advanced battery systems are evaluated with respect to both performance and life. Performance characterization includes the determination of capacity vs. discharge rate, peak power vs. depth-of-discharge, and capacity loss vs. stand-time; life testing involves repeated cycling with simulated driving profile discharges until the capacity declines to <80 percent of its rated value. These evaluations, combined with post-test examinations of the advanced battery systems, provide insight into those factors that limit performance and life and help identify the most-promising R&D approaches for overcoming these limitations.

During FY 1992, tests were performed on single cells and a 120-cell module of four advanced technologies (Na/S, Li/FeS, Ni/Metal-Hydride, and Ni/Zn). Table 4 provides a summary of the Argonne battery test results. Further discussion of these tests follow.

Table 4. Summary of FY 1992 Argonne National Laboratory Battery Testing Results

	Initial Weight kg	Module Capacity[a] A·h	Specific Energy[a] W·h/kg	Energy Density[a] W·h/L	Peak Power[b] W/kg	Efficiency[a] Coulombic %	Efficiency[a] Energy %	Van Life[c] cycles	Van Range[f] mi(km)
Sodium/Sulfur CSPL PB-MK3	29.2	292	79	123g	90	100	88	795	150(240)
Lithium/Monosulfide SAFT of America Prismatic	2.94	203	66	133g	64	95	81	163d	93(149)
Nickel/Metal Hydride Ovonics C-cell	0.081	3.6	54	186	158	92	80	333	97(155)
Nickel/Metal Hydride Ovonics Ext.C-cell	0.093	4.5	57	209	105	90	74	108	— —
Ovonics H-cell	0.628	28.0	55	152	175	90	80	380d	97(155)
Nickel/Zinc Electrochemica R&D Cell	1.69	69	67	142	105	91	77	114d	108(173)

a Determined for 3-h rate CI discharges.
b Determined from driving profile discharge data at 80% DOD.
c Determined with SFUDS discharges to 100% DOD unless otherwise indicated. Ongoing life tests are indicated with the ">" sign.
d Determined with 80% DOD discharges.
e Determined with J227aC discharges.
f Determined for the IDSEP Van with a 695 kg battery on an SFUDS driving schedule.

Sodium/Sulfur

An 8-V Na/S module from Chloride Silent Power Ltd. in England was under test from June 1990 to March 1992. This module contained 120 cells (10-A·h each) configured into 30 parallel-connected strings of four series-connected cells. Life testing with SFUDS discharges to 100-percent DOD was started after completion of the performance tests (approximately 120 cycles). There was a significant drop in module capacity between 450 and 550 cycles, which reflected the loss of four 4-cell strings (approximately 40-A·h loss). End-of-life (<80 percent of initial 2084-W·h SFUDS discharge energy) occurred at cycle 795, but testing was continued to acquire additional statistics for cell failure analyses. Testing was halted after 973 cycles when the SFUDS discharge energy decreased to <75 percent of its initial level. At that time, module peak power had declined to 68 W/kg from an initial 94 W/kg (50-percent DOD), and capacity was approximately 79 percent of its initial 292 A·h. The module was returned to CSPL for post-test analyses.

In addition, twelve Mk-3SF PB cells from CSPL have been under test since October 1990 at Sandia. The intent of this effort is to characterize the effect of different cycling regimes on service life. The 12 cells were divided into 4 groups, and a different EV-related test regime is being followed for each group. The first group of cells is being continuously life-cycled using baseline parameters, while the second group of cells is evaluated using a modified driving schedule. The third group of cells completed a proposed general test plan developed by the EHP Battery Test Working Task Force and is presently performing a limited depth-of-discharge test regime. The fourth group is performing an open-circuit stand test to determine if cell life could be related to time at temperature. The operating temperature of all the cells is 350° C. Eight cells have been tested to failure, and four cells remain on test. A gradual decline in capacity or failure has been observed on several cells after they have been at temperature for more than 50 weeks. Two cells presently on test have accumulated more than 1,500 cycles and still retain 80 percent of their capacity.

Idaho National Engineering Laboratory also performed a series of tests on the CSPL sodium-sulfur battery (see Figure 12) consisting of constant-current and constant-power discharges and simulated driving cycle discharges based on the Federal Urban Driving Schedule (FUDS) and the SFUDS. A total of 38 charge/discharge cycles were run on the battery over a 6-month time period. The battery (24 8-V banks) has a nominal voltage of 200 V and a rated energy capacity of 60 kW·h. The battery consists of 2,880 Mark III cells which were manufactured in 1989. The tests indicated an energy density, based on the actual battery weight of 750 kg, is 55 to 60 W·h/kg and 110 to 120 W·h/kg based on the cell weight of 337 kg. The measured battery A·h capacity (230 to 250 A·h) was significantly less than the nominal 300-A·h rated capacity due to the inoperative 4-cell string in the 24 banks, which caused the test to be terminated by the weakest bank before the remaining banks were completely discharged. The CSPL battery exhibited a calendar life, at a temperature above 300° C, of at least 18 months after 2-1/2 freeze/thaw cycles. The CSPL sodium-sulfur battery tested at the Idaho National Engineering Laboratory was assembled in late 1989 and, therefore, represents the state of cell development, packaging, and enclosure technology of that stage of development.

Lithium/Iron Sulfide

Two 200-A·h Li/Fe cells built by SAFT America, Inc., were delivered to Argonne National Laboratory for baseline performance testing. The first cell was placed on test in May 1991. At an operating temperature of 470° C, this cell achieved a capacity of 182.5 A·h. The operating temperature was raised in 5° C steps to 485° C to observe the effect on cell capacity. The results showed that cell capacity (as well as internal resistance, IR-free voltage, and peak power) was sensitive to temperature. Even though the cell retained 98 percent of its original capacity after 30 cycles, it was removed from the test to conduct a post-test analysis

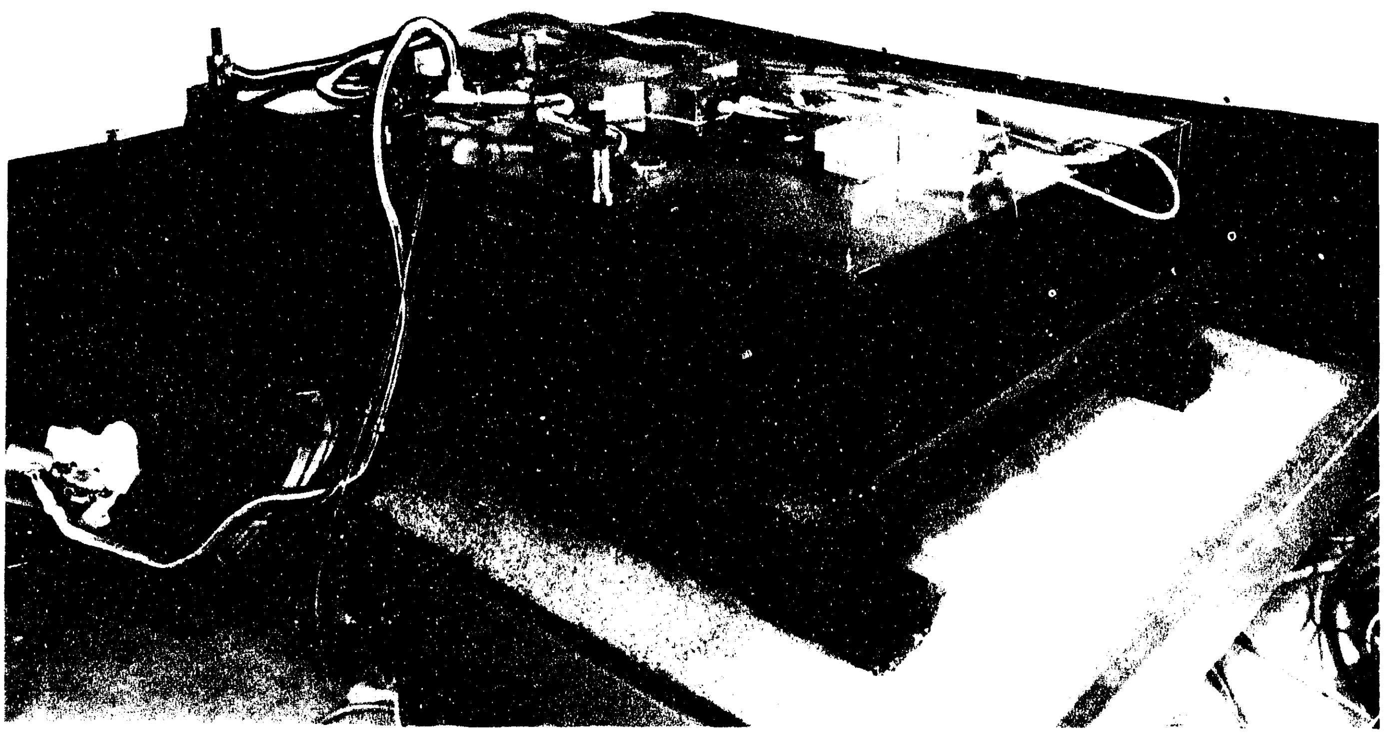

Figure 12. Chloride Silent Power Limited sodium-sulfur battery.

for the purpose of identifying the cause of the cell's abnormally high sensitivity to temperature. Post-test results on this and other baseline cells indicated the need for a higher electrolyte content and refinements in the internal current collector/busbar system. The second cell was placed on test in July 1991. Because the clamping arrangement used in the test fixture for this cell was modified to allow more compression on the electrode face, this cell was less sensitive to temperature and achieved a higher capacity than the first (465°C tests). After 158 cycles, the cell was cooled to ambient temperature for a 2-week period in December 1991. In January 1992, the cell was heated to 465°C and testing resumed. The initial capacity (198 A·h) was greater than that exhibited before the shutdown, but on subsequent cycles, the capacity decreased. The cell exhibited a decline in voltage during the open-circuit period after discharge and was unable to reach the required constant-voltage (CV) charge level (1.5 V with a 120-percent charge return). These factors indicate a high internal self-discharge rate. Testing was suspended at cycle 163.

Nickel/Metal Hydride

Tests have been conducted on nickel/metal hydride (Ni/MH) cells manufactured by Ovonics Battery Company (Troy, MI) prior to the initiation of the battery development contract with the USABC. The initial C-size (3.5-A·h rating) cells exhibited good performance characteristics, but the cycle life of four cells (33, 238, 289, and 333 cycles) was less than expected (500 cycles). Two extended C-size cells (approximately 4.5 A·h) were evaluated in mid-1991. The specific energy of these cells was slightly higher than that of the smaller C-cells, but the cycle life was still less than expected. These early cells exhibited a high self-discharge loss (14 to 38-percent loss in 24 hours and 45 to 79-percent loss in 7 days). Ovonics subsequently modified component materials and reduced the self-discharge loss to 15 to 20 percent in 7 days.

Two 25-A·h Ni/MH H-cells were placed on test in June 1991. These cells represented an intermediate step in an Ovonics program to fabricate and develop large, full-size EV cells. Performance characterization tests were completed, and life evaluation started in November 1991. Life tests are being conducted with SFUDS discharges to 80-percent DOD. All of the Ni/MH cells tested at Argonne have exhibited a very low resistance and exceptionally high peak power capacity (approximately 200 W/kg at 50-percent DOD). The peak-power capability of the H-cell is the highest measured at Argonne (between 35 and 80-percent DOD). A high peak power provides full capacity and maximal vehicle range for all driving profile discharges. One H-cell was removed from life test after 380 cycles due to a sudden decline in capacity (to <70 percent of its initial 25-A·h capacity). A reduced cell weight indicated that the capacity decline was due to electrolyte loss. Water (13.6 g) was added to the valve-regulated cell, and full capacity (26.5 A·h) was achieved on a subsequent discharge. Thereafter, the capacity declined at a rate of approximately 0.5 A·h/cycle. Testing was halted when the capacity declined to 13.8 A·h on cycle 399. Cell weight was reduced again (by 6.3 g). This suggests problems with the integrity of the stainless steel case and/or the pressure release vent. A replacement cell (EV35) was furnished by the manufacturer in April 1992. This cell has a 7-hour rating of 35 A·h and will undergo performance and life evaluation.

The second H-cell is still under life test with SFUDS discharges to 80-percent DOD (26.3-W·h discharges and 23-A·h CI/CI charges). This cell has completed >300 cycles and retains approximately 100 percent of its initial 28-A·h capacity. The weight of this cell is being periodically measured to identify the onset of any electrolyte losses.

Nickel/Zinc

Three Ni/Zn cells manufactured by Electrochemica were tested from May 1991 to February 1992 to determine the suitability of this technology for EV propulsion. Performance characterization tests were conducted on a 17-A·h cell from May to October 1991. This cell continually exhibited unstable capacity, and its capacity declined >20 percent after 170 cycles (end-of-life criterion). Special manufacturer-recommended conditioning cycles were imposed to improve cell capacity, but this rejuvenation process was unsuccessful. Testing was halted after the cell had completed 187 cycles, and its capacity had declined to approximately 40 percent of its initial 14.6 A·h.

Performance tests were then conducted on two larger cells (60-A·h rating). Testing of the first cell was halted after 140 cycles due to excessive heating during the initial constant-current (CI) charge period. This occurred after the cell had inadvertently received a 216-percent return with CI/CV charging during a 50-

percent DOD partial discharge test. Various conditioning cycles were tried to improve the charge acceptance of this cell but were not successful.

During performance testing of the second 60-A·h cell, the initial capacity of 52.3 A·h (110.6 W·h) increased with cycling to 70 A·h. Excellent specific energy (66.7 W·h/kg at 3-h rate) and peak power (185 W/kg at 50-percent DOD) were achieved. Life testing with 80-percent DOD SFUDS discharges and 110-percent return CI/CV charges was started after 95 cycles. The cell completed only 20 SFUDS cycles, when the 100-percent DOD termination condition (maximum power capacity ≤50 W/kg) was reached before the 80-percent DOD energy could be removed (end-of-life). At that time, the capacity was <50 A·h, and a thermal runaway condition was starting during the CV portion of the CI/CV charges. All three Ni/Zn cells were returned to Electrochemica.

Near-Term Battery Tests

Idaho National Engineering Laboratory conducted laboratory experimental evaluations and post-test examinations of currently available lead-acid batteries of sealed and flooded designs to assess their suitability for electric vehicle propulsion. This information will be of use to DOE's Site Operators in selecting batteries for their electric vehicle fleets. Battery performance and life evaluations were performed under uniform test conditions that simulate driving cycle load profiles as well as conditions standard to the battery industry. Post test analysis of cycle life tests included physical and chemical analyses from which the degradation and failure mechanisms are determined, thus identifying areas requiring further research and development. A summary of the near term battery test results is given in Table 5.

Table 5. Summary of Idaho National Engineering Laboratory Near-Term Battery Test Results

	Japan Storage		Sonnenschein	East Penn
	GS E75A	GS E150H	DF6V160	8D8G
Module Wt. (kg)	25	47	33	74
Module Capacity (A·h)				
@ C/3 rate	69	130	139	155
@ C/2 rate	63	115	130	141
@ C/1 rate	53	93	115	122
Ragone Characteristics (W·h/kg)				
@ 7 W/kg	38.6	36.7	27.0	26.8
@ 21 W/kg	26.3	23.4	20.5	19.4
@ 42 W/kg	20.6	17.6	N/A	15.8
@ 60 W/kg	18.2	15.2	N/A	14.2
Volumetric Energy Density (W·h/l)				
@ 7 W/kg	89.2	84.4	77.5	59.9
@ 21 W/kg	60.7	53.8	58.8	43.4
@ 42 W/kg	47.7	40.5	N/A	35.4
@ 60 W/kg	42.1	35.0	N/A	31.8
Specific Energy				
@ C/3 rate (W·h/kg)	24.9	32.2	25.0	29.9
Battery Coulombic Efficiency				
@ C/3 rate	80%	79%	93%	97%
Battery Energy Efficiency				
@ C/3 rate	67%	64%	81%	86%
IDSEP Van SFUDS Range (km)	34	83	132	119

Life cycle testing of two Sonnenschein DF6V160 sealed lead-acid battery modules was conducted using the SFUDS battery discharge profile which simulated the duty cycle expected of the hypothetical IDSEP mini-van on the FUDS. The end of the battery life was reached after 382 discharge cycles when the two modules could not deliver 80 percent of the their original energy on the cycle. Subsequent tests on the weakest module revealed that it had deteriorated to less than 72 percent of the rated ampere-hour capacity due to failure of the negative half-cell. At the completion of life cycle testing, the weakest battery was subjected to an in-depth teardown analysis to determine the precise cause of failure. The results of this analysis will be reported when it is completed.

Characterization tests were performed on three East Penn 8D8G 12 volt batteries. The electrodes used in this battery are manufactured by Sonnenschein and are believed to be the same electrodes used in the DF6V160 battery described above. Characterization test results are currently being analyzed. Preliminary indications are that the performance of the East Penn electrodes are indeed similar to the Sonnenschein DF6V160 electrodes.

Two flooded lead-acid battery designs manufactured by Japan Storage Battery Company were tested and characterized in the Idaho Battery Test Laboratory. These batteries are manufactured in Japan by the Japan Storage Battery Co., Ltd., and imported into the United States by GS Battery (U.S.A.), Inc. The GS E150H model is generally considered the best lead-acid battery in Japan for use in electric vehicles. Performance of these batteries is fairly poor compared to other lead acid batteries.

3.5 Ultracapacitors

High energy density ultracapacitors can be used to load level the traction battery in electric vehicles or the engine in a series hybrid electric vehicle. In the case of electric vehicles, use of ultracapacitors would reduce the peak power required from the battery by a factor of three or more, resulting in a longer battery life. The battery could also be optimized for energy density. In the case of the series hybrid vehicle, the ultracapacitors would be used to supply the peak power of the electric drive system and permit a smaller battery system to handle a level load.

A contract was placed in June 1992 with Maxwell Laboratories, San Diego, CA, and Auburn University, Auburn, AL, to develop bipolar, carbon-based ultracapacitors having an energy density of at least 5 W·h/kg by 1995, which could be configured in a 100 kg unit to store 500 W·h of energy. Very high surface-area electrodes can be achieved with carbon for significant stored energy density. Materials and electrode research at several DOE National Laboratories and at private companies doing research for the Department of Defense has indicated that development of ultracapacitors with an energy density of 10 to 15 W·h/kg may be possible in the future.

High-energy, density capacitors obtained from both domestic and foreign companies are being evaluated in the Idaho Battery Test Laboratory. Tests of the spiral-wound, carbon-based device shown in Figure 13 have indicated an energy density of 2 W·h/kg and a cycle life of 503,000 charge/discharge cycles over a period of 7 months of continuous testing. A contract was placed in September 1992 with

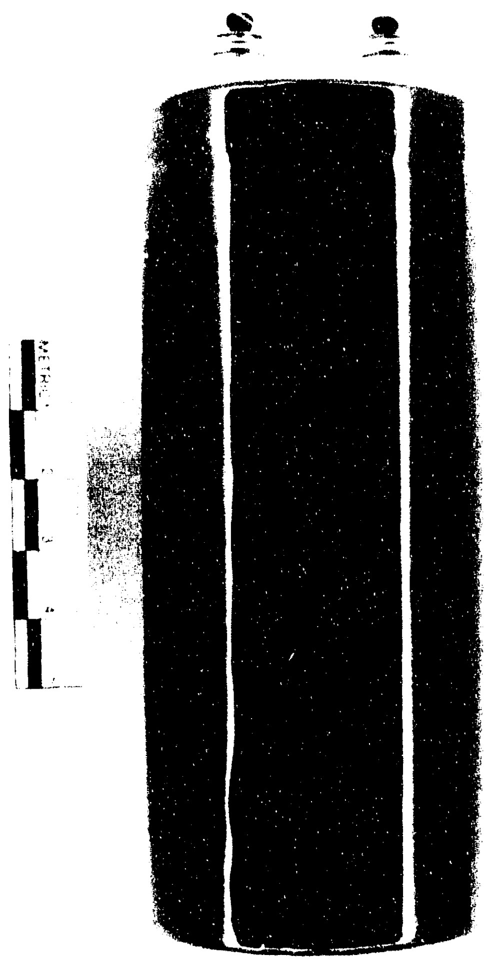

Figure 13. A spiral-wound, carbon-based capacitor (3 V, 600 F).

General Electric, Schenectady, NY, to study the interface electronics needed to utilize the ultracapacitors in an advanced AC driveline, such as that developed for DOE on the MEVP program.

Electrochemists at Sandia National Laboratory conceived the idea of utilizing for double-layer capacitor (DLC) applications, carbon materials that they have developed over the years. Since the 1980s, Sandia has been responsible for an approximately $80M carbon materials development program (involving a wide segment of the DOE complex of National Laboratories and Integrated Contractors) that led to novel preparation techniques, processes, and materials.

A proof-of-concept program was initiated at Sandia, with funding provided by DOE Defense Programs, and demonstrated that some of these carbon materials could be used as electrodes in DLCs. On the basis of the successful outcome of this program, the DOE Office of Propulsion Systems funded a $50K program at Sandia in FY 1992 to continue materials development and evaluation in the hope of identifying superior carbon materials and to fabricate a device using some of these materials in order to determine if these materials could be utilized in a device. The primary emphasis of this program was development of a carbon material exhibiting ≥50 Farads/cm^3 in a device. This program has led to the development of carbon materials that exhibit ≥130 Farads/cm^3 in a device having dimensions similar in size to a standard "D" size battery, *i.e.,* approximately 1-5/16" O.D. by 2-7/16" long. The device fabricated has a capacitance in excess of 1,000 Farads and an energy density of approximately 1.4 W·h/kg. Figure 14 shows the assembled electrode stack that is present inside of the double-layer capacitor laboratory prototype developed and fabricated at Sandia. The two diametrically opposite main electrical leads for the device are outside of, and extending above, the stack. The alternating layers of electrode separators (light color) and carbon electrodes (dark color) that make up the stack are also shown. A metric scale is included in Figure 14 for reference purposes.

In August of FY 1992, DOE initiated a project at Los Alamos National Laboratory to develop conducting polymers as the active charge storage material in electrochemical capacitors for electric vehicle applications. Conducting polymers have an important combination of properties which make them an attractive target for development as active materials in ultracapacitors. They exhibit very high intrinsic charge capacity while being less costly than other candidate materials. During the first months of this project, a new material system consisting of a novel conducting polymer and a new non-aqueous electrolyte was demonstrated to have an energy-density over 40 W·h/kg of active material. This provides ample margin for support materials and packaging to exceed the initial DOE goal of 5 W·h/kg for capacitors in electric vehicle applications. Higher energy capacitors potentially will be desirable for advanced applications.

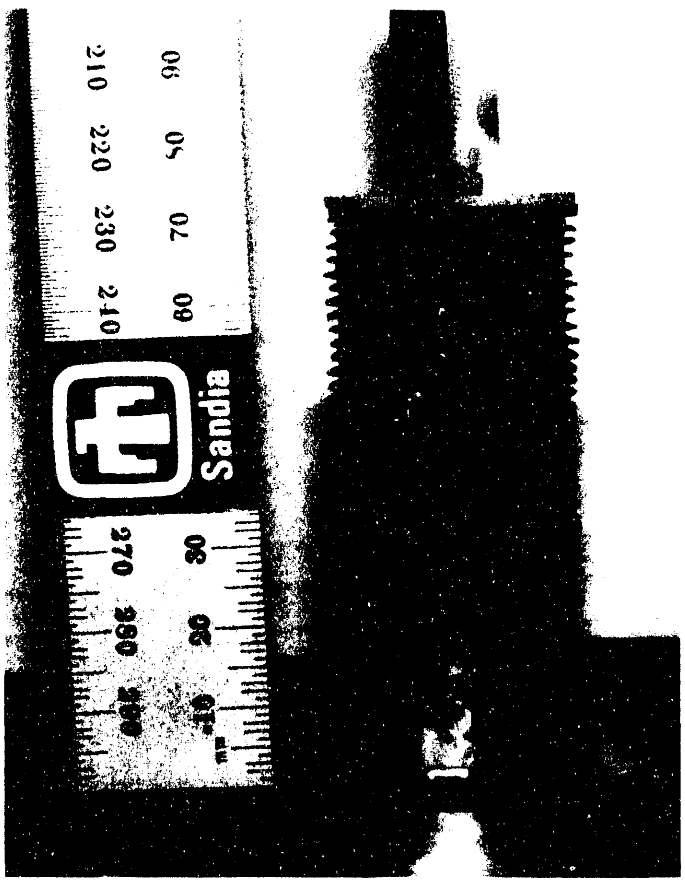

Figure 14. Sandia National Laboratory prototype double-layer capacitor.

4.0 FUEL CELL SYSTEMS R&D

Fuel cells, operating on non-petroleum fuels, can potentially provide an alternative transportation propulsion system with nearly twice the fuel economy and greatly reduced emissions/noise compared to the internal combustion engine. A fuel cell is an electrochemical device that combines hydrogen with oxygen and converts their chemical energy into electricity. The waste product from the process is water; fuel cells emit essentially no carbon monoxide, nitrogen oxides, or particulates.

The objective of the DOE Fuel Cells for Transportation program is to advance fuel cell technologies from the R&D phase, through optimization and scale-up, to demonstration in cars, vans, and buses, in order to provide energy savings, fuel flexibility, and air quality improvements. Near-term efforts are directed at phosphoric acid fuel cells (PAFC) technology, which is the only one suitably developed for transportation at this time. The result will be a methanol-fueled, fuel-cell-powered bus system with performance equivalent to diesel buses, but with a reduction in exhaust emissions of more than 99 percent. For the longer-term, the program is directed at the introduction of proton exchange membrane (PEM) fuel cells into cars and vans. PEM fuel cells can achieve the power density required for cars and vans, but additional R&D is required to reduce costs, optimize performance, and otherwise extend the technology. Advanced reformer technology and improved hydrogen storage systems are being developed to improve the competitiveness of PAFC and PEM fuel-cell-powered vehicles by reducing system size and cost, reducing start-up times, and increasing transient response capability. Fuel flexibility can be attained with the capability of reforming methanol, ethanol, or natural gas into hydrogen for use in fuel-cell-powered vehicles.

During FY 1992, DOE initiated the development of a National Program Plan for Fuel Cells in Transportation. This 10-year plan is being developed from a consensus for the development and commercialization of fuel cell vehicles formed at the two meetings of an ad hoc technical panel consisting of more than 50 representatives from the transportation industry, universities, national laboratories, government agencies, regulatory bodies, and alternative fuels proponents.

4.1 Phosphoric Acid Fuel Cell Bus Project

The objective of this program is to develop and demonstrate a fuel cell propulsion system in an urban transit bus. An urban transit bus was selected as the initial test vehicle because its larger size can readily accommodate the packaging of a first-generation fuel-cell-powered propulsion system, and because the acquisition cost of present-day fuel cell systems can be amortized over a longer service life in a bus than in passenger cars. Methanol fuel was selected because it can be derived from nonpetroleum sources (e.g., coal, natural gas, biomass), it can be easily stored onboard to provide an acceptable driving range, and it can be reformed into hydrogen for fuel cell use at relatively low temperatures.

The phosphoric acid fuel cell was selected because of its near-mature state of development and because its operation on reformed methanol has been demonstrated. The use of a battery in parallel with the fuel cell minimizes the size of fuel cell required; the fuel cell provides the average power required, and the battery, which is recharged by the fuel cell during bus idle periods, provides the supplemental power needed during vehicle acceleration. For maximum energy efficiency, the energy released during vehicle braking can also be used to charge the battery.

This program is co-sponsored by the Department of Transportation/Federal Transit Administration and by California's South Coast Air Quality Management District. Argonne National Laboratory and Georgetown University provide technical management for this program.

In Phase I of this project, two industrial contractors demonstrated the feasibility of the concept by building and testing a laboratory brassboard power system one-half the size needed for the bus. The team of Booz-Allen & Hamilton, Chrysler Pentastar Electronics, and Fuji Electric built and tested an integrated 68-kW power source consisting of a 25-kW fuel cell and 43-kW lead-acid battery. Energy Research Corporation built and tested a 62-kW power source consisting of a 32-kW fuel cell and 30-kW nickel/cadmium battery. In both systems, the test results verified the performance and confirmed the feasibility of the fuel cell bus concept.

Through a competitive procurement process, DOE awarded a 30-month, 25 percent cost-shared contract in 1991 to H-Power Corporation of Belleville, NJ, for Phase II of this project, which includes the fabrication and delivery of three 29-ft, 25-passenger urban buses and the design for a full-size 40-ft urban bus. H-Power will assemble and test the fuel cell/battery systems in its New Jersey laboratories before they are installed on the buses. Key subcontractors on the H-Power team are Transportation Manufacturing Corp. (the largest U.S. bus manufacturer), Bus Manufacturing USA Inc., Booz-Allen & Hamilton, Fuji Electric, and Soleq Corporation. The involvement of major bus manufacturers and their willingness to share in the development costs are evidence of industry support for this project. At the end of FY 1992, H-Power had completed the major subsystem designs and had begun fabrication of the bus structure and the 50-kW phosphoric acid fuel cell system.

In support of the Fuel Cell Bus Project, Argonne carried out evaluation and endurance testing during FY 1992 on several lead-acid and nickel/cadmium batteries selected as potential candidates for the fuel cell bus application. Georgetown University also conducted studies in support of the Fuel Cell Bus Project during FY 1992 under a cost-shared contract with DOE. Georgetown developed a bus performance simulation model and used this model to analyze bus requirements for actual transit routes. Georgetown also carried out a bus industry market study to support the development of a fuel cell bus commercialization strategy. The PAFC battery-powered test bed bus concept is shown in Figure 15.

4.2 Proton Exchange Membrane Fuel Cell Research

The Department of Energy is sponsoring both fundamental and applied research on PEM fuel cells for transportation applications. The PEM fuel cell, when fully developed, will offer significant advantages over the phosphoric acid fuel cell. These advantages include reduced size and weight, faster start-up, and potentially lower cost. When the PEM fuel cell has been developed into an integrated system, it will have the potential for meeting the size and weight requirements for use in automobiles, vans, and light trucks.

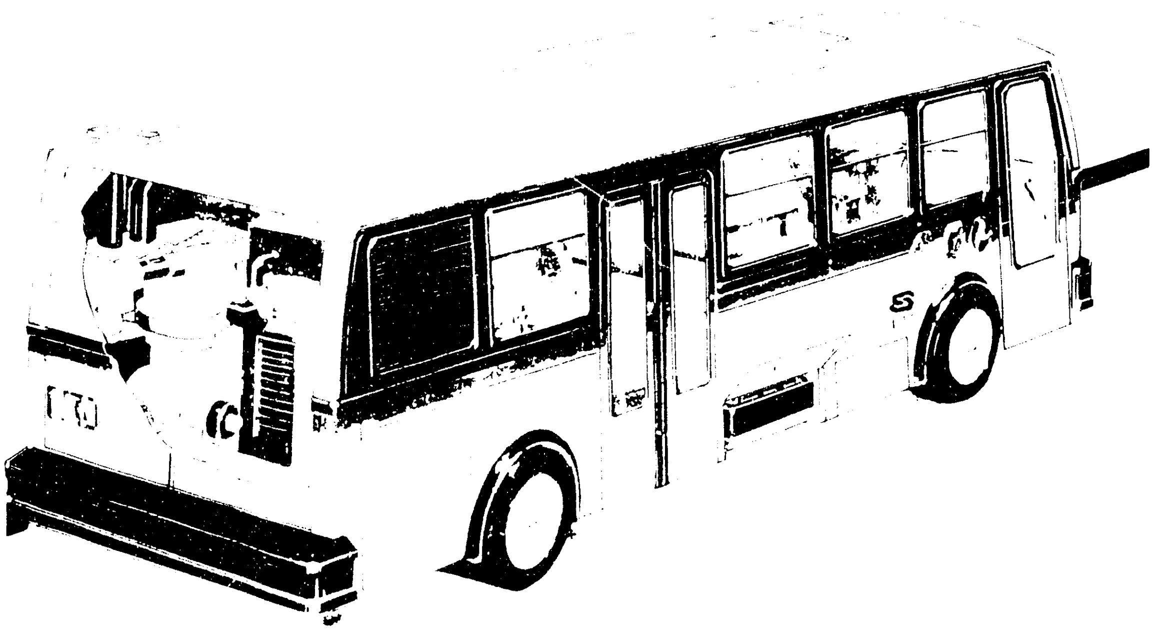

Figure 15. PAFC battery-powered test bed bus.

General Motors Corporation (Allison Gas Turbine Division) completed the second year of a 32-month, 20 percent cost-shared R&D contract for development of the PEM fuel cell as a complete transportation power source system. As the prime contractor for Phase I, Allison is responsible for overall system integration. Support subcontractors are Los Alamos National Laboratory for reformer development and fuel cell testing, Dow Chemical Company for membrane fabrication and testing, Ballard Power Systems for fuel cell stack fabrication, GM Research Laboratories for electrode and catalyst studies, and GM Advanced Engineering Staff for vehicle system engineering. During FY 1992, membranes and electrodes were improved, state-of-the-art 5-kW PEM fuel cell stacks were built and tested, and significant progress was attained in methanol fuel processing and control technologies needed to bring this to a complete system. The Phase I effort will culminate in FY 1993 with the integration and testing of a complete 10-kW PEM fuel cell system, which is expected to provide a demonstration of the feasibility of PEM fuel cells for transportation, thereby laying the groundwork for a potential future engineering scale-up and integration of a PEM fuel cell propulsion system into a vehicle.

The PEM fuel cell uses a fluorocarbon polymer membrane as the electrolyte. Because the membrane contains terminal sulfuric acid groups, it acts as an acidic electrolyte and does not absorb carbon dioxide and thus can be used with reformed hydrocarbon fuels. An advantage of a solid polymer electrolyte is that an immobilized electrolyte simplifies sealing in the production process, reduces corrosion, and may provide for a long cell life. The cell operates at about 80°C, and useful electric power can be drawn from the cell at room temperature. The lower operating temperature allows much faster and easier start-up than the PAFC system which operates at about 200°C.

Two areas of concern for the PEM fuel cell are carbon monoxide (CO) poisoning of the electrocatalyst and the need for humidification of the fuel stream. Fuel cells, such as the PEM, which operate at low temperatures use platinum to catalyze reactions at both the anode and cathode. The adsorption of CO, which is inversely related to temperature, blocks access of hydrogen to the surface of the catalyst. At the 80°C operating temperature of the PEM fuel cell, the allowable concentration of CO in the fuel is only a few parts per million. Water content in the fuel stream must also be maintained at a minimum partial pressure of 400 millimeters of mercury to prevent dehydration of the polymer membrane and a catastrophic increase in electrical resistance. To maintain adequate hydration of the membrane, the system must be pressurized and surplus water must be constantly supplied at the anode.

For best performance, PEM fuel cells require an oxidizer unit between the reformer and the fuel cell to remove CO, a turbocompressor to pressurize the system, and a water management system to maintain hydration of the membrane and removal of the product water. The preferential oxidizer reduces the concentration of CO in the fuel stream coming from the reformer from one percent to a few parts per million. The turbocompressor raises the air pressure at the cathode to about 3 atmospheres (0.3 MPa). A water removal system is required because more water than is needed for reforming must be injected into the fuel stream to maintain hydration of the membrane. A humidification section is included in the design of the cell stack to supply water to the membrane.

Ongoing supporting exploratory and core technology development activities are discussed in section 4.4. The results of these research efforts will be integrated into the PEM system development program.

4.3 Multifuel Reformers and Hydrogen Storage for Fuel Flexibility

Fuel cells operate by electrochemically combining hydrogen and oxygen to produce electricity and water. For transportation applications of fuel cells, oxygen can be obtained from the air, and hydrogen can either be carried on-board the vehicle or derived from hydrocarbon fuels by means of a fuel reformer.

With existing state-of-the-art technology, hydrogen can be stored either as a compressed gas in heavy tanks at high pressure, as a metal hydride, as an adsorbed gas on activated carbon, or as liquid hydrogen at extremely low temperatures. These storage mechanisms all have a large weight and volume per unit of hydrogen stored. As a result, the amount of hydrogen that can be carried on board a vehicle is restricted, and the driving range for the vehicle is limited.

Fuel reformers, as an alternative to hydrogen storage, can extract hydrogen from more plentiful carbon-based fuels such as methanol, ethanol, and natural gas that have a high hydrogen content. For transportation applications, methanol has been the fuel of choice to date since it can be derived from nonpetroleum sources, is easy to transport, and can be converted to hydrogen at relatively low temperatures. With reformers, liquid fuels for fuel cells can be stored in a manner similar to gasoline in internal combustion engine vehicles.

Steam reforming methanol to produce hydrogen involves a reaction of gaseous methanol and steam on catalysts according to the following reaction:

$$CH_3OH + H_2O \longrightarrow CO_2 + 3H_2$$

The reaction proceeds in two steps: the first being decomposition of methanol to hydrogen and carbon monoxide and the second a "shift reaction" of carbon monoxide and water to carbon dioxide and hydrogen. The overall net reaction is endothermic, and the required energy can be supplied from waste heat generated by other components of the fuel cell system. Most reformers developed to date have been designed for stationary applications; they are large, heavy, and lack the fast start-up and dynamic response capabilities necessary for use with fuel cell power systems in automotive applications.

Development of advanced reformer and hydrogen storage technologies will not only provide fuel flexibility for fuel-cell-powered vehicles, but will also reduce system size and cost, reduce start-up time, and increase transient response capability. DOE initiated research on advanced reformer and hydrogen storage technologies to improve the competitiveness of fuel cell vehicles. To this end, DOE awarded a 30-month cost-shared R&D contract in May 1992 to Arthur D. Little, Inc., of Cambridge, MA. One objective of the project is to develop advanced fuel processing systems to reform methanol, ethanol, natural gas, and other hydrocarbons into hydrogen for use in transportation fuel cell systems; a second objective is to develop better systems for on-board hydrogen storage. The work is divided into two phases: the first phase consists of a feasibility study, and the second phase will include fabrication and test of proof-of-concept reformer and hydrogen storage systems. The Phase I Feasibility Study is directed at examining the system tradeoffs (i.e., reformer size, weight, efficiency, quality of reformat, life, cost, transient response capability, start-up time) in the design of hydrogen storage systems and reformers for hydrocarbon fuels. Steam reforming, partial oxidation, or combinations of these processes are being investigated. The outcome of the Phase I Feasibility Study will be specifications for the reformer and hydrogen storage systems to be developed in Phase II, where a 10-kW reformer and a 1-kg hydrogen storage proof-of-concept systems will be built and tested. The project is expected to be completed by November 1994.

Research has been initiated at Argonne National Laboratory to identify and develop suitable catalysts for the steam reforming of ethanol. Ethanol is an attractive fuel for fuel cell propulsion since it has about a 30 percent higher energy content than an equivalent amount of methanol. Further, for fuel cell use, the water remaining in ethanol after the fermentation process does not have to be removed, eliminating the expensive distillation process required for ethanol use in internal combustion engines. Research conducted at Argonne in FY 1992 identified a family of catalysts that can potentially be used to reform ethanol. Although these catalysts can produce acceptably high concentrations of hydrogen in the product gas, these catalysts are not very selective and the hydrogen yield is not as great as is desirable. Work is continuing to develop catalysts that have good activity and high selectivity for the production of hydrogen by the steam reforming of ethanol.

The reforming of alcohols and other fuels to hydrogen by partial oxidation has been identified as a potentially attractive alternative to the steam reforming of the fuel for use in fuel cell propulsion systems. The partial oxidation process can yield reformers that are compact, lightweight, and offer rapid start-up and fast response to varying loads on the system. Experimental investigations were initiated at Argonne in FY 1992 to develop catalysts and processes for partial oxidation of methanol, ethanol, and other fuels. Research thus far has identified some highly promising catalyst formulations, prepared at Argonne and available commercially, that have very good activity and selectivity for the production of hydrogen from methanol. Additional work is continuing to establish the thermal, chemical, and mechanical stability of these catalysts. Catalysts for the partial oxidation reforming of ethanol are also being developed.

4.4 Exploratory Technology Development

Exploratory Technology Development in FY 1992 included cross-cutting research at Lawrence Berkeley Laboratory to provide a technology base and a core technology program at Los Alamos to support the development of fuel cells for transportation applications.

Cross-cutting research at Lawrence Berkeley provides a critical scientific and electrochemical engineering base to support the development of fuel cells for transportation applications. The projects at Lawrence Berkeley include spectroscopic and in situ studies of electrochemical reactions at electrode surfaces, studies of electrocatalysts using advanced surface techniques, electrocatalysis studies, and modeling of electrochemical and transport phenomena. Lawrence Berkeley has developed mathematical models to understand transport and kinetic phenomena occurring in electrochemical systems.

Improvements to the model of a solid-polymer-electrolyte fuel cell were made to include the effects of electrode kinetics, mass transfer to the membrane-electrode interface, and thermal effects. Lawrence Berkeley is using sophisticated surface-sensitive techniques and photothermal deflection spectroscopy (PDS) to study the electrooxidation of CH_3OH on Pt-based electrocatalysts. The PDS study indicates that the rate-limiting step appears to be the transfer of oxygen from water to the Pt catalyst where it can react with CH_3OH to form CO_2. The surface composition of Pt (MPt_3) alloys for methanol electrooxidation was found to be strongly dependent on the strength of the intermetallic Pt-M bond. In $CoPt_3$, for example, where the intermetallic bond is relatively weak, the lower surface energy of Pt produced pure Pt planes on both the |111| and |100| orientation. Investigations of dispersed Pt-Ru electrocatalysts showed they have a much higher catalytic activity for the electrooxidation of vaporized methanol than Pt alone in 72 percent weight Cs_2CO_3 at 120°C. Furthermore, a cell with 72 percent weight Cs_2CO_3 exhibited much lower potential losses than a comparable cell operated with concentrated H_3PO_4 under similar conditions (80°C).

Much of the fuel cell exploratory technology development underway at Los Alamos and Brookhaven National Laboratory is directed at improving the performance, life, and costs of the polymer-electrolyte-membrane for the PEM fuel cell; the focus is on electrocatalysis, theoretical studies, fuel-cell testing, fuel processing, and membrane characterization. Los Alamos has found that processing membrane-electrode assemblies (MEA) with membranes that contain the Na^+ form rather than the H^+ form permits the use of higher processing temperatures, 185 vs. 135°C, and the MEA are more robust, have a lower impedance, and are more tolerant to adverse humidification conditions in fuel cells. Los Alamos has characterized some of the H_2O-management properties of Nafion 117, membrane C, and an experimental Dow membrane. The Dow membrane appears to show the highest H_2O uptake and smallest water drag. These properties are beneficial for obtaining high performance in fuel cells with the Dow membrane. A large 50-cm^2 cell was operated at Los Alamos which attained an initial performance of 2 A/cm^2 on O_2 (5 atm) without experiencing transport losses at the O_2 electrode. The initial performance on air (5 atm) showed only marginal losses up to 1 A/cm^2. Brookhaven is utilizing X-ray absorption spectroscopy to investigate the properties of Pt/C and several of its alloys with Cr, Co, and Ni. The results indicate that alloying with Ni has a large effect on the character of Pt, whereas Cr has little effect. Nickel forms a solid solution with Pt, with the Ni atoms substituting at Pt sites.

Los Alamos is conducting basic and applied research necessary to bring PEM fuel cell technology to the performance and cost levels required for widespread use in transportation. The specific goals are to reduce the intrinsic costs, to increase the power density, to optimize the system for operation on reformed organic fuels and air, and to achieve stable, efficient long-term operation. Major areas of activity in FY 1992 are: optimizing platinum/carbon electrode structure; improving performance on low-pressure air; evaluating long-term endurance and materials stability; studies on catalysis and catalyst utilization; characterizing conductivity and water transport in polymer electrolyte membranes; and research on direct methanol oxidation.

The optimization of Pt/C electrodes for PEM fuel cells has been a focus of effort at Los Alamos since 1984. Over the past 2 years, a thin-film electrode technology that uses carbon-supported platinum in a 4- to 5-mm-thick layer applied directly to the membrane was developed. This electrode structure produces power densities greater than 1 W/cm^2 on H_2 and air, with a platinum loading of 0.12 mg/cm^2. This technology, for an 80 kW peak-power passenger car, would require less than $500 for platinum. The final goal of this task is to produce membrane/electrode assemblies, with platinum loading smaller than 0.25 g/kW, that can be manufactured at a low cost in large areas and that exhibit stable performance over 2,000 to 3,000 hours of drive-cycle operation on methanol reformate and air. In developing thin-film electrodes, significant improvements in the low-pressure air performance have been achieved. Current densities greater than 800 mA/cm^2, at a cell voltage of 0.5 V, have been achieved using ambient pressure hydrogen and air. To determine degradation mechanisms, single cells, with very low platinum loading, were tested for up to 4,000 hours. The cells continue to operate well for these long periods; however, there is a slow loss in performance. The "post mortems" of these cells indicate that the platinum catalyst particles agglomerate, slowly reducing the active catalyst surface area. Preliminary experiments indicate that starting with larger platinum particles may alleviate this problem.

In a PEM fuel cell, the water content and water distribution in the polymer membrane have a dominant effect on performance. To characterize these membranes, water sorption, water diffusion, and water drag coefficients were measured under experimental conditions that mimic the conditions in an operating fuel cell as closely as possible. Substantial data have been accumulated for Nafion 117, Membrane C, and the Dow experimental membrane at both 30° C and 80° C. These data have been incorporated into a detailed microscopic model of water transport that can predict net water transport, water profiles, and membrane resistance as a function of operating conditions.

Fuel cells which could use methanol directly would greatly simplify the vehicle propulsion system by eliminating the need for a reformer. Unfortunately, methanol tends to poison the catalysts and the performance is poor. To overcome these problems, research is being conducted on direct methanol oxidation (DMO). During FY 1992, the work focused on accurately characterizing the effects of methanol on operating PEM fuel cells. Electrodes using methanol-tolerant, Pt:Ru-alloy catalysts were fabricated using the thin-film-electrode technology developed at Los Alamos. Key parameters of the cell were evaluated during operation with a methanol/water vapor mixture at the anode and air at the cathode. These experiments showed that the rate of DMO could be significantly increased by increasing the methanol vapor pressure at a well-designed anode catalyst layer. Losses due to methanol penetration through the membrane were also quantified and possible solutions have been identified.

5.0 VEHICLE SYSTEMS R&D

5.1 Hybrid Propulsion Systems

In August 1992, DOE initiated planning for a 5-year Hybrid Propulsion System Development Program. The program will officially begin in FY 1993. The objective of the program is to support industry in developing alternative fuel hybrid propulsion systems for passenger vehicles and accelerate the commercialization of hybrid vehicles. Throughout the planning process, industry was consulted through numerous individual meetings as well as a program planning workshop that was held in Dearborn, MI, on September 22 and 23, 1992. By involving industry as well as the Environmental Protection Agency and the Department of Transportation in the planning process, the hybrid systems to be developed will be compatible with industry's marketing and production plans as well as the regulatory environment and transportation infrastructure.

A draft program plan was outlined using language from the FY 1993 appropriations bill. The approach taken calls for competing industry teams to develop and demonstrate, within 5 years, hybrid propulsion systems that are feasible for mass production. Though minimum technical performance standards will be set, wide discretion will be given as to the choice of energy storage and conversion components, as well as system configuration.

The Idaho National Engineering Laboratory performed a study to develop test procedures for evaluating the energy consumption (electricity and liquid fuel) and emissions from hybrid vehicles when they are driven on the Federal Urban and Highway cycles. The study indicated that, when testing hybrid vehicles in the hybrid operating mode, the test should be started and stopped with the battery in the same state-of-charge rather than at fixed distances (at the end of the Federal cycles) as is customary with conventional engine-powered vehicles. This procedure permits the determination of the fuel economy and emissions of the hybrid vehicle in the hybrid operating mode and the calculation of the average annual emissions of the hybrid vehicle if the all-electric range and use-pattern of the vehicle are known. Average emissions of a hybrid/electric minivan as a function of the all-electric range of the vehicle are shown in Figure 16 for 12,000 km of urban travel.

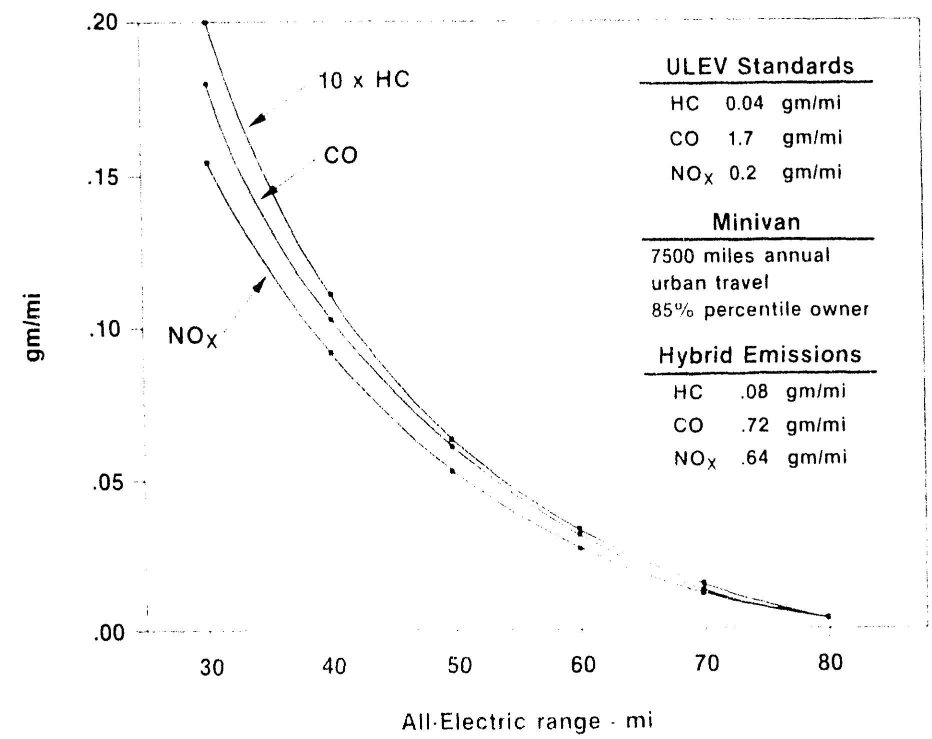

Figure 16. Annual average emissions of the hybrid minivan in urban driving.

Phase II of the Range Extender Hybrid Vehicle (REV) study that was initiated in FY 1991 was completed in FY 1992. The near-term approach utilized in Phase I (FY 1991) was based upon off-the-shelf components and existing vehicle platforms. A performance requirement of 25 mph operation under generator-only power allowed use of small (6 to 10 kW_e) generator sets. The Phase II (FY 1992) analysis evaluated higher performance REV conceptual designs. National Highway Traffic Safety Administration standards for electric vehicles as well as development requirements for the Ford ETX-II and Modular Electric Vehicle Programs were used to provide the basis for comparison. These included acceleration, speed at grade, and minimum top speed requirements. Analysis indicated that significantly larger generator sets would be required, pointing to use of more advanced engine technologies. A number of engine types and sizes were examined for application to the REV, including advanced four-stroke, two-stroke, gas turbine, rotary, Stirling, and compression ignition engines. The engines selected for analysis ranged from 24 kW_e to nearly 63 kW_e. Overall, the Phase II analysis demonstrated that higher-performance REVs could be developed, using more advanced heat engine/generator configurations. This higher performance should appeal to a broader range of potential users (compared to the Phase I design), increasing the REV's potential market penetration.

5.2 Modular Electric Vehicle Program

The objective of the Modular Electric Vehicle Program (MEVP) is to bring electric vehicle propulsion system technology closer to commercialization by developing subsystem components of a common design that are applicable to a wide range of vehicles, i.e., to modularize the components. This concept would allow early market introduction of electric vehicles because the economies of mass production could be realized across a variety of models and sizes. Modularization would reduce design and capital investment costs and/or shorten the time required to realize a return on the investment, and consequently, reduce consumer cost. The technical effort is contracted by DOE to Ford Motor Company with General Electric Company as a major subcontractor for the development of the electric subsystem. This is the third and final generation of the ac single shaft propulsion system development that began with ETX-I in the mid 1980s.

To the extent possible, components and technology developed in the First and Second Generation Single-Shaft Electric Propulsion System Programs have been employed in developing a family of components that would satisfy small passenger vehicles, compact vans, and full-size vans in both front-wheel and rear-wheel drive applications. Three targets for component designs were chosen: a 50-hp two-passenger commuter-type vehicle or micro-van, a 75-hp small van (mini-van), and a 100-hp full-size van.

Preliminary System Studies (Phase I) completed in FY 1991 concluded that a modular powertrain is a viable concept and provided a well-documented, quantitative definition of the electric vehicle subsystems that have determined the subsystem designs for the whole project. Specific objectives which were achieved include: evaluation of fundamental concepts; factoring of multi-power capability into the component designs; determination of performance specifications for each of the target vehicles; and trade-off analyses which were used in formulating the designs of the components and subsystems. Preliminary specifications for all components and subsystems were completed during this Phase.

The Phase II, Component Design, Build, Integration, and Test, is currently in progress and focuses on detailed designs of all components that make up the complete deliverable electric vehicle. Final specifications have been written and component designs for the 75-hp powertrain have been implemented in hardware and bench tested. The fully developed components have been integrated into about 10 test bed vehicles for testing as the program progresses.

The Vehicle Control Subsystem task concentrated on the debugging and fine-tuning of the control system during integration in the prototype test bed vehicle. Based on the integration efforts, major revisions to the Vehicle System Controller specification were made. Development efforts also concentrated on the Diagnostic Data Logger Module (DDLM), including hardware and software design and identification of a supplier for the module. In addition, communication between the Off-Board Diagnostic System and the DDLM was tested and successfully demonstrated.

The Electric Subsystem task concentrated on testing invertors and controls with redesigned control-printed wiring boards and transferring the design from engineering to manufacturing for pilot production. A chassis dynamometer facility at GE-Drive Systems (GEDS) was completed and is being used for evaluating MEVP propulsion systems performance tests in vehicles. The first engineering prototype test bed vehicle for the MEVP program to be tested at this test facility was shipped to GEDS during FY 1992. Initial tests which were performed evaluated the interaction between the electric drive and the vehicle's mechanical systems.

The Battery Subsystem task included discussions with sodium-sulfur battery suppliers in anticipation of delivery of prototype units for testing in the prototype test bed vehicle. A prototype ABB sodium-sulfur battery was received and was used for preliminary battery controller work and testing in this vehicle. The battery controller software for sodium-sulfur batteries was tested using this vehicle connected via an umbilical cord to the sodium-sulfur battery. The battery controller specification was updated using data accumulated through this testing and subsequent discussions between the vehicle system controller engineers and the battery controller engineers.

The Transaxle task concentrated on speed sensor and electrical connector development and lubrication and cooling issues, including build of a special rig to determine how the oil for lubrication and cooling is distributed among the gears, bearings and motor. Extensive transaxle development testing began during FY 1992.

The Test Vehicles task concentrated on integration of the electrical system and powertrain components in the prototype test bed vehicle. Ride and drive demonstrations of this vehicle were provided to several members of Ford Motor Company's Senior Management and Board of Directors.

The status of Phase II at the end of FY 1992 is as follows:

- Initial efforts concentrating on 75 hp design;
- Specifications issued for all major components and designs complete;
- Electrical/electronic system specification drafted;
- Motor/transaxle assembly designed and prototype hardware built;
- Invertor designed and prototype hardware built;
- Brassboard invertor/motor controls built;
- Vehicle system controller designed and prototype hardware built;
- 75-hp prototype hardware being tested in about 10 prototype test bed vehicles;
- Diagnostic module operational requirements specification drafted;
- European Escort Van chosen as 75-hp deliverable test bed vehicle;
- Battery controls development underway
  - DC power subsystem configured;
  - Battery control functions and algorithms in process;
  - Sodium-sulfur battery cooling system specified;
  - Specifications written for 50-, 75-, and 100-hp powertrains;
  - High voltage selected for all power levels.

Phase II efforts will continue during FY 1993, with delivery of the 75-hp test bed vehicle (see Figure 17). Component design studies will continue for the 50-hp system, as well as packaging studies for the test bed vehicle.

5.3 Site Operator Program

During FY 1992, interest in EVs and the Site Operator Program increased because of several factors, including concerns with urban air quality, the California Air Resources Board regulations requiring that a percentage of California new vehicle sales be zero emission vehicles beginning in 1998, and a continuing interest in reducing oil imports. The Site Operator Program currently includes 13 participants, representing a wide diversity of operating environments that includes weather conditions, geography, the urban, suburban, and semi-rural nature of the organization's location and program emphasis. The Program has an active presence in 10 of the 25 largest Metropolitan Statistical Areas in the country, including 5 of the 10 largest cities. The Program provides good financial leverage for DOE funds, with the Site Operators providing about $2.50 from their own and other sources, not including large "in kind" contributions, for each $1 of DOE support. Collectively, the participants represent over a million miles of EV operations and over a hundred person-years of EV operating experience. These sites and the DOE are the interface between the marketplace and auto manufacturers. Table 6 shows the participants in the Program as of the beginning of FY 1993.

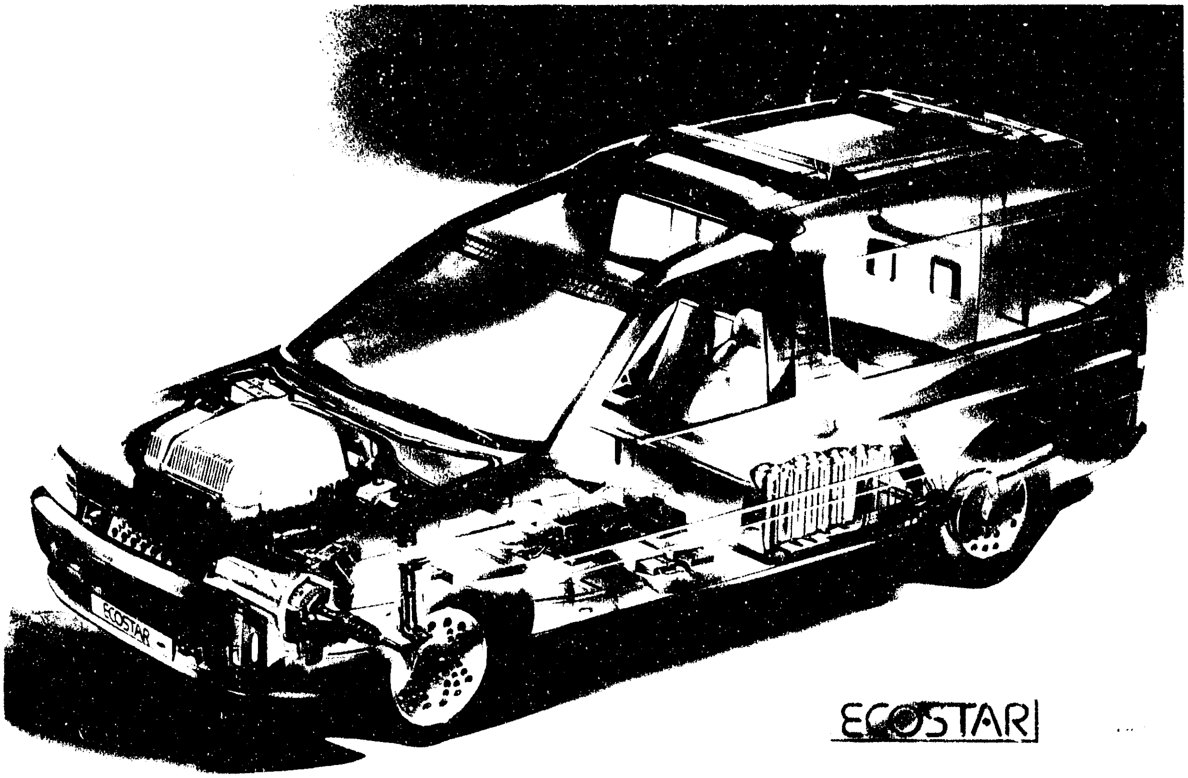

Figure 17. MEVP 75-hp test bed vehicle – Concept vehicle – Ecostar.

Table 6. Electric and Hybrid Vehicle Program Site Operators

Continuing Site Operators
Arizona Public Service Company*
Kansas State University in cooperation with KEURP
Los Angeles Department of Water & Power
Orcas Power and Light Company
Pacific Gas and Electric
Platte River Power Authority
Public Service Gas & Electric Company
Southern California Edison*
Texas A&M University in cooperation with South Central Utility Consortium
University of South Florida in cooperation with the City of Tampa and Florida Power
York Technical College* in cooperation with the City of Rock Hill and Duke Power
U.S. Navy
New Site Operators
Potomac Electric Power Company

* Participants under prior program

Idaho National Engineering Laboratory continued its role of Program Management and expanded efforts to establish and coordinate inter-organizational activities through participation in conferences, workshops, task forces, and committees. Efforts have increased the cooperation between the Site Operator Program, the Electric Power Research Institute (EPRI), the Electric Vehicle Association of the Americas (EVAA), and the American automobile manufacturers. Information on the program and the EV industry has been provided to a large number of interested individuals and organizations including the Swedish Office of Science and Technology and the Northern States Power Company. All Site Operators are seeking to improve public awareness and interest in EVs through various activities including public displays, presentations and "ride and drive" events. Audiences include the general public, organizations, companies, and government officials.

Approximately half of the vehicles in the Site Operator Fleets are G-Vans (see Figure 18). The G-Van is the first mass-produced EV in the country and the first EV to be certified as meeting the Federal Motor Vehicle Safety Standards crash test criteria. The G-Van has proven to be a reliable workhorse for the participating organizations and has provided practical EV operating experience. Early identification and resolution of problems in operating these vehicles will result in better public reception of EVs. When some of the G-Vans experienced a reduction in range per charge from 60 to less than 40 miles, adjustments were made. Most of the vehicles did experience an increase in range, but only for a short period of time. Conceptor, along with EPRI, has engaged in a full-scale investigation to identify the source of the problem. This example shows the value of field testing performed by the Site Operator Program. A summary of EV performance data collected by the Site Operators Program is given in Table 7. As shown, the EVs appear to be cheaper to operate than comparable size internal combustion engine vehicles.

Figure 18. Photograph of a G-Van used in the Site Operator Program.

Table 7. Summary of Site Operator EV Performance

Vehicle	Miles Driven	kW·h Used	kW·h/ mile	Cost/Mile	
				EV	ICE*
G-Van	104,683	121,888	1.16	$0.44	$0.55
EVcort	15,454	7,282	0.47	$0.28	$0.35
Solectria	4,655	2,197	0.47	$0.19	$0.35

* cost for comparable size Internal Combustion Engine vehicle

Participants in the Site Operator Program belong to several consortia and organizations that represent most of the major EV research in the country. These include the South Central Electric Vehicle Consortium, Carolinas Consortium for Electric Vehicle Systems, the Florida EV Consortium, Kansas Consortium, Mid-Atlantic Electric Transportation Coalition, Calstart, Tex-Start, NESCAUM, EPRI, EVAA, and the USABC. Numerous projects involve testing, demonstrations, and infrastructure development. Several Site Operators are committed to developing the technologies and organization necessary to support the anticipated large numbers of EVs to be operated by the public. The Site Operators' activities are described below.

Arizona Public Service established its Electric Vehicle Program in 1967 and has been a part of the Site Operator Program since 1979. The Arizona site has a total of 13 electric vehicles of which eight are new demonstration vehicles (three EVcorts, one Solectria, and four G-Vans). The Solectria "Force" is a converted Geo Metro powered by widely available lead acid batteries. Financial support is provided by DOE to partly finance the purchase G-vans and newer battery types, such as sealed lead-acid, improved flooded lead-acid, and zinc-air. During 1992, Arizona Public Service and Motorola announced a joint research project on zinc-air batteries in conjunction with Dreisbach Electromotive, Inc., whose zinc-air powered Honda CRX had traveled 251 miles on a single charge. As a corporate sponsor for the Solar & Electric 500 races at the Phoenix International Raceway, Arizona Public Service entered two zinc-air powered vehicles in the EV race. This site operator also loans EVcorts to local government agencies to demonstrate electric vehicle reliability and convenience. These loans have resulted in a strong and sustained interest within the agencies and several purchased EVs for their fleets.

Kansas State University funding from DOE supported the purchase of one G-van and one EVcort. DOE funding also supported the operation and maintenance of the vehicles as they were used within the Kansas State fleet, by outside organizations, and for demonstration. This site has been involved in EV demonstrations for groups including Federal and local government representatives, senior corporate executives, and students. Organizations are given the opportunity to examine the latest EV prototypes under actual operating conditions. Kansas State has purchased a G-Van built by Conceptor Industries, Toronto, Canada, procured an order to purchase two Ford EVcort station wagons built by Soleq Corporation of Chicago, Illinois, and presently owns a Renault "Mars II" EV used by the Kansas State campus police. The G-Van has logged an average of 18 m/day while maintaining a full schedule of public relation tours; this site has been contacted by companies in Nebraska and Iowa requesting information and involvement in the program. Also, Kansas State will provide design support and testing for a consortium that includes McKee Corporation, Grumman Aircraft, and others to design a state-of-the-art electric vehicle for the U.S. Postal Service.

Los Angeles Department of Water & Power participated in the DOE Site Operators Program in FY 1992 at no cost to DOE. The Electric Transportation Program established by the Los Angeles site works with local, state, and Federal agencies, along with the private sector, to further the City of Los Angeles' low emission goals. The first Clean Air Transport LA 301 vehicle, a four-passenger parallel hybrid electric/internal combustion engine (ICE) sedan has already been received, but is classified as a prototype and cannot be operated on public roads so is limited to the Los Angeles site operator facilities. The ICE drives one side of the transmission and the electric motor the other side. Initial impressions are that the vehicle is well designed and built and provides very satisfactory performance and comfort. Increased public awareness regarding electric transportation issues is continuing through media advisories and press conferences. The Los Angeles Department of Water & Power acts as the CALSTART Infrastructure Program Manager, and, under this program, a public awareness plan is being structured to advise and educate the public that early supporting EV infrastructure will be available.

Orcas Power and Light Company is a rural electric coop in northwest Washington State serving 9,000 customers on the 20 San Juan islands. DOE funding was used to purchase two EVs (one G-Van and one Solectria GEO) for mail and bank runs, errands, and engineering field work, to install charging facilities at four locations in the anticipated driving area, and for operation, maintenance, and data collection on the vehicles. In addition to testing and evaluation of the two vehicles, Orcas Power seeks to encourage EV use among San Juan County residents through public exposure. The vehicles are taken to public presentations and demonstrations and are being incorporated into the local school energy program.

Pacific Gas and Electric Company activities are concentrated in two primary areas; namely, testing and evaluating pre-commercial and limited-production commercially available EVs and advanced EV components and development and evaluation of mechanisms to safely and efficiently supply electricity for EVs while minimizing the impact on the transmission and distribution system. DOE funding during the first year of participation in the Site Operator Program was used to support establishing the program, operation and maintenance of the Pacific Gas EV fleet, and collection of data on the EVs. The Pacific Gas site has been actively involved in EV development and commercialization through national and statewide organizations and in public and private demonstrations that showcase electric G-vans, a public charging station at a local mass transit station, and an electric battery-powered transit bus on an actual transit route. Pacific Gas & Electric also continues to assess emerging electric transportation technologies such as magnetic levitation, superconducting magnetic energy storage, station or neighborhood vehicles, advanced chargers and advanced battery technologies, and flywheel energy storage.

Platte River Power Authority's evaluates the year-round performance, operational costs, reliability, and life-cycle costs of EVs in the front range region of northern Colorado. They also evaluate an EV usability and acceptability, and test EV component design improvements and/or technological improvements. With DOE support, the Platte River site is purchasing two EVcorts, which it will operate and maintain and from which it will collect performance data. Platte River Power will also operate and maintain, at no cost to DOE, a DOE-owned 1984 Griffon van for a 12-month period. Idaho National Engineering Laboratory personnel have visited this site to provide instructions on the vehicle use.

Potomac Electric Power Company's objective is to showcase and demonstrate emerging electric vehicle technology to the greater Washington, DC, community. Washington, DC, has been designated by the EPA as a serious non-attainment area for ozone and carbon monoxide. Preliminary analysis indicates that the DC area will see an improvement in air quality if significant numbers of ICE automobiles are replaced with EVs. DOE funding has been provided to support this site in operating, maintaining, and making available for DOE use in the DC area the DOE-owned G-Van.

Public Service Electric & Gas Company operates a fleet of eight G-Vans in an area extending from Philadelphia to New York City. DOE funding was used for operation, maintenance, and data collection, and G-Vans were purchased with site operator funds. During cold weather last winter, use of the vehicles was limited due to a severe reduction in range. The problem was investigated and opportunity charging was implemented to resolve some of the low-mileage range. This site operator is working with the manufacturer and EPRI to find a long-term solution and is assessing the possibility of using a nickel-cadmium battery in one G-Van pending tests underway by EPRI.

The Public Service Electric & Gas Company initially assigned six of the eight G-Vans to various operating departments throughout the State based on overall usage and need. The G-Vans are used primarily for work orders, transporting material, tools, electrical equipment, and meters. The seventh G-Van is on loan to the New Jersey Department of Environmental Protection and Energy for an independent assessment. The eighth van is dedicated to the site operator's main corporate headquarters in Newark. Pending a 1-year performance review, the site operator may expand its usage to other purposes including commuting its employees. The site operator is reviewing an on-board data collection system that will automatically collect and record energy use (kW·h), mileage, and temperature data while greatly simplifying the collection of test data from operating fleets.

Southern California Edison seeks to ensure its readiness and capability to provide the "fuel" to power electric transportation within its service territory. The Southern California site EV fleet includes 17 G-Vans, 2 Solectria Forces, a Shuttle Bus, a converted sedan, and a converted pick-up truck. The vehicles are used in company operations (e.g., mail runs and employee van pools) and to conduct research on how others might use EVs within their service territory. All the EVs in the Southern California site fleet have been purchased with corporate funds. DOE funds are used to support operation, maintenance, and data collection. This site operator is active in the research and testing of EVs and vehicle components. Most of its activities are joint efforts with local colleges and universities, the California Air Resources Board, the South Coast Air Quality Management District, and others.

Texas A&M University started and remains the headquarters of the South Central Electric Vehicle Consortium whose membership includes seven utilities, a university, Conceptor Industries, and EVAA. The consortium was formed to facilitate the commercialization of EVs through education and demonstration in Texas and adjoining states. The Texas A&M site provides data on 13 G-Vans and 2 older Jet Industries vehicles to the Site Operator database. These vehicles are located and operated at six locations ranging from Amarillo to Houston. DOE funding supported the purchase, operation, and maintenance of 3 G-Vans and the data collection on the 13 G-Van fleet operated by the Consortium.

University of South Florida, in collaboration with Tampa Electric Company and other organizations, is determining the efficiency of EVs under commuter and fleet conditions within the metropolitan area of Tampa, St. Petersburg, and Clearwater. DOE funding supported the purchase of three EVs as well as their operation and maintenance. DOE also supported data collection on these three EVs, one sedan operated by the City of Tampa, and two vans operated by Florida Power Company. Another feature of the program is the development of a utility interconnected photovoltaic system for charging EVs (see Figure 19). This system consists of a 12-bay parking facility equipped with roof-mounted photo-

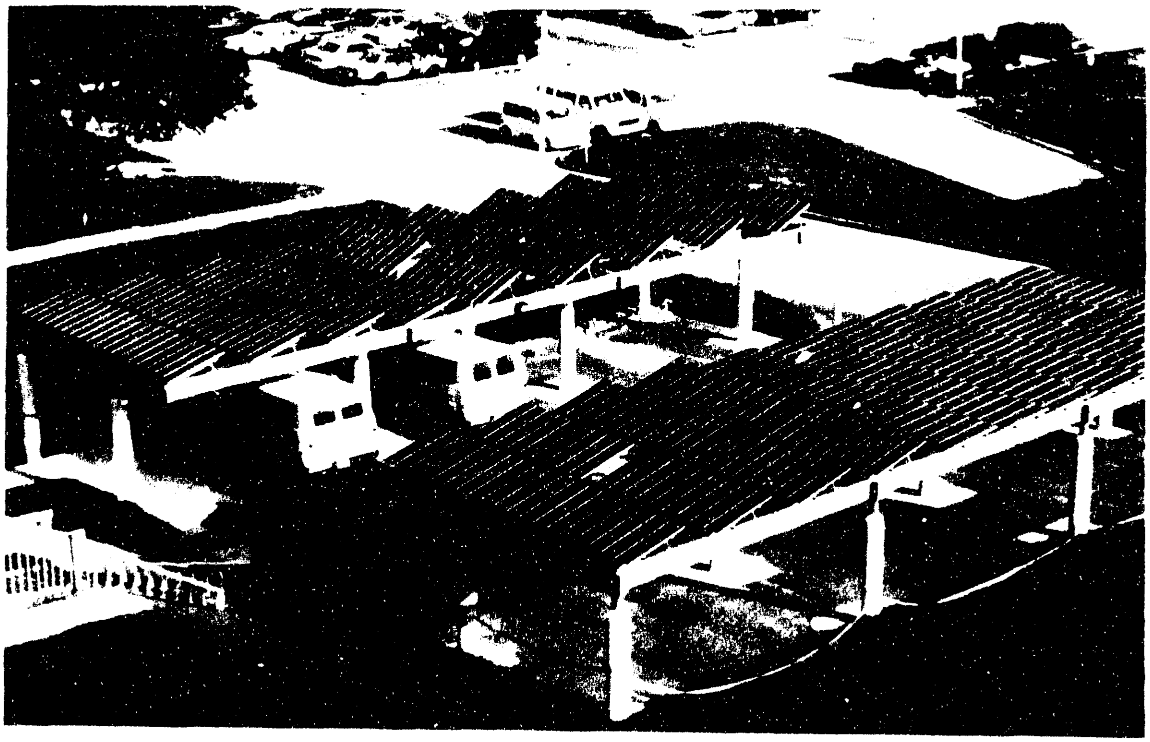

Figure 19. University of South Florida interconnected photovoltaic charging system.

voltaic panels. These panels will provide charging power and, through connection to the power grid, will allow energy generated during the day to be routed to the power company and "stored" while the vehicles are absent. At night when the vehicles return, the energy "stored" in the grid can be recovered for charging. This system design will provide a 20-kW peak.

The **U.S. Navy** has one of the largest fleets of electric vehicles which are in daily use and can be found on bases from Alaska to Bermuda. The Navy is the advisor to the Department of Defense on EV applications and is a major force in conversion from older EV technology to current technology. The Navy participated in the Site Operators Program in FY 1992 at no cost to DOE. The Navy EV database has provided significant information on EV use.

York Technical College can be described as a bridge from "pure research and development to applied technology." Much of York's practical know-how is coming through its fleet of 18 electric vehicles. These vehicles are being operated in several locations, including two that are operated by Duke Power Company out of its Second Street Garage in Charlotte, NC. DOE funding was used to support the purchase of newer EVs and operation, maintenance, and data collection of the entire fleet. York has converted one nickel-iron battery-powered pickup truck to a lead-acid battery pack. They have also installed in this vehicle a battery charger powered at a 110-V conventional household outlet. The same type battery charger has been installed in a Volkswagen pickup truck which utilizes nickel-iron battery technology. York received the early test vehicle (ETV-1) from the Idaho National Engineering Laboratory. This vehicle is on display at the Science Nature Museum, Discovery Place, in Charlotte, NC. (see Figure 20). The display was viewed by over 10,000 people during the first month.

The development of a curriculum outline for EV maintenance training at York continues. From this curriculum, technicians of the future will learn how to service batteries, traction motors, chargers, controllers, converters, and other items not now familiar to most automobile mechanics and drivers. The course promises to be the first of its kind in the world, and already the list for enrollment is growing.

5.4 Engineering Evaluation Testing

Dynamometer and laboratory tests on electric vehicle systems and components are conducted to evaluate their performance under repeatable and well-defined operating conditions that duplicate or simu-

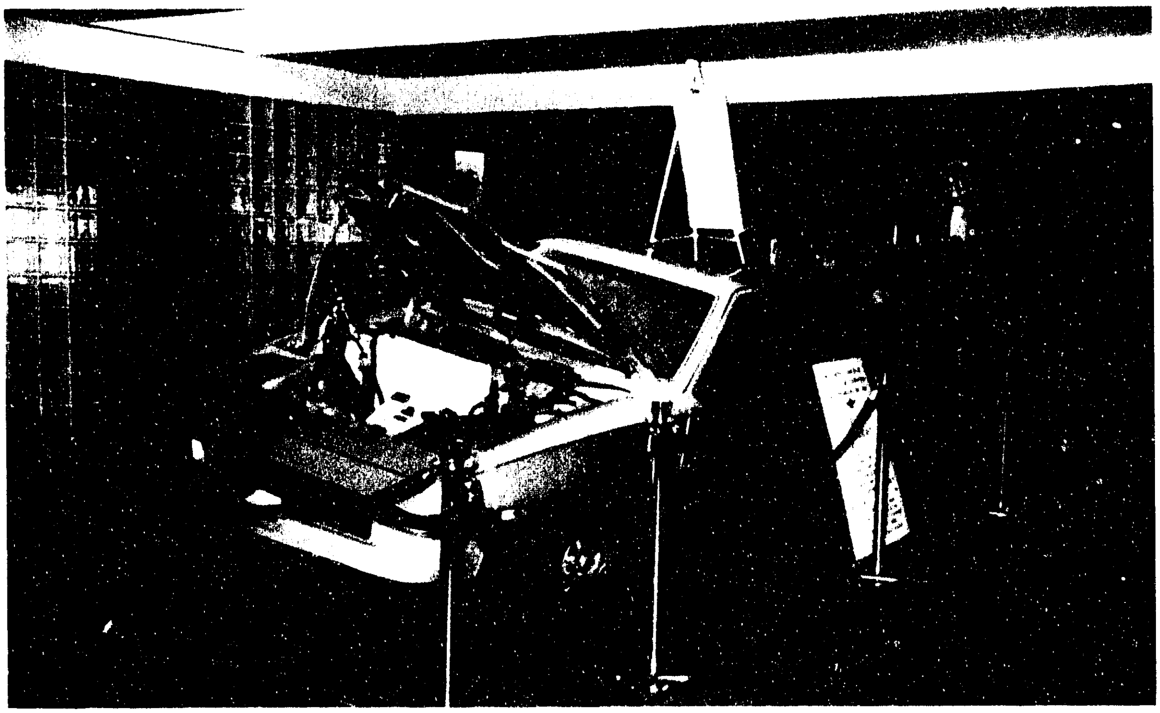

Figure 20. ETV-1 vehicle on display at the Science Nature Museum in Charlotte, NC.

late actual EV operation and environments. Test and evaluation programs are in process that (1) subject batteries to the actual electrical loads of high technology EVs in test bed vehicles on a dynamometer; (2) integrate advanced EV drive systems in vehicles, and test them on the track, road, and dynamometer; (3) test and characterize auxiliary systems, such as battery chargers, state-of-charge indicators, and battery monitoring and thermal management systems in a realistic EV environment; and (4) 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°C to +80°C.

Since FY 1984, the Idaho National Engineering Laboratory has performed testing activities at their dynamometer and battery test laboratories which were established for this purpose. Typical standard driving profiles on which vehicles are routinely tested are the Society of Automotive Engineers (SAE) EV driving cycles (SAE J227a) and the SFUDS. Special tests have been performed in the laboratory and on the test track to provide direct comparisons of AC and DC powertrains, measure regenerative braking performance, evaluate air-conditioning concepts, evaluate interior noise levels, and measure electromagnetic emissions.

In FY 1991, Idaho installed a new-generation dynamometer system controller and enhanced the data acquisition processing and display capabilities of the dynamometer laboratory with the installation of an integrated laboratory data acquisition system. It acquires and logs data, monitors for alarms, and displays "real time" and/or historical data via high-resolution graphic displays. The operating system provides a real-time, multi-user, multi-tasking, and networkable operating environment.

In FY 1992, Idaho tested the Ford/GE Second Generation Single-Shaft Electric Propulsion (ETX-II) System test bed vehicle and the CSPL sodium-sulfur battery. The vehicle test program included a series of constant speed tests, energy economy tests, SAE J227a/C, and FUDS cycles performed on a chassis dynamometer (see Figure 21). The dynamometer tests demonstrated that the ETX-II vehicle operated well with the CSPL sodium-sulfur battery, yielding a range of >180 km (110 mi) at 88 km/h (55 mph). The sodium-sulfur battery easily provided sufficient power to utilize the maximum power (52.5 kW) capability of the ETX-II interior permanent magnet motor. The test results provided in Table 8 indicate that all the performance goals for the program have been achieved.

Table 8. ETX-II Performance Versus Program Goals

	GOAL	RESULTS
Acceleration (sec) [0 to 80 km/h]	<20	17.35
Gradeability limit (%)	30	30
Top speed (km/h)	96	105
Payload (kg)	545	590
Energy consumption (kW·h/km) [on FUDS]	0.250	0.212
Range on FUDS (km)	>160	>160

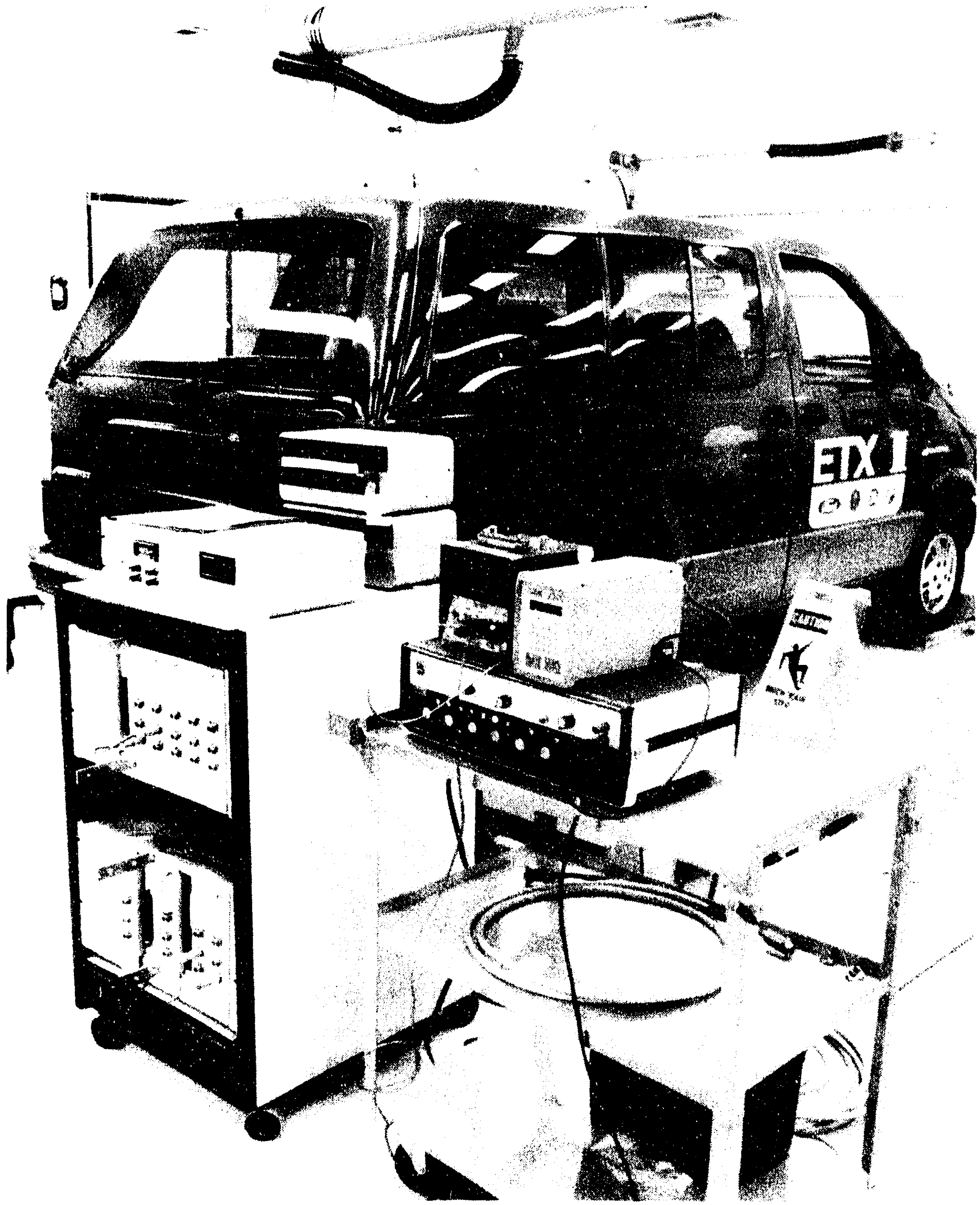

Figure 21. ETX-II test bed vehicle on chassis dynamometer at Idaho National Engineering Laboratory.

6.0 STUDIES AND ASSESSMENTS

6.1 Battery Test Task Force

The Electric and Hybrid Program (EHP) Battery Test Working Task Force (BTWTF) was formed in 1983 to coordinate the battery evaluation work at the DOE- and EPRI-funded laboratories. During FY 1992, the mission of the Task Force was expanded to include coordination of testing activities with the USABC. Present members of the Task Force include the following National Laboratories:

- Idaho National Engineering Laboratory
- Sandia National Laboratory
- Argonne National Laboratory
- Los Alamos National Laboratory

and the USABC.

The major accomplishment of the BTWTF in FY 1992 was the development of a generic test plan for battery testing. From this plan, a set of generic tests were written to assure that the results obtained from the battery tests at one laboratory would be generally comparable to data from the other member laboratories.

6.2 Database Development

In FY 1992, Idaho continued to develop and maintain an electric and hybrid vehicles technology database consisting of electric vehicle simulation programs, battery test and evaluation data, site operators data, and an electric vehicles technical library.

Idaho has implemented a computer software configuration management (SCM) database system in order to manage the software for which Idaho is cognizant. The purpose of this system is to provide a means of providing network access to these software packages by the electric and hybrid vehicle community. Electric and hybrid vehicle simulation codes in the database system include:

- ELVEC, a general purpose electric and hybrid vehicle computer simulation program.
- HEAVY, the Hybrid and Electric Advanced Vehicle Systems computer simulation program.
- SIMPLEV, Simple Electric Vehicle computer simulation program.

The Idaho database programs and electric vehicle data acquisition programs are also managed utilizing the SCM system database.

Idaho completed the development of Version 1.0 of the Personal Computer (PC) -based electric vehicle simulation program, SIMPLEV. During FY 1992, SIMPLEV Version 1.0 was licensed to 6 industrial companies and 14 colleges and universities participating in the Ford/DOE Hybrid Challenge and was distributed for use by 6 other Government institutions including the Environmental Protection Agency, Argonne National Laboratory, and Sandia National Laboratory.

SIMPLEV was enhanced to include the capability of simulating series hybrid vehicles, giving estimations of fuel consumption, and regulated emissions. Additional enhancements include simulation of the effects of anti-lock braking, various keyboard controls of the simulation while running, as well as many enhancements which will make the simulation easier to use. These enhancements were completed in FY 1992 and will be available for release as Version 2.0 in early FY 1993.

Idaho continued the development of a PC-based database for storing battery physical characteristics, manufacturer information, and charge/discharge test data for the various batteries that have been tested for EV applications at DOE laboratories. The Electric Vehicle Battery Test Database, Version 1.0, was released to DOE for review and comment in April 1991. This version of the database was designed to run on a stand alone PC and contained complete test data summary tables, but did not include any detailed test data because the data files were too large to be included on floppy disks. Early in FY 1992, Version 1.1 of the Idaho Electric Vehicle Battery Test Database was implemented on the Idaho Energy Programs NOVELL computer network for use by the Idaho EHV Program. It included 1,323 test data summaries and 297 detailed test data files. Over 1,323 files of detailed test data remain to be loaded but await completion of a large-capacity optical disk installation. Neither telephone nor off-site network access was provided for in this version.

In January 1992, Version 2.0 of the Idaho Electric Vehicle Battery Test Database was completed and included network specific programming. Telephone access to the database was also implemented. Upon completion of the testing, parties outside the Idaho were able to access the database via a personal computer equipped with a telephone modem. The Idaho Battery Test Data Database, Version 2.0, and telephone access to it were demonstrated March 5, 1992, at the EPRI Battery Testing Project Review Meeting at Electrotek in Chattanooga, Tennessee.

The Site Operator Database is a continuing record of the Site Operator program and contains information on the operators, vehicles, and vehicle operation and maintenance records. This information is available as background-expanded activities in electric vehicle technology and applications. The first database was compiled starting in 1988. Cognizance of the database was given to the Idaho during the summer of 1991. As a result of review and use of the database by the site operators, recommended modifications of the Site Operator Database programs are in progress at the close of FY 1992.

Maintenance and updating of the EHV Library by the Idaho continued through FY 1992. Presently, the library contains 2,900 entries of technical electric and hybrid vehicle literature, ranging from technical reports from a multitude of public and private sources, to meeting papers from various technical societies. During FY 1992, over 400 volumes were added to the library. In order to provide easy retrieval of information, a program was developed and furnished to the DOE which searches the library database for publications based upon keywords provided by the user.

6.3 Environment, Health, and Safety Studies

Environmental Impact

The National Renewable Energy Laboratory is conducting environmental, health, and safety (EH&S) assessments of advanced batteries for electric vehicles. In FY 1992, National Renewable Energy published the following reports on EH&S issues relevant to cell and battery design, shipping, in-vehicle use, and recycling and reclamation of sodium-sulfur (Na/S) batteries.

Volume I, *Cell and Battery Safety*, covers cell design and engineering as the basis of safety for Na/S batteries and describes and assesses the potential chemical, electrical, and thermal hazards and risks of Na/S cells and batteries. Research and development performed in the past, currently underway, or needed in the future to address these hazards and risks are also reviewed.

Volume II, *Battery Recycling and Disposal*, gives an overview of the Resource Conservation and Recovery Act (RCRA), discusses RCRA regulations governing Na/S battery recycle/reclamation, and contains a preliminary regulatory analysis for Na/S recycling and reclamation.

Volume III, *Transport of Sodium-Sulfur and Sodium-Metal Chloride Batteries*, discusses issues associated with the transport of Na/S and sodium-metal chloride cells and batteries. In Volume III, batteries employing either technology are generically described as sodium-beta (Na-beta) batteries, and, for purposes of transport, no distinction is drawn between them. Volume III examines the regulations that govern the shipment of dangerous materials. Elemental sodium contained in Na/beta batteries is classified as a dangerous material and is listed on both the national and international hazardous materials listings. Both national and international regulatory processes are considered in the report, and the interrelationships as well as the differences between the two processes are highlighted.

Volume IV, *In-Vehicle Safety*, covers the in-vehicle safety issues of electric vehicles powered by Na/S batteries. The report is based on a review of the literature and on discussions with experts at DOE, National Laboratories and agencies, and private industry. It has three major goals: (1) to identify the unique hazards associated with EV use; (2) to describe the existing standards, regulations, and guidelines that are or could be applicable to these hazards; and (3) to discuss the adequacy of the existing requirements in addressing the safety concerns of EVs.

Work began in FY 1992 on a similar assessment of nickel/metal hydride batteries. Although the same EH&S issues will be addressed, (i.e., cell and battery design, shipping, in-vehicle use, and recycling and reclamation) the format will be slightly different. Because much of the information on the regulatory issues pertaining to shipping and in-vehicle safety is not battery dependent, the assessment of nickel/metal hydride batteries will focus on unique cell and battery characteristics and will include a brief discussion on shipping, in-vehicle safety, and recycling issues particular to nickel/metal hydride batteries.

To provide current information on regulatory issues, the National Renewable Energy Laboratory intends to publish an annual report on regulatory developments pertaining to EV batteries, such as proposed modifications to the Federal Motor Vehicle Safety Standards (FMVSS) affecting EVs.

EV Battery Readiness Working Group

The Ad Hoc EV Battery Readiness Working Group was formed by DOE/EHP in May 1990 as part of a government-industry effort to identify regulatory issues associated with the safe shipment, in-vehicle use, and recycling-reclamation of advanced batteries. The original mission of the Working Group was to assist in the development of Federal regulations to address EH&S issues in these three areas. In FY 1992, the Working Group objectives were updated to include developing action plans to remove regulatory barriers, identify requirements for the commercialization of EVs, and to act as an advisory body for EH&S programs relating to hybrid and electric vehicles. The Working Group consists primarily of representatives from battery developers, automobile manufacturers, Federal agencies, and National Laboratories.

The sub-working groups originally assembled in May 1990 to address the most important regulatory issues on shipping, in-vehicle safety, and recycling-reclamation have been maintained for subsequent meetings. The Shipping Sub-working Group provides organizational and technical support as needed to facilitate collection of needed information for regulatory applications, facilitates the preparation and submission of regulatory applications for general exemptions and for international and DOT regulations, establishes the scope of ruling(s) sought, and oversees the development of a database at the National Renewable Energy Laboratory to track the shipment of sodium/beta batteries. The In-vehicle Safety Sub-working Group works with industry to analyze hazards associated with batteries in EV propulsion and reviews and comments on FMVSS-proposed rules. The Recycling/Reclamation Sub-working Group works with battery developers, industry representatives, and the EPA to share information pertaining to reclamation/recycle processes for advanced EV batteries and to work on the development of regulations that will facilitate the recycle/reclamation of these batteries.

In FY 1992, two meetings of the Working Group were held in Washington, D.C. During the first meeting, held on January 14-15, 1992, the Shipping Sub-working Group formulated a time schedule and a preliminary assessment of content for a proposed submittal to the United Nations to obtain an entry for international shipment. It also determined the data items to be included in a Na/beta shipping database. The In-Vehicle Safety Sub-working Group reviewed the National Highway Traffic Safety Administration (NHTSA) Advance Notice for Proposed Rulemaking (ANPR) on EVs and formulated a collective response by the group to NHTSA. It also proposed that a risk assessment, which would define safety testing needs and requirements for Na/beta batteries, be conducted. The Reclamation/Recycle Sub-working Group discussed regulations needed to facilitate the collection and storage of EV batteries prior to reclamation/recycle. With respect to legislation, the Sub-working Group agreed that it would take an active role in reviewing proposed rulemaking on consumer batteries that might apply to EV batteries, as well as in the RCRA reauthorization process.

At the second Working Group meeting held on September 24-25, 1992, the Shipping Sub-working Group decided on the content of a general exemption for the domestic shipment of "hot" and "cold" Na/beta batteries and on the time schedule for submittal to DOT. It also discussed recent developments in an application for revision to an existing exemption. The In-Vehicle Safety Sub-working Group determined that it would submit a coordinated response on NHTSA Notice of Proposed Rules on EVs as a follow-up to its response to the ANPR. It also decided to work on defining areas in which standards should be developed for EVs and to initiate contact with the Society of Automotive Engineers' Standards Forum concerning potential EV standards. The Recycling Sub-working Group agreed that it would obtain more information about the proposed EPA rule exempting the collection phase of battery recycling from RCRA regulatory requirements. The Sub-working Group will assemble comments and submit a coordinated reply. It will also review information about RCRA reauthorization legislation.

The accomplishments of the Working Group in FY 1992 include obtaining a United Nations entry for the international shipment of sodium/beta batteries, developing and submitting applicable international and domestic regulations pertaining to the shipment of sodium/beta batteries, reviewing several recycling/reclamation processes for sodium/beta batteries, providing comments to the NHTSA on the ANPR for EVs, and maintaining a national forum for government-industry cooperation on regulatory issues affecting advanced batteries and EVs.

Environmental and Economic Studies on Fuel Cell Vehicles (FCVs)

An environmental assessment to identify critical environmental, safety and health issues involved in the use of fuel cells for transportation applications was continued by the National Renewable Energy Laboratory in FY 1992. In addition, two other small studies were completed: an independent comparative assessment of the environmental impacts of fuel cell vs. internal combustion engine vehicles was developed; and a life-cycle cost analysis was performed to provide quantitative economic comparisons between conventional vehicles and fuel-cell-powered vehicles. Comparisons were developed for cars, vans, and buses using phosphoric acid or proton-exchange-membrane fuel cells where applicable.

The environmental benefits of using FCVs in place of conventional vehicles were estimated in terms of "avoided emissions"—regulated pollutants affecting local air quality and carbon dioxide affecting global climate change that would have been emitted by the conventional vehicles displaced by FCVs. The estimated cumulative benefits for the period 1990 to 2030 resulting from avoided emissions due to FCVs comprising 24 percent of the total light-duty vehicle miles travelled were about $5 billion for FCVs using methanol reformed on-board and about $5.8 billion for FCVs using on-board hydrogen. These avoided emissions were calculated using a total fuel-cycle approach that tries to capture the emissions from fuel production as well as those from use of the fuel in vehicles.

The successful commercialization of FCVs will have significant economic and energy security benefits in the years after 2000, as FCVs begin to displace conventional vehicles that consume petroleum-derived fuels. In FY 1992, as part of the national program to develop FCVs, the National Renewable Energy Laboratory estimated the energy, economic, and environmental benefits resulting from the use of FCVs as future light-duty passenger vehicles. These estimates are based on analyses supporting the National Energy Strategy. Estimates of energy, economic, and environmental benefits are based on assumptions about the number of FCVs in the total vehicle fleet, which in turn depend on assumptions about the performance and economic competitiveness of both FCVs and conventional and alternative vehicle systems that will be available at the same time. The estimates of benefits assume that FCVs will constitute 24 percent of the light-duty vehicle miles travelled by the year 2030.

The cumulative energy, economic, and environmental benefits of FCVs were calculated for the period 1990 to 2030 under two scenarios: one for FCVs fueled by methanol and the other for FCVs powered directly by hydrogen. Energy benefits calculated for both scenarios showed a net savings of 2 million to 4 million barrels of oil per day by 2030 after energy required to produce fuel for these FCVs was subtracted. Methanol for the methanol-fueled FCV was assumed to be produced from a mixture of domestic and foreign natural gas. For the hydrogen-powered FCV scenario, hydrogen was assumed to be produced only from domestic natural gas. Total economic benefits were approximately $38.5 billion (in 1990 dollars with a 4.6 percent discount rate).

The National Renewable Energy Laboratory intends to conduct additional analyses to provide information on system benefits and costs related to future FCVs. Both absolute and incremental benefits and costs need to be determined for a range of technologies, fuels, and infrastructure alternatives. Additionally, benefits and costs of FCVs will be analyzed and compared with other promising alternative systems in order to assess the cost-effectiveness of FCVs.

7.0 INCENTIVES

The major incentives-related activities of the Electric and Hybrid Vehicles Program include the Corporate Average Fuel Economy (CAFE) and Loan Guarantee activities. In addition to these activities, the recently enacted Energy Policy Act of 1992 (EPAct) offers new incentives for electric and alternative fuel vehicle commercialization and development.

CAFE Regulations

Section 13(c)(1), 15 U.S.C. §2512(c)(1), of Public Law 94-413 directed the Secretary of Energy "to conduct a seven-year evaluation program of the inclusion of electric vehicles. . . in the calculation of average fuel economy . . . to determine the value and implications of such inclusion as an incentive for the early initiation of industrial engineering development and initial commercialization of electric vehicles in the United States."

This 7-year evaluation program was conducted by DOE, and a final assessment report on this activity was completed in February 1987. DOE's final recommendation was that the EV CAFE provision be continued, to the extent that the CAFE regulation remains intact, in the average fuel economy calculations under the Motor Vehicle Information and Cost Savings Act.

DOE has initiated action to revise 10 CFR 474 (Equivalent Petroleum-Based Fuel Economy Calculation) dated April 21, 1981, to provide a means of calculating the CAFE- equivalent fuel economy for electric vehicles, including those equipped with range extender devices. The action was temporarily postponed to review the existing conversion method against those for natural gas and alcohol fuels provided in the Alternative Motor Fuels Act of 1988. A new method for calculating the electric-vehicle, CAFE-equivalent fuel economy will be ready for proposed rulemaking in the spring of 1993.

Energy Policy Act of 1992 (EPAct)

The Energy Policy Act of 1992 (P.L. 102-486), enacted on October 24, 1992, includes both tax incentives and research, development and demonstration authorizations for electric vehicles. Section 1913 of EPAct provides a 10 percent tax credit (up to $4,000) for electric vehicles. Title VI of EPAct authorizes up to $50 million for electric and electric hybrid vehicle demonstrations between 1993 and 2002, as well as $40 million for electric vehicle infrastructure development between 1993 and 1997. Section 2025 of EPAct authorizes up to $485 million for electric vehicle and equipment research and development between 1993 and 1998.

Planning Grants

There was no activity in this incentive program during FY 1992.

Loan Guarantees

DOE authority for making principal and interest assistance contracts under the Electric and Hybrid Vehicle Loan Guaranty Program expired on September 17, 1983, as provided for by the notice of final rulemaking published in the *Federal Register* on May 31, 1979 (44 FR 31510).

8.0 USE OF FOREIGN COMPONENTS

Section 14(2) of Public Law 94-413, 15 U.S.C. §2513(2), requires the Department to examine "the extent to which imported automobile chassis or components are being used, or are desirable, for the production of vehicles [under Section 7]. . . , 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. Activities following the development progress of foreign-made batteries, drivetrain components, and vehicle systems are continuing.

9.0 RECOMMENDATIONS FOR INITIATIVES

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

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ACRYNOYMS

BTWTF	Battery Test Working Task Force
CAFE	Corporate Average Fuel Economy
CRADA	Cooperative Research and Development Agreement
CSPL	Chloride Silent Power Limited
DEMI	Dreisbach Electromotive, Incorporated
DOD	Depth-of-Discharge
DOE	Department of Energy
EHP	Electric and Hybrid Program
EH&S	Environment, Health, and Safety
EHV	Electric and Hybrid Vehicle
EPRI	Electric Power Research Institute
ERIM	Environmental Research Institute of Michigan
EV	Electric Vehicle
EVAA	Electric Vehicle Association of the Americas
FMVSS	Federal Motor Vehicle Safety Standards
FUDS	Federal Urban Driving Schedule
GM	General Motors Corporation
ICE	Internal Combustion Engine
IIT	Illinois Institute of Technology
MEVP	Modular Electric Vehicle Program
NHTSA	National Highway Traffic Safety Administration
OEM	Original Equipment Manufacturer
PAFC	Phosphoric Acid Fuel Cell
PEM	Proton Exchange Membrane
RCRA	Resource Conservation and Recovery Act
SAE	Society of Automotive Engineers
SFUDS	Simplified Federal Urban Driving Schedule
USABC	United States Advanced Battery Consortium

UNITS

A	ampere
A·h	ampere-hour
cm	centimeter
cm^2	square-centimeter
cm^3	cubic-centimeter
F	farad
ft	foot
g	gram
g/kW	gram per kilowatt
h	hour
hp	horsepower
kg	kilogram
km	kilometer
km/h	kilometer per hour
kW	kilowatt
kW_e	kilowatt-electric
kW·h	kilowatt-hour
l	liter
mA	milliampere
mA/cm^2	milliamp per square-centimeter
mg	milligram
mg/cm^2	milligram per square-centimeter
mi	mile
mm	millimeter
MPa	megaPascal
mph	miles per hour
mV	millivolt
sec	second
V	volt
W	watt
W·h	watt-hour
W·h/kg	watt-hour per kilogram
W·h/l	watt-hour per liter
W/cm^2	watt per square-centimeter
W/kg	watt per kilogram
W/kW·h	watt per kilowatt-hour
W/l	watt per liter

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11/29/93