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Electric and Hybrid Vehicles Program

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PREFACE

This fifteenth annual report on the implementation 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 seg., referred to herein as the Act, complies with the reporting requirements established in Section 14 of the Act. In addition to informing Congress of the progress and plans of the Department of Energy's Electric and Hybrid Vehicles Program, 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. The Electric and Hybrid Vehicle Program is being expanded as recommended in the National Energy Strategy.

During FY 1991, significant progress was made toward fulfilling the intent of Congress in passing the Act. In September, the Department signed an agreement with the United States Advanced Battery Consortium partners for a 50/50 cost-shared program that will support advanced battery developers and companies in the research and development of advanced batteries for electric vehicles. The Consortium is a partnership formed in January 1991 by the three major domestic automobile manufacturers and was later joined by the electric utility industry as represented by the Electric Power Research Institute. For the first time, the Federal government and a major U.S. industry are working cooperatively in a research and development program that will accelerate commercial applications of advanced battery technologies and, more specifically, the commercialization of electric vehicles.

Research and development efforts continue to show steady progress in achieving the technologies for batteries, fuel cells, and propulsion components. 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.

TABLE OF CONTENTS

1.0 INTRODUCTION

The Department of Energy's (DOE) Electric and Hybrid Vehicles (EHV) Program is conducting research, development, testing, and evaluation activities to encourage the use of electricity and alternative fuels for transportation. This program supports the expanded DOE involvement as recommended in the National Energy Strategy.

The transportation sector is the single largest user of petroleum; it consumed 63 percent of all petroleum used in the United States last year. Only a small fraction (5 percent) of electricity is generated from petroleum. Electric vehicles, which are themselves virtually pollution-free, could play a key role in helping to reduce both urban pollution and our dependence on petroleum imports. The program's goals are to develop, in cooperation with industry, the technology that will lead to the production and introduction of pollution-free electric 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, was intended 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 $25.1 million for the EHV Program in FY 1991.

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 major participants in the Electric and Hybrid Vehicles Program, 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 1991, the Big Three U.S. auto manufacturers, General Motors, Ford, and Chrysler, formed the United States Advanced Battery Consortium (USABC) for the research and development of advanced battery technologies for use in electric vehicles. In September, DOE and the Consortium formalized a Cooperative Agreement on a 50/50 cost-shared advanced battery research and development program.

The Electric and Hybrid Vehicles Program in FY 1991 continued to emphasize battery, fuel cell, and propulsion systems development up to the level of testing and evaluating proof-of-concept vehicles in the laboratory and in fleet operations. The battery program was reoriented in FY 1991 to concentrate on those technologies that could satisfy the mid- and long-term goals of the automobile manufacturers as determined by the USABC. Near-term projects that were not consistent with the USABC goals were discontinued.

This report describes progress achieved in developing electric and hybrid vehicle technologies, beginning with highlights of recent accomplishments in FY 1991. Detailed descriptions are provided of program activities during FY 1991 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. In accordance with the reporting requirements of the Act, this Annual Report contains a status report on incentives and use of foreign components and concludes with 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.	25%
Chloride Silent Power	19%
Saft America, Inc.	20%
Universities	
Georgetown University	14%
Fleet Testing Site Operators 1/	
GTE Service Co.**	50%
Arizona Public Service (APS)	50%
United States Navy**	80%
Southern California Edison (SCE)	65%
Los Angeles Dept. of Power & Water**	54%
Kansas State University	49%
Orcas Power & Light	59%
Platte River	58%
Pacific Gas & Electric	33%
Public Service Gas & Electric	62%
So. California Edison	65%
Texas A&M	86%
University of South Florida	39%
York Technical College	30%

1/ The variance in the cost-share percentage by site operators is due to the different activities and contractual arrangements with the site operators. The United States Navy is using its own operation and maintenance funds to operate the electric vehicles transferred at no cost by the Department of Energy from completed site operator contracts. Therefore, the cost share from the Navy is relatively high (80%).

* All contracted efforts are with fee waiver.

** Operations completed in FY 1991.

*** Cooperative Agreement between DOE and USABC was formalized in September 1991. It calls for 50/50 cost-sharing of R&D.

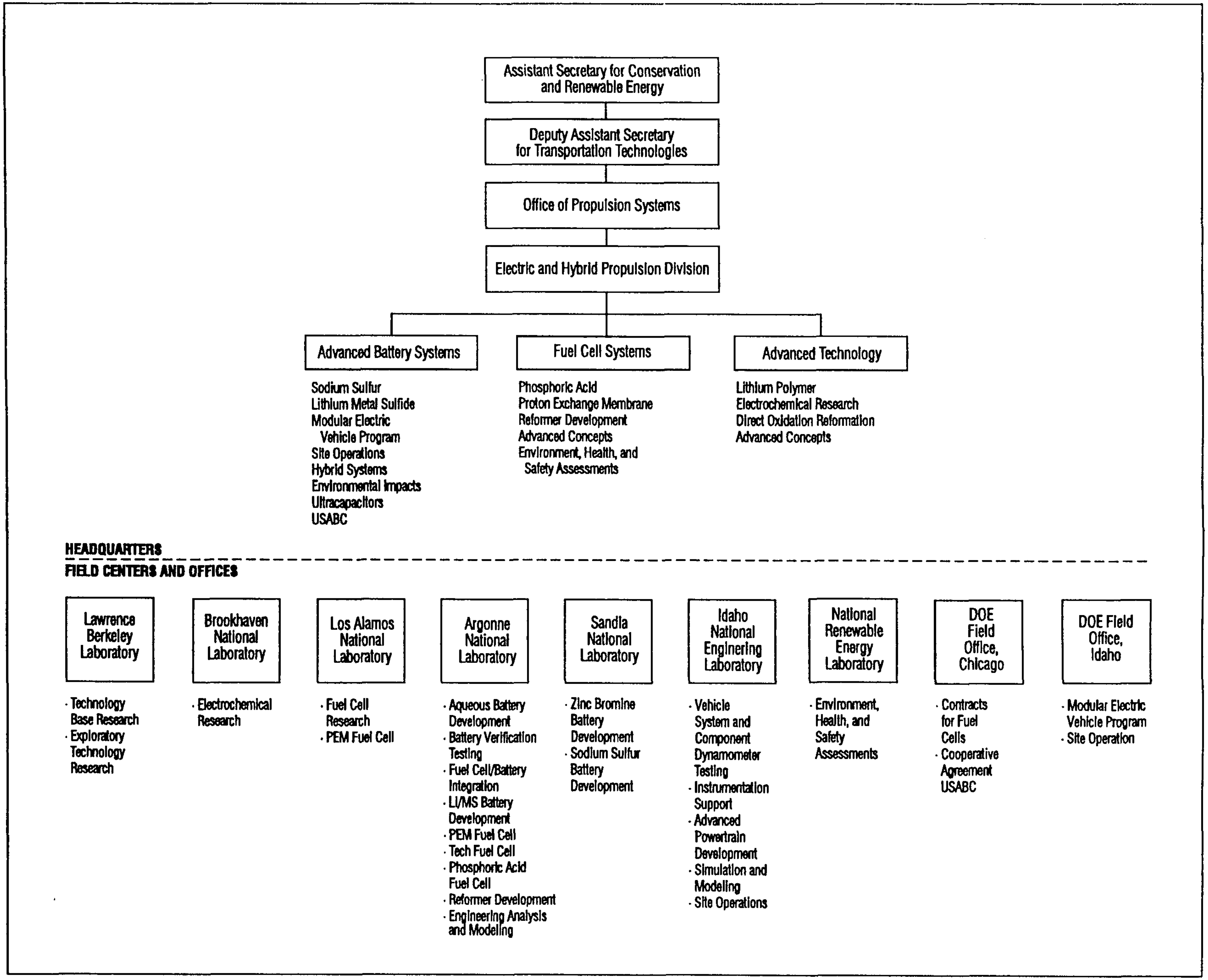


Figure 1: EHP Program Structure

2.0 FY 1991 ACCOMPLISHMENTS

Significant progress occurred in each of the Electric and Hybrid Propulsion (EHP) Systems Program areas during FY 1991. The following are highlights of those achievements.

- A Cooperative Agreement was signed between DOE and the USABC partners for a 50/50 cost-shared research and development (R&D) program. The Consortium was formed in January 1991 as a partnership of the domestic automobile manufacturers and was later joined by the electric utility industry. 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 Cooperative Agreement will allow the USABC to draw on the experience and facilities of DOE and the national laboratories. DOE will be substantially involved in the direction of USABC development programs. The USABC has collected information on the status and potential of the various battery technologies under consideration and will select battery candidates for development in early FY 1992.

- Beta Power has completed a conceptual design of an advanced sodium/sulfur cell for electric vehicle applica tions. The important design factors included the physical and electrical requirements of four van batteries, service life, manufacturability, thermal management, and safety. The capacity of this cell is approximately the same as that of the CSPL-PB cell (10 Ah). To reduce cost, the cell uses substantially fewer components than found in the baseline PB cell. In its optimum configuration, the new cell offers a 50% improvement in energy capacity and nearly a 100% improvement in peak power over the existing PB cells. A battery constructed with such cells would significantly exceed the battery consortium's mid-term performance specifications.

- The DOE Idaho Operations Office conducted a procurement for new participants in the site operators' program. From approximately 21 applicants (including 3 universities and 10 electric utilities and utility consortia), 10 were selected. Contracts have now been signed with all parties.

- The National Renewable Energy Laboratory (NREL) continued to lead the EV Battery Readiness Working Groups. These government/industry groups meet periodically to identify and resolve issues concerning trans port, in-use safety, and disposal of advanced batteries. The current focus is on the sodium/sulfur battery. NREL also initiated an environmental assessment of fuel cell technologies to identify critical environmental, safety, and health issues involved in the use of fuel cells for transportation applications.

- Testing at the Idaho National Engineering Laboratory (INEL) demonstrated the capabilities of advanced ultracapacitor devices operating for over 100,000 cycles at power levels of 250 watts/kg with an average power of 150 watts/kg. These devices are being evaluated to determine their suitability for meeting the high peak-power demands placed on standard traction batteries.

- DOE initiated Phase II of the Fuel Cell/Battery Powered Bus System Project to build fuel-cell-powered, test-bed buses. A 30-month cost-shared contract was awarded in August 1991 to H-Power Corporation of Bloomfield, NJ, through a competitive procurement. The Phase II work includes the fabrication of three 27-ft, 25-passenger urban buses and the design for a 40-ft urban bus.

- DOE initiated a 2-year, 20% cost-shared contract with Allison Gas Turbine Division of General Motors for R&D to advance the proton-exchange-membrane (PEM) fuel cell technology to a complete power source system operating on reformed methanol and air for transportation applications. The work includes the conceptual design and fabrication of a complete 10-kW breadboard PEM fuel cell system.

- DOE issued a Request For Proposals for two projects: development of multifuel reformer systems to reform methanol, ethanol, natural gas, and other hydrocarbons into hydrogen for use in transportation fuel cell systems and development of advanced systems for on-board hydrogen storage. These projects 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.

- Lawrence Berkeley Laboratory has been able to greatly extend the cycle-life performance of nickel/zinc battery cells. A sealed, maintenance-free cell has accumulated 500 deep-discharge cycles with almost no shape change, and a vented cell has accumulated more than 800 deep-discharge cycles with about 30% capacity loss. Previous shape-change problems were overcome by use of carbonate- or fluoride-containing electrolytes. Dendritic shorting and reformation problems were solved by the use of a sealed, electrolyte-starved cell configuration in which O_2, which is generated during charge, scavenges incipient Zn dendrites that may be present.

- Argonne National Laboratory (ANL) has developed new sealant materials (a mixed chalcogenide), which are electronic insulators and bond strongly to metals and ceramics, even after exposure to molten salt containing Li alloy or FeS_2 at 400-450°C. The mixed chalcogenide exhibits a bond strength that is about ten times stronger than that of commercially available bonding agents such as borosilicate glass and silane-based products. ANL has fabricated a bipolar, four-cell Li/FeS_2 stack with the new sealant materials, which operated for over 500 cycles with a coulombic efficiency of greater than 98%.

- The Los Alamos National Laboratory (LANL) study indicates that 0.8 W/cm^2 can be obtained in a PEM fuel cell with a 5-mil thick membrane and only 0.4-g Pt/Kw. The LANL test showed that no performance degradation was observed with 0.45 mg/cm^2 Pt loading in over 1200 hours of continuous operation at 0.50-0.75 A/cm^2. In addition, International Fuel Cells, which has a subcontract with LANL, tested PEM fuel cells with low Pt loadings. They were able to duplicate the results obtained at LANL in small 5 cm x 5 cm cells.

- The Ford Motor Company completed the Phase I system and subsystem design of the Modular Electric Vehicle Program. At the end of FY 1991, the major components for the mid-sized 75-HP system had been built and testing initiated.

3.0 BATTERY SYSTEMS R&D

3.1 Advanced Batteries

This section discusses battery development work that DOE supported in FY 1991 prior to the formation of the cooperative agreement between DOE and USABC. In future years, DOE will work with the USABC in selecting advanced battery systems for research and development, which may or may not include those that were funded in the past.

Air-Cathode Development - Nonprecious Metal Electrocatalysts

The objective of this research project is to design and develop stable, nonprecious metal macrocyclic complexes as possible electrocatalysts for the reduction of oxygen in metal/air batteries.

During FY 1991, polymeric cobalt macrocyclic complex was successfully synthesized and impregnated onto carbon substrate. When the carbon-catalyst was heat-treated, the catalyst became insoluble in most of the commonly used organic solvents and mineral acids. Approximately 500 grams of acetylene black-carbon-catalyst were made. Each of the following companies received 100-150 grams of this mix to process into air cathodes: Alupower Inc. of Warren, NJ; Electromedia Corp. of Englewood, NJ; and Giner Inc. of Waltham, MA.

The carbon-catalyst mixes were processed into air cathodes. Test cells were built and operated in 30% KOH at room temperature. Initial results showed that the cobalt macrocyclic complex catalyst has good catalytic activity for O_2 reduction. All three companies have reported oxygen reduction potential of 0.80 V and 0.74 V versus Reference Hydrogen Electrode at 10 mA/cm^2 and 50 mA/cm^2, respectively. Initial storage data indicates good catalyst stability in KOH solutions at 60°C.

Sodium/Sulfur Battery

During FY 1991, progress was made on the final phase of an effort to design and fabricate the best electric-vehicle sodium/sulfur battery possible with today's state-of-the-art cell technology, which was developed under a complementary, DOE-supported, core-technology program. In September 1986, a cost-shared contract was placed by Sandia National Laboratories (SNL) with Chloride Silent Power Limited (CSPL) to advance the sodium/sulfur technology specific to electric-vehicle applications. This program was modified in 1987 and again in 1990 to specify that two sodium/sulfur batteries be designed, fabricated, and qualified to be suitable for evaluation in the ETX-II experimental electric vehicle. Total DOE funding for this five-year activity is approximately $2.7 million.

The first battery (1990) is currently being tested at INEL in the cargo bay of the EXT-II experimental vehicle. It has been at temperature for over 15 months, although less than 60 full cycles have been completed. During FY 1991, mechanical and electrical improvements were made that will permit a second-generation battery to be installed and tested under the vehicle floor. The battery at INEL and a module at the ANL underwent over 500 Simplified Federal Urban Driving Schedule (SFUDS)-based cycles and 13 months of operation before any capacity decline was observed. The 500+ cycles at ANL represent a total range of over 70,000 miles. Based on the test results, a battery service life of more than 600 cycles and over one year are now expected. Weight reduction of the battery is the major goal of the current activity. Other important battery-level component advancements include cell and battery interconnects, the thermal enclosure, and the control electronics.

A preliminary packaging study selected a two-thermal enclosure configuration in order to minimize thermal losses while taking into consideration the shipping and handling problems encountered with the first ETX-II battery delivered to Ford. The design activity focused on packaging of the thermal enclosures in the ETX-II pannier and the internal arrangement of the banks to facilitate assembly of the banks within the enclosure and feed-through access. In order to install the battery underneath the vehicle, the overall height of the battery must be less than 270 mm; this is 77 mm less than that of the earlier ETX-II battery. CSPL was not able to keep its ETX-II battery engineering program on schedule, primarily due to its commitment to the design and construction of the pilot production facility at Clifton Junction, which was commissioned in September. CSPL has been granted a no-cost contract extension that will give it the time to ensure that the battery will have a relatively long service life (May 1992). The battery is to be fabricated with qualified cells from Clifton Junction that contain CSPL's improved glass seal.

The second FY 1991 sodium-sulfur activity was performed under a 30% cost-shared contract with Beta Power, Inc. The objective of this effort is to design a universal cell (and possibly module) for use in electric utility vans that are suitable for entry-level markets. As such, this work will allow the ultimate mid-term capabilities of the sodium-sulfur technology to be defined. The following four vehicles are being considered as models for this study: G-Van, TeVan, ETX-II and MEV-2 (75-hp). During the first quarter of FY 1991, a task was added to also consider prototype passenger vehicles. The period of performance for this $460,000 contract is 18 months.

The work at Beta Power achieved significant progress during FY 1991. A conceptual design was completed for a central sodium cell that satisfies a peak power-to- energy ratio target of 2:1 and maximizes the volumetric energy density. High energy (250 Wh/kg and 420 Wh/l) and power densities (600 W/kg and 1010 W/l) should be achievable with this simplified cell design. An original objective of this design study was to eliminate the need for any active cooling in batteries to be used in the mid-term. However, this new cell design utilizes volume very efficiently and minimizes component weight, a combination which results in such a low thermal mass that sustained high-power periods will overheat the battery. As such, it appears that active cooling will probably be required in advanced sodium/sulfur electric vehicle batteries. Further improvements in cell performance only amplify the problem. Finally, follow-on feasibility studies of battery modularity have resulted in different conclusions for the four vehicles being considered. A reasonable degree of success using self contained, thermally enclosed, battery modules can be obtained for the TeVan, G-Van, and ETX-II, although with a penalty of some loss of available volume. The 75-hp MEV vehicle, however, shows significant loss in available volume with this approach. A general conclusion is that internal modularity within the constraints of the thermal enclosure, with flexible electrical inter-connection, is the most effective modular scheme.

Lithium-Aluminum/Iron Sulfide Battery

In FY 1991, DOE supported the development of lithium-aluminum/iron sulfide (Li-Al/FeS) batteries at SAFT-America, Inc. and Argonne National Laboratory. SAFT is developing prismatic Li-Al/FeS batteries under a three-year, $4.2 million cost-shared contract with DOE, which was awarded in April 1990. Under a separate agreement with DOE, the Electric Power Research Institute supports the R&D project at SAFT, via the DOE cost-share. ANL provides technology transfer, R&D support, and technical management of the SAFT project, while DOE-Chicago provides contract administration. This technology has the potential to meet DOE's performance and life goals for a light-duty van--100 Wh/kg, 106 W/kg, and 600 cycles on the Simplified Federal Urban Driving Schedule. Additionally, DOE supports R&D on a second-generation, bipolar, Li-Al/FeS2 battery technology at ANL.

During FY 1991, SAFT built and tested Li-Al/FeS baseline cells that form the standard by which R&D improvements will be judged. In testing at SAFT, baseline cells accumulated 270 cycles while continuing to perform well above the end-of-life criteria. This testing will continue in FY 1992. Cells of this type were fabricated for inclusion in a 12-volt module that SAFT will assemble and test in early FY 1992. This module will be installed and tested in a thermal enclosure with its own thermal management system. During FY 1991, SAFT developed thermal management system components and established their optimal configuration within the thermal enclosure using a thermal simulator. Also, SAFT delivered baseline cells to ANL for independent evaluation and developed an improved cell technology. ANL is currently evaluating baseline cells and will evaluate improved cells as they become available.

In its R&D on the second-generation technology, ANL established a fabrication facility for producing 13-cm diameter, bipolar, Li-Al/FeS_x cells. In support of this cell fabrication and development activity, SAFT produced the anode, cathode, and electrolyte/separator pellets for these large bipolar cells. Using its new fabrication facilities, ANL developed suitable compositions and processing methods for producing 13-cm diameter peripheral seals for lithium/sulfide bipolar cells. The first sealed cells were fabricated during the last quarter of FY 1991. Figure 2 illustrates projected performance bands for prismatic Li-Al/FeS, bipolar Li-Al/FeS, and bipolar Li-Al/FeS_2 batteries. The bands show the variation in energy and power density that can be achieved by different battery designs based on these technologies. It can be seen that the bipolar Li-Al/FeS_2 battery is projected to meet the performance requirements for a variety of electric vehicle applications, including those for high-power, hybrid-vehicles where a small battery provides full power for vehicle acceleration.

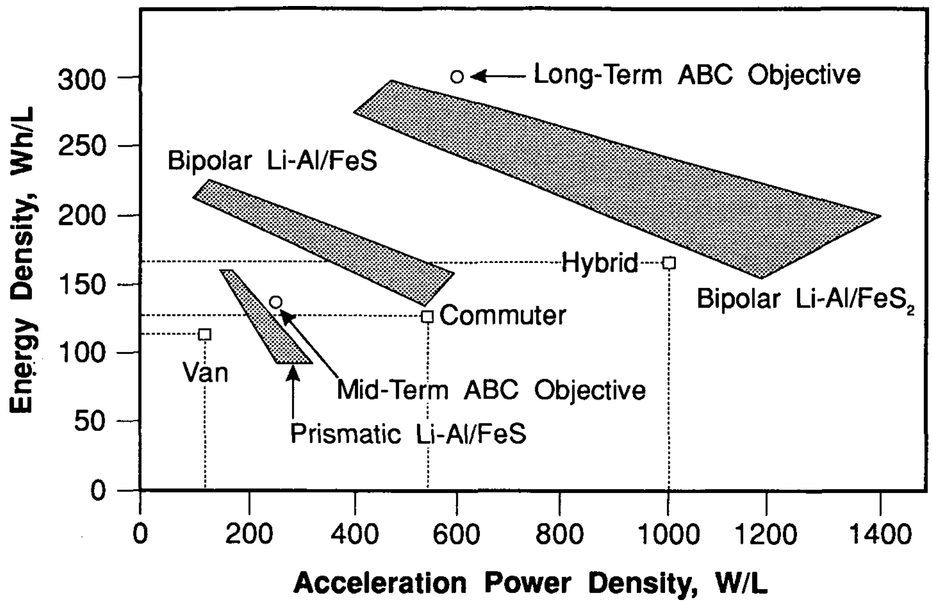


Figure 2. Projected Performance of Li-Al/FeS$_x$ Batteries

3.2 United States Advanced Battery Consortium

The USABC was formed on January 30, 1991, as a partnership of Chrysler, Ford, and General Motors. The rationale that led to the formation of the USABC was based on conclusions arrived at by the automobile manufacturers when confronted with the need to provide zero-emission vehicles by the late 1990s in response to new California automotive emission regulations. The manufacturers determined that there was no clear advanced battery choice that could satisfy the performance and cost requirements necessary for the successful commercialization of electric vehicles. In addition, they concluded that the development of a satisfactory advanced battery would require significant resources beyond those available from any one company. Consequently, after examining the alternatives, and faced with the very short time schedule, they determined that the most viable approach was one wherein all interested parties from Government and industry work collectively to develop a satisfactory advanced battery, the critical missing link to the successful commercialization of electric vehicles.

The major objectives established by the USABC were:

- Establish the capability for a U.S. advanced battery industry;
- Accelerate the market potential for electric vehicles (EVs) by jointly researching the most promising advanced battery alternatives; and
- Develop batteries capable of providing EVs with range and performance competitive with conventional petroleum-based systems.

Immediately after signing the partnership agreement in January, the partners approached the electric utility industry and requested their participation. In early spring, an agreement was signed between the USABC and the Electric Power Research Institute (EPRI), representing the electric utility industry. This agreement provides for financial, technical, and management support for the USABC.

On April 15, 1991, the USABC proposed to DOE a 50/50 cost-shared program of advanced battery research and development. During the balance of FY 1991, the DOE staff worked to negotiate and finalize a formal agreement with the USABC.

The formation of the Consortium represents a major milestone in Government/industry cooperation in the development of technologies for public use in commercial products. The significance of this historic event was recognized with a ceremony in the White House Rose Garden on October 25, 1991, when President Bush announced the formation of the Cooperative Agreement between the Department of Energy and the USABC.

The Consortium intends to work with advanced battery developers and manufacturers, as well as DOE laboratories, to conduct the necessary research and development on advanced batteries for electric vehicles. The goal is to provide increased range and improved performance for electric vehicles that can be commercialized in the late 1990s. The USABC has developed mid-term and long-term criteria for the batteries it plans to develop. These criteria are shown in Tables 2 and 3. In the third quarter of FY 1991, the USABC solicited information from the battery industry on battery technologies that could satisfy these criteria. The Consortium is currently reviewing this information and preparing to enter into negotiations with developers for research and development contracts. The battery systems that will be pursued will be announced with the selection of the contractors in the first or second quarter of FY 1992.

TABLE 2: USABC Advanced Battery Technology Primary Criteria

Primary Criteria	**Mid-Term Goals**	**Long-Term Goals**
Power Density W/L	250	600
Specific Power W/kg (80% DOD/30 sec)	150* (*200 desired)	400
Energy Density Wh/L (C/3 Discharge Rate)	135	300
Specific Energy Wh/kg (C/3 Discharge Rate)	80* (*100 desired)	200
Life (Years)	5	10
Cycle Life (Cycles) (80% DOD)	600	1000
Power & Capacity Degradation (% of rate spec)	20%	20%
Ultimate Price ($/Kwh) (10,000 units @ 40 Kwh)	<$150	<$100
Operating Environment	-30 to 65°C	-40 to 85°C
Recharge Time	<6 hours	3 to 6 hours
Continuous Discharge in 1 hour (No Failure)	75% (of rated energy capacity)	75% (of rated energy capacity)

TABLE 3: USABC Advanced Battery Technology Secondary Criteria

Secondary Criteria	Mid-Term Goals	Long-Term Goals
Efficiency C/3 Discharge 6-hour charge	75%	75%
Self-Discharge	<15% in 48 hours	<15% per month
Maintenance	No maintenance Service by qualified personnel only	No maintenance Service by qualified personnel only
Thermal Loss (for high	3.2 W/Kwhr 15% of capacity 48-hour period	3.2 W/Kwhr 15% of capacity 4 8-hour period
Abuse Resistance	Tolerant Minimized by on board controls	Tolerant Minimized by on board controls
SPECIFIED BY CONTRACTOR Packaging Constraints Environmental Impact Safety Recyclability Reliability Overcharge/Overdischarge Tolerance		

3.3 Near-Term Battery Testing

Laboratory experimental evaluations and post-experimental examinations were conducted at ANL to assess the suitability of various battery technologies for (EV) propulsion. These activities provided insight into those factors that limit the performance and life of these battery technologies and help identify the most-promising engineering approaches for overcoming these limitations. Battery performance and life evaluations were performed under uniform test conditions that simulate driving cycle load profiles. Evaluations were conducted on a 5-kWh zinc/bromine (Zn/Br) battery, developmental hardware from nickel/iron (Ni/Fe) battery R&D programs, and lead-acid modules of tubular plate design. Post-test examinations included physical and chemical analyses from which the degradation and failure mechanisms are determined and those areas requiring further R&D are identified. The results of these evaluations provided an independent measure of battery technology status, comparisons between technologies, and basic data for performance and cost modeling. A summary of the near-term battery test results is given in Table 4.

Table 4. Summary of Near-Term Battery Test Results

Battery Description Manufacturer	Model	Type	Modiule Weight (kg)	Module Capacity 3-h Rate (Ah)	Specific Energy 3-h Rate (Wh/kg)	Volumetric Energy Density (Wh/L)	Peak Pwr. for 15s 50% DOD (W/kg)	Battery Coulombic Efficiency (%)	Battery Energy Efficiency (%)	IDSEP Van SFUDS Range (miles)
SEA	ZBB-5/48	Zinc-Bromine	81	126	75	56	53	93	75	93
Eagle-Picher	NIF200	Nickel-Iron	25	203	51	118	112	74	58	87
Chloride	3ET205	Lead-Acid	32.8	185	33	78	92	87	68	47

Zinc/Bromine Technology

A 5-kWh 48-V Zn/Br module (ZBB-5/48) from the Studiengesellschaft fur Energiespeicher und Antriebssysteme (SEA), Research Group for Energy Storage and Propulsion Systems in Austria, has completed EV performance and life testing. Life cycling with SFUDS-simulated driving profile discharges to 100% depth-of-discharge (DOD) was started in March 1990 after performance testing (~130 accrued cycles). The module reached end-of-life (>20% loss of initial capacity) after 334 cycles. Early in its life, electrochemical maintenance was performed on the module about every five cycles. This was accomplished by completely discharging the module (to zero voltage for about 4 hours to strip all the Zn from its electrodes). Between stripping cycles, module capacity with the SFUDS discharges declined at the rate of approximately 2.5%/cycle. After 300 cycles, this decline in capacity suddenly increased to about 7%/cycle. Electrolyte analyses were conducted to assess the sudden change in module performance. The electrolyte pH level was high, and HCl was added at the request of SEA, but there was no change in module performance. Testing was halted when a capacity of <80% of its initial level (126 Ah) was obtained on the first cycle after stripping. The module is being prepared for shipment to SEA for post-test analyses.

Advanced Nickel/Iron Technology

Two 6-V advanced Ni/Fe modules (NIF200) manufactured by Eagle-Picher Industries (EPI) with sintered-powder nickel electrodes were evaluated during FY 1991. The NIF200 design provides a capacity of 200 Ah in the same module package as the 170 Ah module developed for the Eaton Dual-Shaft Electric Propulsion program. Due to a change in program direction, testing was halted in January 1991. At that time, one module was under life test using SFUDS discharges to 100% DOD, and the second module was just starting performance characterization. The module on life test had undergone performance characterization in FY 1990. It had completed 185 cycles and retained about 95% of its initial 198 Ah capacity when testing was halted. It was returned to EPI for additional life tests. The second module had completed only 8 cycles of capacity verification. It was sent to the Idaho National Engineering Laboratory for additional performance characterization testing.

Tubular Lead-Acid Technology

Two advanced tubular lead-acid modules (3ET205) manufactured by Chloride Electric Vehicle Systems Ltd. were acquired and tested in January 1991. The three-cell modules have tubular positive electrodes and are representative of battery packs being vehicle tested. The purpose of this test was to measure and compare 3ET205 cycle life on SFUDS discharges (100% DOD) with that achieved in an EPRI-sponsored test using J227aC/G-Van driving profile discharges to 100% DOD. Both of the new modules completed an abbreviated performance characterization, and one was life tested using SFUDS discharges to 100% DOD. After about 150 cycles, the module reached end of life (<80% of initial energy). In the EPRI test (1990), the 3ET205 completed 715 cycles before reaching end of life. Post-test analyses of the EPRI module revealed that failure was due to deterioration of the negative electrodes because of the presence of high levels of antimony and poor adhesion between the active materials and the grids. The antimony was generated by corrosion of the positive grids and plated onto the negative electrodes during operation. The result was reduced charging efficiency and decreased effective capacity of the electrodes. Post-test analyses have been initiated on the DOE module.

3.4 Summary Of Advanced Battery Testing

Laboratory experimental evaluations and post-experimental examinations were conducted at ANL in support of the EV Advanced Battery R&D Activities. These activities provide insight into those factors that limit the performance and life of advanced battery technologies, and help identify the most promising R&D approaches for overcoming these limitations. Battery performance and life evaluations were conducted under uniform test conditions that simulate driving cycle load profiles. Evaluations were conducted on a 22-kWh sodium/sulfur (Na/S) battery, a 2.4-kWh Na/S module, prismatic H-type (34 Wh) and extended C-size (4.4 Wh) nickel/metal hydride (Ni/MH) cells, and developmental hardware from the lithium/iron monosulfide battery R&D program. Post-test examinations include physical and chemical analyses from which the degradation and failure mechanisms are determined and those areas requiring further R&D are identified. The results of these evaluations provide a measure of the success of the battery development efforts and insights into the direction the research programs should take. The advanced battery test results are summarized in Table 5.

Table 5. Summary of Advanced Battery Test Results

Battery Description Manufacturer	Model	Type	Module Weight (kg)	Module Capacity 3-h Rate (Ah)	Specific Energy 3-Rate (Wh/kg)	Volumetric Energy Density (Wh/L)	Peak Pwr. 15s 50% DOD (W/kg)	Battery Coulombic Efficiency (%)	Battery Energy Efficiency (%)	IDSEP Van SFUDS Range (miles)
ABB	B-11	Sodium-Sulfur	253	238	81	83	151	100	91	154
CSPL	PB-MK3	Sodium-Sulfur	29.2	292	79	123	94	100	88	150
SAFT-America	R&D Cells	Lithium-Iron Monosulfide	3.675	203	66	133	83	95	81	95
Ovonics	H-cell	Nickel-Metal	0.628	28	55	152	183	90	80	97

Sodium/Sulfur Technology

A 90-V, 22-kWh Na/S battery (B11) fabricated by ASEA Brown Boveri (ABB) had been under test since May 1990. This battery technology was evaluated to determine its technical status, compare its performance with that of other technologies, and acquire basic data for system performance and cost modeling. The B11 battery has 360 cells (30 Ah each) configured into three series-connected sections, each having eight parallel-connected strings of fifteen series-connected cells. It was heated to operating temperature (310°C) in April 1990 and shipped to ANL at temperature. A battery management unit was provided which included a complete thermal management system (thermal enclosure, heaters, cooling blower, and temperature controller) and an operational safety system. The thermal management system has maintained the battery temperature within the 310 to 350°C operating range (blower energized at 335°C) for high rate discharges to 50 W/kg. The average heater power needed to maintain a battery temperature of about 310°C over a 72-h open-circuit period was 176 W (enclosure heat loss). This heat loss would cause a capacity decline of about 0.8%/h if the battery was used to power its own heaters (self-discharge loss). EV performance characterization tests were completed and life tests started in October 1990 using SFUDS-simulated driving profile discharges to 100% depth-of-discharge. Early in FY 1990, the battery was cooled down to repair its positive voltage output terminal, which became disconnected inside the enclosure. After returning the battery to operating temperature, a cell in its center section was found to have low capacity. This cell and a corresponding cell in each of the parallel-connected strings in this battery section were short circuited. Hence, the battery was reduced to 352 cells and 88 V. Life testing was resumed in November 1990, and no loss in SFUDS range (154 miles) was exhibited. Testing was terminated after 591 cycles because the battery operating temperature dropped below 290°C, while its heaters were continuously energized. The outside case temperature had reached 45°C with one bottom location reaching 90°C. The battery was cooled to room temperature and returned to ABB for post-test analyses, which are in progress.

An 8-V, 300 Ah Na/S module, fabricated by CSPL, has been under test since June 1990. This module contains 120 cells, which are configured into 30 parallel-connected strings of four series-connected cells. The cell design and hardware assembly used with this module are the same as those for the 24 series-connected modules in the full-sized battery system for the Ford ETX-II vehicle. The ANL test program is an extension of the evaluation of the full-sized ETX-II battery. The CSPL module was furnished without a thermal case and had to be installed in an existing ANL thermal enclosure that possessed no cooling capability. At an operating temperature of 330°C, the maximum continuous CI and CP discharge rates that could be applied without exceeding the 370°C maximum temperature limit specified by CSPL were 150 A and 40 W/kg, respectively. Performance testing was completed (140 cycles accrued), and life testing started in October 1990. Life tests are continuing, and the module has successfully completed more than 700 cycles and retains approximately 85% of its initial 292 Ah capacity (3-h rate). The decline in capacity indicates the loss of four, 4-cell strings. The resistance of the module has increased with life (from 5.5 to 7.1 mW) causing the available energy for SFUDS discharges to decline by almost 20% (<80% of initial energy is end of life).

Nickel/Metal Hydride Cells

Performance and life characterization tests are being conducted on 25-Ah prismatic and 5-Ah extended C-size Ni/MH cells manufactured by Ovonic Battery Company (Troy, MI). The ANL tests are being performed to evaluate the suitability of this technology for EV applications. Previously tested (1990) C-size, 3.5-Ah cells exhibited good performance characteristics, but the cycle life of four cells (33, 238, 289 and 333 cycles) was less than expected (500 cycles). These early cells exhibited a high self-discharge loss (14 to 38% loss in 24 hours, and 45 to 70% loss in 7 days). Ovonics has since modified component materials and reduced the self-discharge loss to 15 to 20% in 7 days. Preliminary data indicate that the performance of the new H-type and extended C-size cells exceeds that of the earlier cells. Life testing is continuing.

Lithium/Iron Monosulfide Cells

Two lithium/iron monosulfide cells were delivered to ANL for baseline performance testing under the R&D development contract with SAFT America Inc. The first cell was placed on test in May 1991, and a test was conducted to determine its performance as a function of temperature (465 to 485°C). The results showed that cell capacity, internal resistance, and IR-free voltage were very sensitive to temperature. After 30 cycles, the cell still retained 98% of its initial capacity, but was removed from test to undergo post-test analyses. These analyses showed that increased compression was needed to improve cell performance and reduce the cell's sensitivity to temperature. A second cell was placed on test in July 1991 with an improved clamping fixture. This cell is undergoing performance characterization and is exhibiting a reduced temperature sensitivity. After characterization, the cell is scheduled to be life tested with SFUDS discharges to 80% depth-of-discharge.

3.5 Near-Term Battery R&D Program Completions

Nickel/Iron Batteries

EPI completed a multi-year contract to develop high-performance nickel/iron batteries. In recent years, the emphasis of this program has been on cost-reduction and pilot-plant engineering. Activities were suspended in mid-FY 1991, as DOE shifted its support to the more advanced battery technologies. During FY 1991 DOE support was beneficial in two key areas: EPI developed and implemented improved, in-house quality assurance procedures for iron electrodes—reducing rejection rates to less than 2%—and EPI completed the installation and debugging of a production-sized furnace for reducing iron ore to iron powder and the subsequent sintering of the powder into electrodes. Also, a lower-cost method of impregnating nickel electrodes was developed. Independent evaluation of nickel/iron hardware is covered in Section 3.3

In a separate small contract, Electrotek Industries Inc. investigated methods of improving the charge efficiency of nickel/iron batteries. Screening tests were used to identify alternative charging techniques and electrolyte additives that improve efficiency. EPI will supply electrodes to be used in verifying these improvements in cells.

Lead-Acid Batteries

Johnson Controls Inc. (JCI) is in the final stages of a 6-year contract to develop advanced lead-acid batteries. The emphasis of this program has been to demonstrate higher-performance and lower-maintenance lead-acid battery technologies for EV applications. JCI fabricated four, 3-cell modules as final contract deliverables, and these modules are being tested at JCI under a no-cost extension to the contract. Two modules are of a flow-by design to enhance performance, while the other two are of a sealed oxygen-recombinant design to reduce maintenance. The flow-by modules exhibited 38-42 Wh/kg (gross) on the SFUDS, but exhibited limited life. The oxygen-recombinant modules exhibited 35-36 Wh/kg (gross) on the SFUDS, and testing of these two modules continues with over 100 accumulated cycles by JCI.

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 with 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), the only suitably developed technology for transportation at this time. The result will be a methanol-fueled, fuel-cell-powered bus system with a performance equivalent to diesel buses, but with a reduction in exhaust emissions of more than 99%. For the mid-term, the program is directed at the introduction of PEM fuel cells into cars and vans. PEM fuel cells can achieve the power density required for cars and vans, but much additional R&D is required to reduce costs, optimize performance, and otherwise extend the technology.

The hydrogen used in fuel cells can be produced from many sources, such as methanol, ethanol, or natural gas. The hydrocarbons are converted into hydrogen and carbon dioxide through a thermal/chemical process in a fuel reformer. Advanced reformer technology is 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.

The DOE programs on fuel cell technology are described in the following paragraphs. ANL provides technical management and support for DOE/EHP's fuel cell activities, while DOE/Chicago Field Office provides contract administration for cost-shared contracts with industry.

4.1 Phosphoric Acid Fuel Cell/Battery-Powered Bus System

The objective of this program is to develop a methanol-fueled, phosphoric acid fuel cell/battery propulsion system for an urban transit bus. An urban 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 was selected as the fuel for this program because it can be derived from nonpetroleum sources (e.g., coal, natural gas, biomass), it is readily transportable, and it can be reformed for fuel cell use at relatively low temperatures.

The phosphoric acid fuel cell was selected for this program 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/Urban Mass Transportation Administration, and the California 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, a 43-kW lead-acid battery, a power conditioner (dc chopper) to step up the fuel cell output voltage to match that of the battery, and overall system controls. The team of Energy Research Corporation, Los Alamos National Laboratory, and Bus Manufacturing Inc. built and tested a 62-kW power source consisting of a 32-kW fuel cell and 30-kW nickel/cadmium battery, connected in parallel. In both systems, the test results verified the performance predicted by the design analyses and confirmed the feasibility of the fuel cell bus concept.

During FY 1991, Phase II was initiated, which includes the fabrication and delivery of three, 27-foot, 25-passenger urban buses and the design for a full-size, 40-foot urban bus. Through a competitive procurement process, DOE awarded a

30-month, cost-shared contract in April 1991 to H-Power Corporation of Bloomfield, NJ. 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.

Georgetown University conducted fuel cell bus design and application studies during FY 1991 in support of the Fuel Cell/Battery Bus Project. Georgetown completed development of a bus performance simulation model and used this model to carry out analyses of bus requirements for representative routes and for bus integration studies. Georgetown also initiated development of a fuel cell bus commercialization strategy.

Fuel cells are designed to continuously meet the average power demand for the mission, while auxiliary devices such as batteries provide short-duration power needed during acceleration and store the energy recaptured during braking. ANL is initiating work directed at identifying and evaluating the best load-management devices specifically tailored for this application.

4.2 Proton-Exchange-Membrane (PEM) Fuel Cell Research

DOE is sponsoring both fundamental and applied research on 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 weight and size, 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.

DOE has established a four-phase development program for the PEM fuel cell, with a decision point at the end of each phase. Phase I, feasibility evaluation, was initiated in September 1990, and includes work on the conceptual design of a PEM-based propulsion system to advance the technology to meet transportation application needs, and integration and testing of a complete 10-kW, breadboard PEM fuel cell system. In Phase II, the system will be scaled-up to a 25-kW brassboard system to show proof of feasibility. Phase III will consist of laboratory evaluation of a full-size, propulsion system. In Phase IV, the complete propulsion system will be installed and evaluated in a test-bed vehicle.

During FY 1991, Allison Gas Turbine Division of General Motors initiated work on a 2-year, 20% cost-shared Phase I contract directed at demonstrating system feasibility. 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.

Research tasks being addressed in Phase I include fuel cell components, fuel processing, electronic controls, gas pressurization, water and heat management, and battery type and specifications for start-up and to help meet transient power needs. Other areas under study include development of a system conceptual design, and system modeling to permit tradeoff analyses. The Phase I effort will culminate 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.

The PEM fuel cell differs from other fuel cell types in that it uses a fluorocarbon ion- exchange membrane as the electrolyte. Because the membrane contains terminal sulfuric acid groups, it acts as an acidic electrolyte and does not absorb carbon dioxide. Like the PAFC, the PEM fuel cell can use hydrogen derived from reformed carbon-based fuels such as methane and methanol. Another advantage of a solid polymer electrolyte is that an immobilized electrolyte simplifies sealing in the production process, reduces corrosion, and provides for longer cell life and stack life. The cell operates at less than 100°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 200°C.

There are two major research concerns for the PEM fuel cell: extreme sensitivity to carbon monoxide (CO) poisoning of the electrocatalyst and the need for humidification of the fuel and oxidant streams. The PEM, which operates at low temperatures, uses 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 streams 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.

The system design of the PEM fuel cell is similar to that of the PAFC except for the addition of a preferential oxidizer 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 0.5% 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.

Research on the PEM fuel cell in recent years has improved the technology base to the point where the performance necessary for automotive applications can be achieved with a hybrid PEM fuel cell/battery system. Although previous applications of the PEM fuel cell has been only for space missions, Dow Chemical recently developed a new membrane with lower electrical resistance. This new membrane can carry higher current densities which should make the PEM fuel cell more economical for transportation applications. Los Alamos National Laboratory has developed a method to decrease platinum loading, and manufacturers have developed less expensive graphite separator plates, similar to those used in PAFC stacks, to replace expensive metal plates.

Ongoing fundamental research on materials and components for PEM fuel cells is being conducted at Los Alamos National Laboratory. This core technology research is directed at reducing the cost and improving the performance and endurance of PEM fuel cells. The results of this research effort will be integrated into the subsequent phases of the PEM system development program.

4.3 Multifuel Reformer Development

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.

Reforming methanol to hydrogen involves a reaction of gaseous methanol and steam on heterogeneous catalytic surfaces:

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

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. Both reactions are carried out at 200°C or more and require a different catalyst for each reaction. The 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. DOE is undertaking research on advanced reformer and hydrogen storage technologies to improve the competitiveness of fuel-cell-powered vehicles. One objective of the program 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. 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 plans to award a 30-month development contract in FY 1992. The work will be divided into two phases: the first phase will consist of a feasibility study and the second phase will be directed towards the fabrication and test of proof-of-concept reformer and hydrogen storage systems. DOE issued a Request-For-Proposals in May 1991, and an industrial contractor for this work will be selected through a competitive procurement now in progress.

The Phase I Feasibility Study will identify the reformate requirements for phosphoric acid and proton-exchange-membrane fuel cells, and then examine the system tradeoffs (i.e., reformer size, weight, efficiency, quality of reformate, life, cost, transient response capability, start-up time) in the design of hydrogen storage systems and reformers for the various hydrocarbon fuels. Steam reforming, partial oxidation, or combinations of these processes will be 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. The Phase II work will consist of the fabrication and test of the proof-of-concept reformer and hydrogen storage systems.

While DOE is the major sponsor of this work, the State of Illinois Department of Energy and Natural Resources plans to co-sponsor the development of ethanol reforming technology. Ethanol is a renewable energy resource produced from corn or other biomass and has 30% more energy than an equal amount of methanol.

4.4 Thermo-Electrochemical (TECH) Power Source R&D

The Thermo-Electrochemical (TECH) system is an electrochemical concept for producing electric power from fuel or waste heat. TECH consists of an electrochemical cell which produces direct current electricity, and a regenerator which thermally regenerates the cell reactants. Acid and base fluids are fed into the electrochemical cell where they react across a cation-exchange-membrane to produce electricity and form a chemical salt. Thin layers of porous catalyst are bonded on each side of the membrane to act as the electrodes where the cell reactions take place. The product salt stream leaving the stack then flows to the regenerator where it is decomposed and converted back into acid and base, completing the closed-loop cycle. The temperature difference between the regenerator (where thermal decomposition takes place) and the ambient temperature condenser (where heat is rejected) determines the maximum (Carnot) thermodynamic efficiency for the process. A major emphasis in the development of this technology is to demonstrate high efficiency at a reasonable projected cost for the system.

A conceptual design for a TECH system in transportation applications has been developed. The TECH system can use almost any fuel as the heat source, and can provide power for electric propulsion with much lower emissions than internal combustion engines because TECH's external combustion of fuel is much cleaner.

During FY 1991, the Delco Remy and Hughes Aircraft Divisions of General Motors Corporation completed the second year of a DOE contract directed at evaluating the feasibility of TECH as an electric-propulsion power source. This project is supported on a 50/50 cost-shared basis by DOE and Delco Remy, with matching funds provided by General Motors.

During the first year of this project, Hughes was able to quadruple the cell operating current density, achieving over 200 mA/cm^2 in cells with an active area of 10 cm^2. During the second year of this project, Hughes employed a new technique for bonding the membrane to the electrode which created a much better interfacial contact between membrane and catalyst. This led to a decreased ohmic loss in the cell, improved catalyst utilization, and resulted in a further 30% increase in current density to 260 mA/cm^2.

Hughes then scaled-up the cell size from 1.6 sq. inches to the 6-inch by 6-inch size that would be required for a vehicle electric-propulsion system. At the end of FY 1991, Hughes had completed fabrication of the cells with a 6-inch x 6-inch active area, and was ready to begin closed-loop system tests to evaluate the feasibility of the system and supply information necessary for engineering assessment of overall system efficiency.

4.5 Database Development for Fuel Cell Systems R&D

During FY 1991, ANL established a multifaceted database for the fuel cell systems R&D programs being sponsored by DOE/EHP. This database includes information on the past, present, and future programmatic milestones across the entire spectrum of the R&D programs. It also includes comprehensive information on the different fuel cell systems, organized by technologies or specific fuel cell type. This information includes: contractual information, such as the name and address of the contractor and responsible contact, contract period and history, funding levels, etc.; and information on technical goals and progress achieved, including significant accomplishments and recent highlights.

The database has been set up using hypertext tools that permit the inclusion of standard text files into the database with only minor changes. The database provides an intuitive user interface, which can be modified easily to accommodate new information, new programs, or new perspectives as desired. In addition, the main user interface provides a transparent link to the Contacts Information Management System database, which contains the name, address, telephone and telefax numbers, research interests, and other information for a large number of individuals involved in fuel cell research around the world.

4.6 Market-Derived Specifications for Fuel-Cell-Powered Vehicles

Polydyne Inc. of San Mateo, CA, carried out an analysis of market-derived design specifications for fuel-cell-powered electric vehicles under a small subcontract with ANL. Polydyne used their Advanced Vehicle Design and Simulation Model, previously developed with private funds, to determine component specifications for fuel-cell-powered vehicles; to project the resulting capital and life-cycle costs for various assumed production levels and learning curves; and to examine the impact of the resulting market penetration rates on the concomitant benefits in petroleum displacement and emissions reductions. A project report was prepared by Polydyne to document the results of the study.

4.7 Life-Cycle Cost/Economic Analyses

A life-cycle cost analysis study was initiated in late 1991 to make quantitative economic comparisons between conventional vehicles and fuel-cell-powered vehicles. Comparisons will be made for cars, vans, and buses, using phosphoric acid or proton-exchange-membrane fuel cells where applicable.

5.0 EXPLORATORY TECHNOLOGY DEVELOPMENT

LBL manages the Exploratory Technology Research Program, which is charged with conducting research on electrochemical phenomena that limit the performance and lifetime of rechargeable batteries and fuel cells, developing new materials and cell components, discovering new electrochemical cells with superior performance and durability, and providing graduate-level training for electrochemical engineers and electrochemists. This Program also involves applied research at LANL, Brookhaven National Laboratory (BNL), universities, and industrial companies.

5.1 Exploratory Research

The major thrust of this project element is to evaluate promising electrochemical couples for advanced batteries for electric vehicles. Exploratory research is carried out on Li/polymer and Zn/NiOOH cells.

Li/polymer cells contain thin electrodes of Li and metal oxide that sandwich a polymer membrane capable of conducting Li^+ ions. This simple cell design is expected to be easily fabricated using existing thin-film technology. LBL has developed a novel Li/organosulfur cell, and cycle testing is underway to evaluate organosulfur cathodes [$(SRS)_n$, where R is an organic moiety such as CH_2CH_2, C_2H_4, etc.] or solid redox polymerization electrodes (SRPEs). To date, over 350 charge/discharge cycles have been obtained with laboratory-scale cells. A number of new SRPEs were synthesized and evaluated in solid-state Li cells. These include polymers based on 2,4-dithiopyramidine, 2-mercaptoethyl ether, 2-mercaptoethyl sulfide, and ethane dithiol. The poly(diethyl ether disulfide) polymer (termed X0) exhibited good discharge kinetics and was exceptionally easy to cast as a homogeneous film due to its solubility in acetonitrile. The oxidation product of ethane dithiol, polyethylene disulfide (termed X8), also exhibited excellent discharge characteristics in solid-state cells and attained the highest surface capacities seen to date for solid-state Li/polymer cells. Figure 3 was developed to compare the discharge curves of one-, two-, and three-layer X8 cathodes. Results indicate that three-layer cathodes have a larger charge efficiency than those with fewer layers.

New approaches to extend the cycle life of nickel-zinc (Zn/NiOOH) cells are underway at LBL that involve modifying the electrolyte composition. The shape-change problem has been significantly reduced by the use of electrolyte compositions having low zincate solubility. In flooded, vented cells cycled at 100% depth-of discharge, a cell with 2.5 M KOH-2.5 M K_2CO_3-0.5 M LiOH electrolyte retained 60% of its initial capacity after 470 cycles, and a cell with 3.5 M KOH-3.3 M KF electrolyte retained 70% of its initial capacity after 820 cycles (Figure 4).

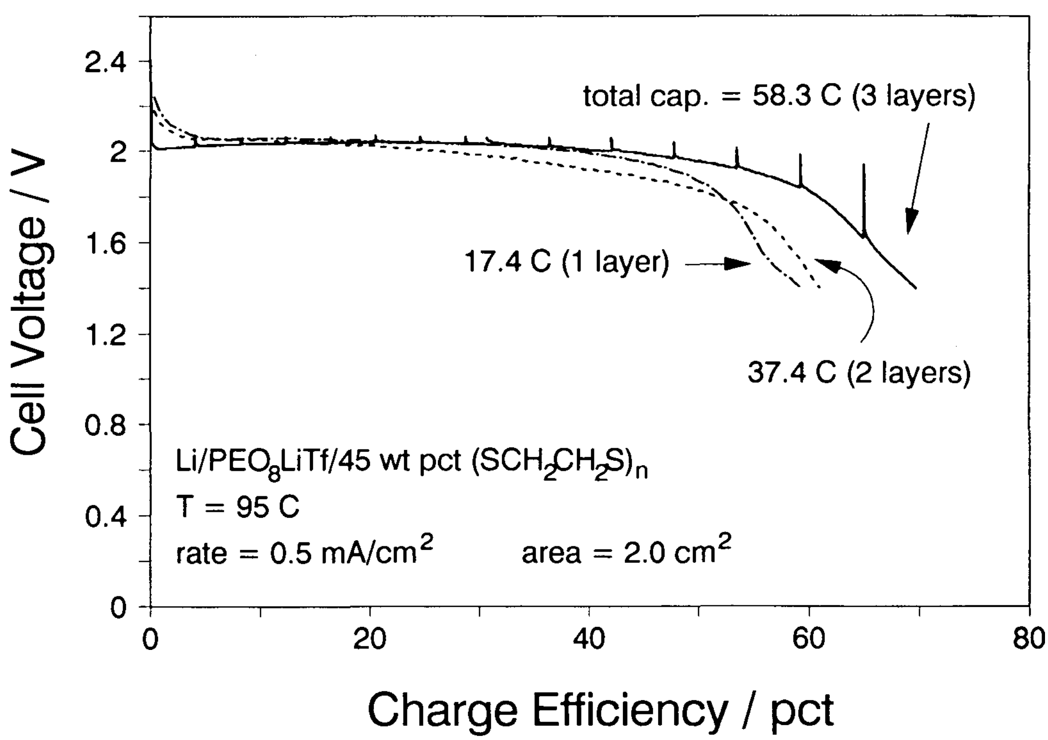


Figure 3. Discharge curve for X8 multilayer cathode. (XBL 917-1420)

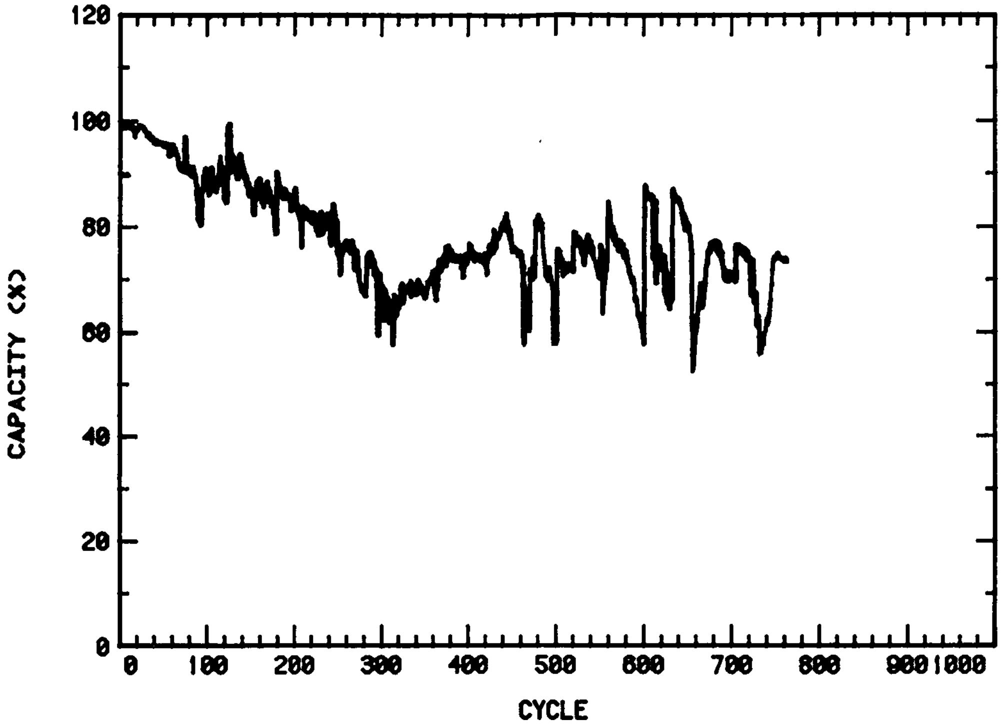


Figure 4. Capacity vs cycle number (100% DOD) for cell containing 3.5 M KOH -3.3 M KF. (XBL 917-1419)

5.2 Applied Science Research

The objectives of this project element are to provide and establish scientific and engineering principles applicable to advanced batteries and electrochemical systems; and to identify, characterize, and improve materials and components for use in batteries and electrochemical systems.

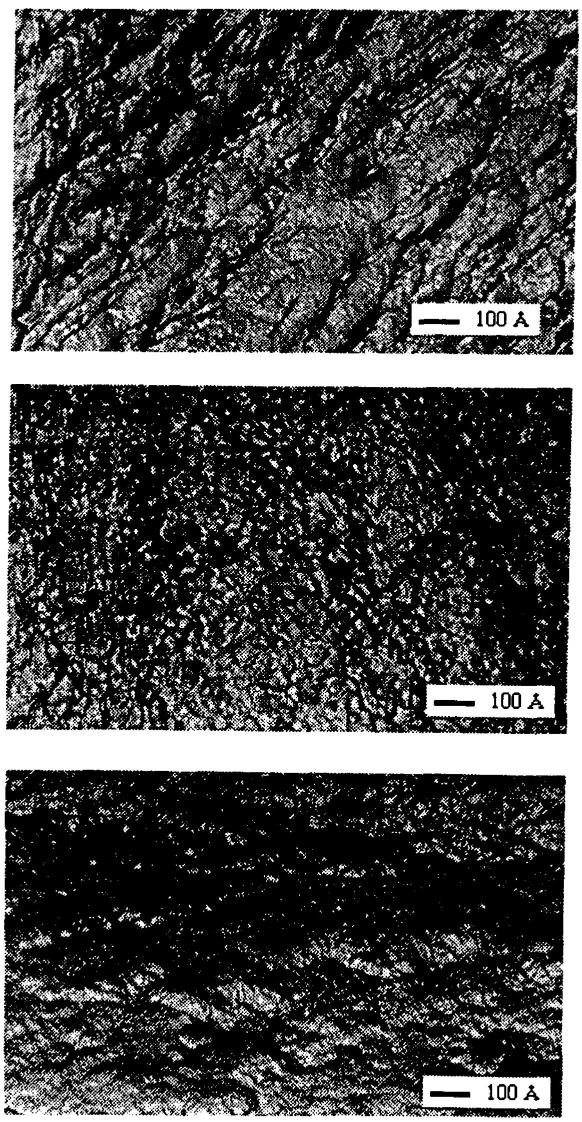
The Illinois Institute of Technology is investigating the use of electrochemical- and chemical-vapor deposition to form pinhole-free coatings of molybdenum carbide (Mo_2C) on low-carbon steel. Several coated samples have been tested at Chloride Silent Power Limited (CSPL) in Na/S cells, and the preliminary results are encouraging. Evaluation of electrode-posited Mo_2C-coated Ni in a Li/FeS_2 cell showed that these coatings are stable at 1 to 2.1 V (versus LiAl reference electrode) for 57 h.

Laser Raman spectroscopy and cyclic voltammetry were also employed by LBL to investigate anodic Zn films in 1 M KOH. Evidence was obtained for the formation of a $Zn(OH)_2$ film during the active portion of the anodic sweep, and diffusion of hydroxide ions to the metal/film interface becomes rate limiting near the active-passive transition potential.

The University of Pennsylvania is working closely with the Energy Research Laboratory (Odense, Denmark) to develop high-conductivity polyethylene oxide (PEO) electrolytes for rechargeable batteries. Polymers containing a plasticizer (propylene carbonate or polyethylene glycoldimethylether) and Li salts showed encouraging ionic conductivity, mechanical, thermal, and transport properties. SRI International is conducting research on the synthesis of polyethylimine derivatives which can be used as highly conductive solid polymer electrolytes. A Li-ion conducting polysiloxane was produced which has one of the highest ionic conductivities (1.8×10^{-4} $ohm^{-1}cm^{-1}$ after exposure to CH_3CN) at room temperature. A Case Western Reserve University project is directed at improving the understanding of the Li/electrolyte interface by use of sophisticated surface techniques. Studies of the Li/PEO interface by *in situ* Attenuated Total Reflection Fourier Transform Infrared Spectroscopy suggested that the ether-type bonds in PEO were cleaved and alkoxide functionalities (e.g., $-(CH_2)-O-Li^+$) were formed.

Johns Hopkins University (JHU) and Jackson State University (JSU) are investigating electrochemical phenomena in nonaqueous electrolytes of interest for rechargeable Li cells. JHU observed that Armco iron and 1018 carbon steel, which are scratched to mechanically disrupt the air-formed film, are rapidly repassivated in dimethoxyethane (DME)/$LIAsF_6$ containing 300-ppm H_2O. The adsorption of DME molecules or the precipitation of an iron hexafluoroarsenate salt film is believed to be responsible for the rapid repassivation. JSU has observed by *in situ* Raman spectroscopy that Li is more reactive in diethyl carbonate (DEC) than in dimethyl carbonate. However, the addition of methyl formate to DEC suppressed the reactivity of Li.

Cross-cutting research at LBL provides a critical scientific and electrochemical engineering base to support the development of many electrochemical energy storage and conversion devices. The projects at LBL encompass the following: spectroscopic and *in situ* studies of electrochemical reactions at electrode surfaces, studies of electrocatalysts using advanced surface techniques, electrocatalysis studies, modeling of electrochemical and transport phenomena, and fundamental studies of the formation of different morphologies *(e.g.*, mossy, nodular dendrites) that influence the life of Zn electrodes. LBL is developing a mathematical model to improve the understanding of the incomplete rechargeability of the S electrode which limits the performance of Na/S batteries. LBL is also measuring the ionic conductivity of sodium polysulfide melts as a function of concentration and temperature. The structural changes that occur during the cycling of thin nickel oxide electrodes between Ni(II)hydroxide and Ni(III) hydroxide are being investigated at LBL to identify the reasons for capacity loss and the memory effect in Ni-containing cells. Evidence for the nucleation of semiconducting oxy-hydroxide in the insulating hydroxide layer was obtained by scanning tunneling microscopy (STM) in Figure 5, and these results are in agreement with the earlier interpretation of transient and spectroscopic ellipsometer measurements. A mechanistic model for the propagation of the phase boundaries during film transformation is being developed.



Etched Ni Substrate with 20 Å Native $Ni(OH)_2$

Ni Substrate with 80 Å Charged $Ni(OH)_2$ film with NiOOH penetrating nuclei

Ni Substrate with Discharged Film Removed by Dissolution

Figure 5. STM images of NiOOH nucleation. (XBB 917-5126)

The electrocatalysis studies are focused on understanding the mechanism of methanol electrooxidation and identifying improved electrocatalysts. LBL has observed that the single-crystal face of the ordered alloy Pt_3Sn is not as good an electrocatalyst for methanol electrooxidation in sulfuric acid as a low-index single-crystal Pt with electrodeposited Sn. Photothermal deflection spectroscopy is being developed at LBL to study the electrooxidation of CH_3OH on Pt electrocatalyst. Preliminary studies suggest that the reaction pathways involving platinum oxides play a significant role in the overall reaction rate for CH_3OH electrooxidation.

5.3 Air Systems Research

The objectives of this project element are to identify, characterize, and improve materials for air electrodes; and to identify, evaluate and initiate development of metal/air battery systems and fuel-cell technology for transportation applications.

The performance of two Zn electrode designs, which were invented at LBL, are under investigation in Zn/air cells. The two cell configurations incorporating the Zn electrode designs consist of either a reticulated flow-through structure or small stationary Zn particles. The viability of the reticulated structure as a substrate for Zn deposition/dissolution has been independently verified by MATSI, Inc., under subcontract to LBL. The performance of the reticulated structure in Zn/air cells is being examined at LBL using the SFUDS cycling regimen. Experiments on particulate-bed electrodes which rely on natural convection are also underway, and Zn/air cells with these electrodes are being evaluated using SFUDS cycling (without regenerative braking).

The PEM fuel cell is a leading fuel cell candidate for transportation applications, and much of the fuel cell research in this program is directed at improving the performance, life and costs of the PEM fuel cell. Another major thrust is to develop a suitable electrocatalyst-electrolyte combination that will promote the direct electrooxidation of methanol in a compact, high-performance fuel cell. A mathematical model is being developed at LBL to improve the design and performance of PEM fuel cells. This model describes the transport of water and the phenomena at the three-phase region of the membrane/electrode interface in PEM fuel cells. The validity of the model will be checked with the behavior of small laboratory cells which will be tested at LBL and at LANL. BNL is conducting research to develop improved electrocatalysts for oxygen reduction and direct methanol oxidation, and is utilizing Extended X-Ray Absorption Fine Structure (EXAFS) studies to examine electrocatalyst/electrode interfaces. The presence of Sn-O interactions was observed on underpotential deposited (UPD) Sn on Pt by EXAFS. These interactions are most probably the reason that UPD Sn on Pt is a good catalyst for the direct oxidation of methanol.

LANL is involved in R&D to optimize the structure of membrane/electrode assemblies, characterize water transport properties, develop CO-tolerant catalysts, and test PEM fuel cells. The self-diffusion coefficient of protons in Nafion with different degrees of hydration was measured by ^1H NMR. The results indicate that the diffusion coefficient decreases with a decrease in the water content. A model was developed which shows that the electroosmotic water drag causes a local depletion of water near the anode, which becomes more severe at higher current densities. The performance of the oxygen electrode in PEM fuel cells decreased as the temperature was increased to 80°C, which is attributed to the loss of water from the Nafion film.

5.4 Ultracapacitors

INEL continued the study of high energy density ultracapacitors that can be used to load-level the traction battery in electric propulsion systems. This reduces the peak power required from the battery by a factor of two or more, which could permit the traction battery to achieve longer life and higher energy output. State-of-the-art ultracapacitors having capacitance up to 500 Farads and an energy density of 2 wh/kg were obtained and evaluated in the INEL Battery Laboratory. Pulsed cycle tests of the devices indicated that their charge and discharge characteristics are suitable for the electric vehicle applications. Life cycle testing showed cycle lives of up to charge/discharge 120,000 cycles. A contract was placed 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 wh/kg by 1995, which could be configured in a 100 kg unit to store 500 wh of energy.

5.5 Sodium/Nickel Chloride Battery Research

DOE supports research and development at ANL on sodium/nickel chloride batteries as potential power sources for electric vehicles. The technology offers the promise of a safe battery system with excellent reliability and the potential to serve as a power source for both vans and passenger vehicles.

During FY 1991, ANL research was directed toward improving both the specific power and energy characteristics of the sodium/nickel chloride battery system. The objective of the research is to identify those parameters which limit the specific power and energy of the battery system and to develop approaches to ameliorate those limitations. In the course of this work, it was found that the performance of the battery couple could be significantly improved through the use of appropriate chemical additives and pore-forming materials that enhance the conductivity characteristics of the nickel chloride electrode. Through use of a combination of additives and improved electrode morphology, the power of the battery at the end of the discharge was nearly doubled and the available battery energy was increased by over 30%.

Through carefully controlled experimental cell studies, data were developed to model the performance characteristics of the battery in various configurations. The results of these modeling studies are presented in Figure 6 as projected performance bands. The performance bands show the variation in energy and power density that can be achieved by different battery designs based on this technology.

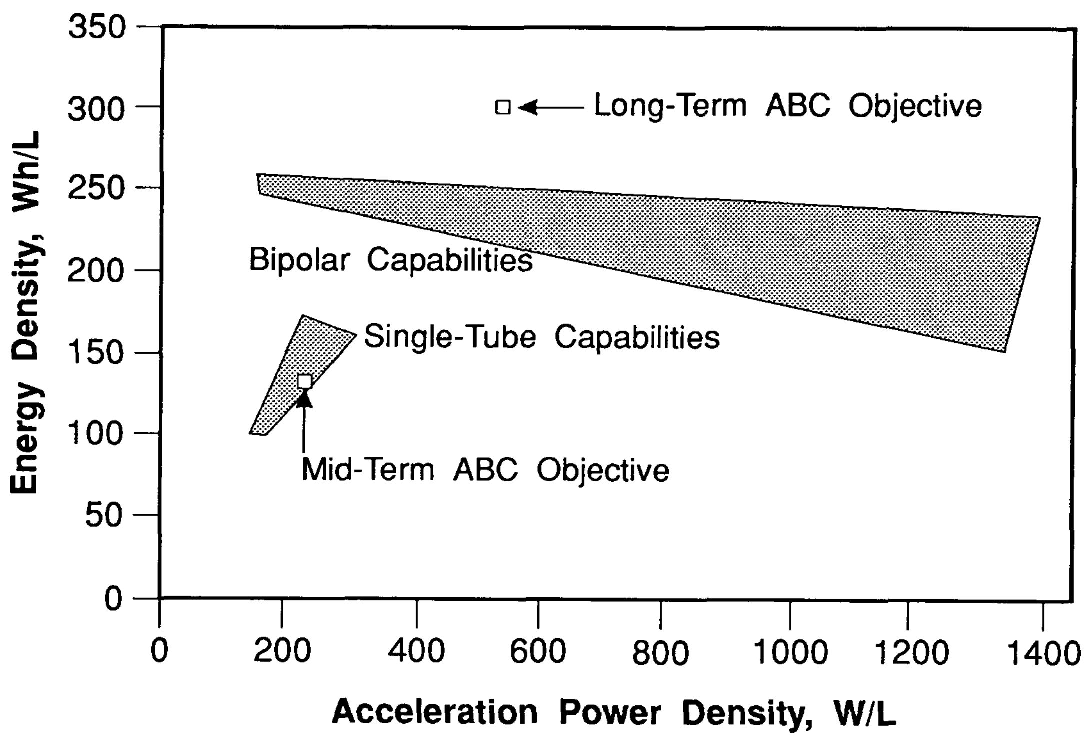


Figure 6. Performance projections for $Na/NiCl_2$ battery

6.0 VEHICLE SYSTEMS R&D

6.1 Modular Electric Vehicle Program

The Modular Electric Vehicle Program (MEVP) is an EV propulsion system development program in which the technical effort is contracted by DOE to Ford Motor Company. The General Electric Company is a major subcontractor to Ford for the development of the electric subsystem. The four-year research and development effort is cost-shared among Ford, General Electric, and DOE. The program objective is to bring electric vehicle propulsion system technology closer to commercialization by developing subsystem components which can be produced from a common design and accommodate a wide range of vehicles (i.e., modularized components). This concept would enable industry to introduce a wide range of electric vehicles into the marketplace sooner than would be accomplished via traditional designs because the economies of mass production could be realized across a spectrum of product offerings. This would eliminate the need to dedicate the design and capital investment to a limited volume product offering which would increase consumer cost and/or lengthen the time required to realize a return on the investment.

To the extent possible, components and technology developed in the First and Second Generation Single-Shaft Electric Propulsion System Programs have been employed. It is envisioned that a family of components could be developed that would satisfy small passenger vehicles, compact vans, and full-size vans. These components could be used 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 (minivan); and a 100-hp full-size van.

The project is divided into two phases. During FY 1991, Phase I, Preliminary System Studies, was completed, and the results were presented to DOE on April 3, 1991. Phase II, Component Design, Build, Integration, and Test, is currently in progress.

Table 6. Major Components Comprising the MEVP Propulsion system:

Powertrain • Motor/Transaxle Assembly - An AC induction motor integrated with a single-speed transmission on the drive axle of the vehicle (single-shaft); • DC to AC Inverter and Inverter/Motor Controller; and • Vehicle System Controller.
Battery Subsystem • Traction Battery; • Battery Controller; and • Battery Charger.
Ancillary Vehicle Subsystems • Power Steering; • Power Brakes; and • Climate Control.
Performance goals for the deliverable test-bed vehicles are: Acceleration to 50 mph in less than 18 seconds; 30 mph in less than 7 seconds Top speed 70 mph Gradeability limit ≥ 30% Automotive acceptable driveability Energy consumption 0.095 Wh/lbs-mi (from the battery on SFUDS) Range greater than 100 miles on SFUDS

The results of the Phase I activities 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 for this phase were the evaluation of fundamental concepts, the 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.

Table 7. MEVP Phase I R&D Major Issues and Conclusions

Powertrain system issues addressed during Phase I: • DC or AC system; • Single or multiple motor drive; • Single or two-speed transmission; • System voltage; • Maximum motor torque versus motor speed; • Maximum inverter voltage and current; • Battery energy and power; • On-board versus off-board charger; and • Transaxle maximum torque and gear ratio.
Conclusions drawn from this study dictated the following characteristics: • The modular powertrain is a viable concept; • AC system with an AC induction motor; • Single traction motor with a single-speed (12.2:1 gear ratio) transaxle; • System voltage of nominally 336 V; • Air cooling of inverter; and • On-board charger for charging the traction battery.
Modularity achievements expected from MEVP: • Transaxle modularity can be accommodated by load sharing through additional pinions; • Inverter rating can change as a function of output devices (power semiconductor and filter capacitor); • Motor parameters are close enough to yield acceptable compromises for 50 - 75 - 100 hp powertrains; • Modularity of battery design is limited to cells and enclosures; • Additional component variations can be accommodated through software changes for the system controller, inverter/motor controller, and battery controller; and • No changes are required for the charger, DC-DC converter, and contactor sized for largest application.

The Phase II efforts in progress focus on detailed designs of all components which make up the complete deliverable electric vehicles. These component designs are currently being implemented in hardware and bench tested. The fully developed components will be integrated into test-bed vehicle and tested as the program progresses.

Table 8. The status of Phase II efforts at the end of FY 1991 are as follows:

• Initial efforts concentrating on 75-hp design; • Specifications issued for all major components; • Overall vehicle system specification in process; • Motor/transaxle assembly designed, and prototype hardware built; • Inverter designed, and prototype hardware built; • Brassboard inverter/motor controls built; • Vehicle system controller designed, and prototype hardware built; • 75 hp prototype hardware testing in progress with prototype test-bed vehicle; and • Battery controls development begun.

Additional traction battery efforts consist of extensive interaction with battery suppliers to obtain design data for candidate technologies, and with USABC for guidance on battery technologies. Sodium-sulfur battery technology will be provided for the 75-hp test-bed vehicle.

A schematic of the MEVP propulsion system is shown in Figure 7, and a photograph of the 75-hp prototype motor/ transaxle assembly cutaway is shown in Figure 8.

Phase II efforts will continue during FY 1992, with completion of the 75-hp propulsion system design, build of the hardware, and integration into the test-bed vehicle. In addition, component design and packaging studies will commence for the 50-hp system.

6.2 Site Operators

Changes in the structure and organization of the Site Operator program begun in FY 1990 were continued during FY 1991. The Request for Proposal (RFP) issued at the end of FY 1990 resulted in the selection of ten organizations for participation in the Program. Financial Assistance Agreements were signed with these organizations during the year. These ten included seven new groups and three which were participating prior to the RFP. In addition to the three prior participants included in the new Financial Assistance Agreements, significant ongoing activities continued in four of the existing programs and these were carried over into FY 1992, resulting in a total of fourteen participants at the end of FY 1991. These four will be closed out during FY 1992, as the work is completed. The new structure includes three universities, a technical college, and six utilities. The physical locations of the participants provides a diversity of geographies and climatic conditions. Included are most of the worst air pollution non-attainment areas in the country, including Los Angeles, Phoenix, Houston, and the New York metropolitan area. The intent for these new grants includes one year funding with one year extensions for the following four years, contingent on available funding.

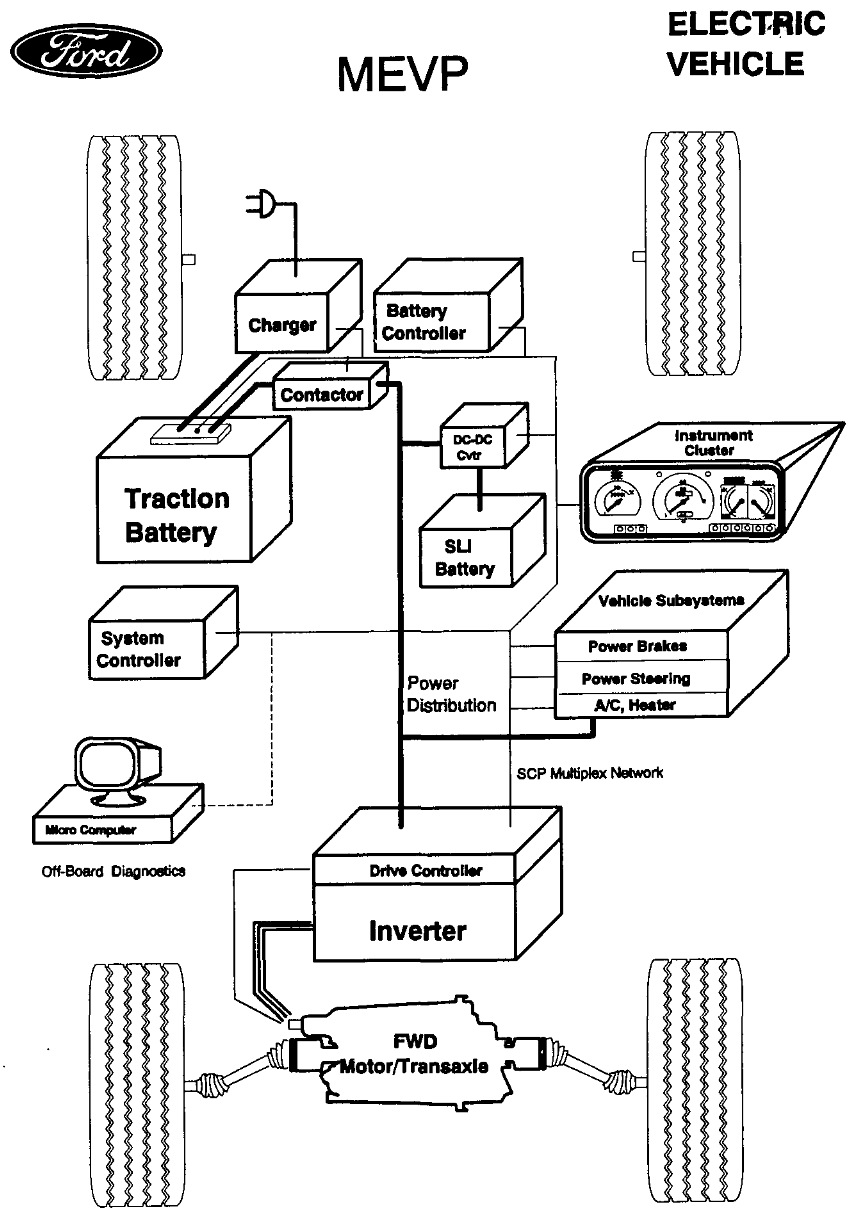


Figure 7. MEVP propulsion system schematic

Emphasis among the participants during the past year was concentrated on the new vehicles becoming available, particularly the Vehma manufactured G-Van. Seven of the ten Programs have G-Vans in use or on order, providing a group of over thirty of these vehicles--the first EVs to undergo National Highway Traffic Safety Administration crash testing and certification--for use across the country. The vans are in daily use in routine fleet operations and have been extensively demonstrated to the public in both static displays and "ride and drive" exhibitions. They have proved to be very popular with the owners, operators, and the public.

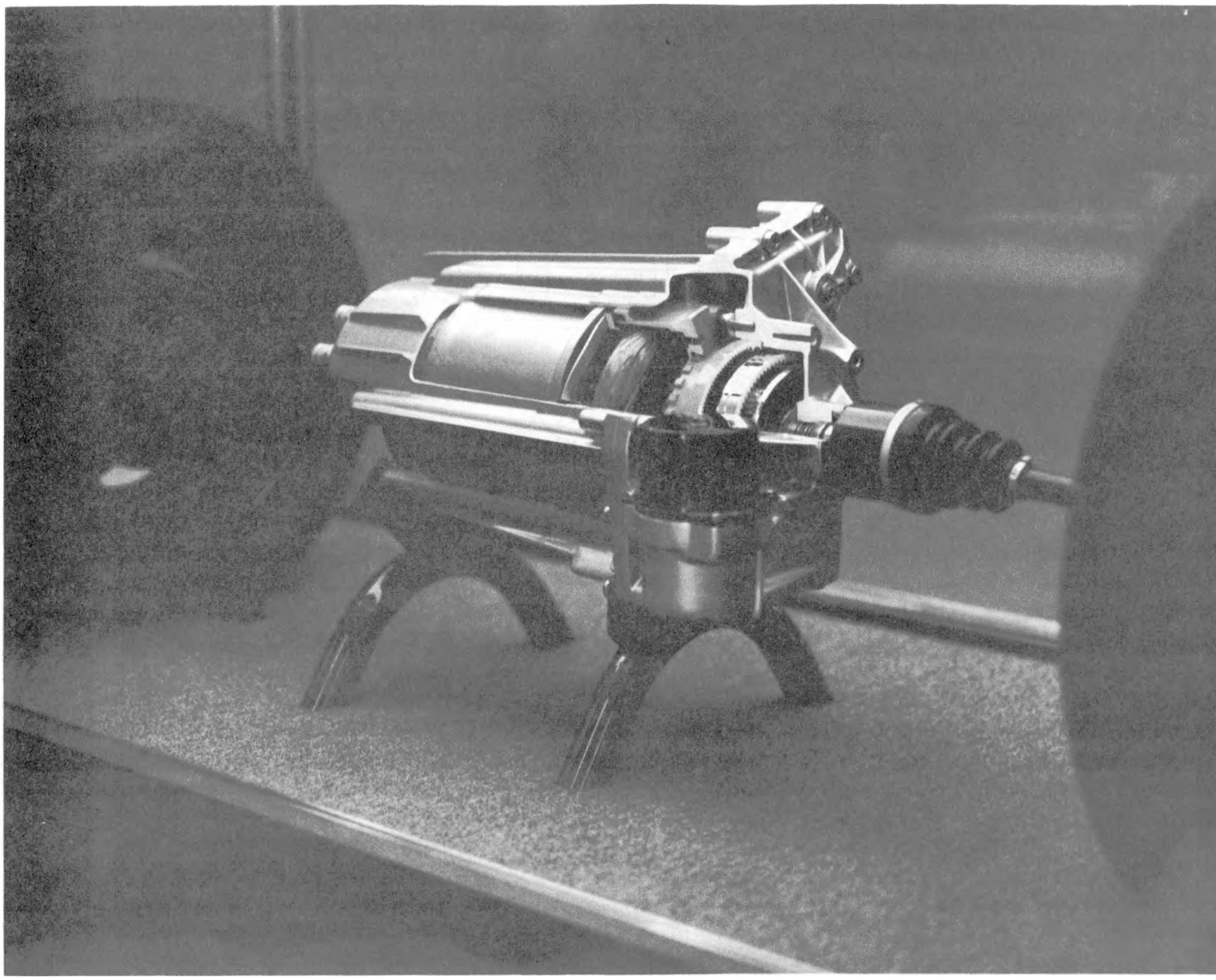


Figure 8. 75-hp prototype motor/transaxle assembly cutaway

Table 9 shows the participants in the program as of the beginning of FY 1992. The list is broken into two sections, showing the new organizations separate from those still operating under the older agreements.

Arizona Public Service (APS) has been part of the Site Operator Program since 1979. During that time it has accumulated over 400,000 miles on its EV fleet. APS currently operates a fleet of 14 vehicles and is involved at varying levels with seven more. These seven were previously part of the APS fleet and have been donated to other organizations. During this year APS has embarked on an aggressive program to increase public and organizational awareness and acceptance of EVs. This has included demonstrating, loaning, and donating vehicles to a wide group of organizations. These have included government agencies at the local, state, and Federal level; educational institutions; and private companies. On October 1st, APS hosted a convention in Phoenix, inviting a large group of EV manufacturers to demonstrate their products to a group of potential buyers. These activities have resulted in an expressed interest by several organizations to convert all or part of their vehicles to EVs. These organizations include the Grand Canyon National Park, Sky Harbor Airport in Phoenix, the City of

Phoenix, the State of Arizona, and others. APS is also involved with Southern California Edison Company and Dreisbach Electromotive Inc. (DEMI) in the development of a zinc air battery. In conjunction with this effort, APS has worked with Motorola in the development of a new generation of high current, high efficiency controllers for EVs.

Table 9. Electric and Hybrid Vehicle Program Site Operators (Operating During FY 1991)

New Site Operators	
Arizona Public Service Company*	
Kansas State University in cooperation with KEURP	
Orcas Power and Light Co.	
Platte River Power Authority	
Pacific Gas and Electric	
Public Service Gas & Electric Co.	
Southern California Edison Co.*	
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	
Holdover Site Operators	
Los Angeles Department of Water and Power	U.S. Navy
Sandia National Laboratories	University of Hawaii

* Participated under prior program

The program at Kansas State University (KSU) includes a close cooperation with the Kansas Electric Utilities Research Program (KEURP) and several private sector companies. KEURP is a contractual joint venture between six major electric utilities within Kansas. The initial KSU program will involve demonstration, test, and evaluation of two vehicles, a G-Van and a second vehicle, which will not be a G-Van. Additional vehicles will be added to the fleet during the out years.

Orcas Power and Light Co. (OPALCO) provides two unique opportunities to the Site Operator Program. The utility serves a group of 20 islands in the San Juan Straights area of Washington. The largest of the islands is approximately 40,000 acres (62 sq. mi.). Speed limits in the area range from 25 mph to a maximum of 45 mph. High gasoline prices, low electric rates, and short driving distances have created a spontaneous interest among the residents in EVs for use on the islands. In response to this interest, the utility will test and evaluate two vehicles, with a major objective of encouraging EV use among the residents. This provides the possibility of developing an area in which a significant portion of the vehicles are EVs, the first such location in the country. In addition, OPALCO is a priority-firm customer of the Bonneville Power Administration (BPA). The BPA has expressed an interest in the OPALCO program, with the intention of using its results as a basis for introducing EVs into the BPA service area, which includes the Northwest part of the country.

The Platte River Power Authority is located in Ft. Collins, CO, which is located at the foot of the Rocky Mountains, 60 miles north of Denver. This location provides the Site Operator Program with an opportunity to obtain operating information on vehicles used in a mountainous, cold weather environment. Platte River is in the process of obtaining a hybrid vehicle, which will be assigned to their fleet.

Pacific Gas and Electric Company (PG&E) is operating a group of prototype and production G-Vans in the San Francisco Bay area. The vehicles are owned by PG&E and public agency fleets in the area. Operations are being conducted from the dedicated PG&E facility at San Ramon, located on the east side of the bay, approximately 20 miles east of Oakland.

Public Service Gas and Electric Company (PSE&G) is located in Newark, NJ, and serves approximately 75% of the New Jersey population. The company has purchased and operates a fleet of eight G-Vans in the corridor extending from Philadelphia to New York City, an area with significant air quality problems. PSE&G is operating its EV fleet in cooperation with several local utilities as part of a regional users group that includes the New York State utilities.

The Southern California Edison Company (SCE) continues to be one of the leaders in the effort to commercialize the EV concept. With a fleet of 18 G-Vans, SCE operates one of the largest fleets in the country, and the largest group of a single type of vehicle. The vans are used within the SCE fleet and loaned to organizations throughout the SCE service area. Through the loan program, which provides a vehicle to an outside organization for 3 weeks, the company has introduced over 50 private companies and government agencies to EVs. In addition to the G-Van program, SCE is supporting DEMI in the development of the zinc air battery.

Texas A&M University, through the Texas Engineering Experiment Station, has organized the South Central Electric Vehicle Consortium, a group of utilities and government agencies in Texas and the four adjoining states. Fleet activities are centered around 12 G-Vans located at six sites around Texas. The sites range from Houston, a major air quality non-attainment area, to Amarillo, in the northern panhandle of the State. Activities include fleet operation of the vans, as well as public demonstrations and a loan program with other organizations in the areas where the vans are located.

The University of South Florida (USF), in cooperation with the City of Tampa and Florida Power Corporation, has begun a program directed at introducing EVs to the Tampa metropolitan area. In addition to the operation and demonstration of the vehicles, USF is working toward the demonstration of the feasibility of using solar-powered charging stations for opportunity charging of their vehicles. In connection with this work, USF has agreed to move the solar charging station originally planned for the U.S. Navy project on Bermuda to a location in the Tampa area.

York Technical College (York) has obtained an extension from the Department of Transportation for the five Griffon vans. The original waiver was to expire September 30, after which the vehicles could no longer be used on public roads. The extension allows the vehicles to be driven for an additional year. Two of the vans will be operated by the City of Rock Hill, SC, the other three by Duke Power Corp. York will continue to collect the operating data. York is also operating and maintaining the DOE G-Van until a location in Washington, D.C., can be located to house the vehicle.

Sandia National Laboratories currently operates a fleet of 11 Jet Electrica sedans. All 11 of the vehicles are in routine use with missions ranging from daily commuting to travel to and from remote construction sites. Since the beginning of the EV program at Sandia in the early 1980s, the vehicles have accumulated a total of over 80,000 miles with no significant maintenance problems. The vehicles have replaced internal combustion engine (ICE) vehicles and demonstrated a capability to perform an assigned mission and provide operator satisfaction. The vehicles have been in use since 1981 with no unusual maintenance. Activities during FY 1991 included upgrading the appearance and performance, including new paint and new electronics.

The EV program at the University of Hawaii continues to center around the field testing of traction batteries. The island location provides a unique opportunity for testing batteries and vehicles in an environment with limited range requirements.

The Navy has decided to halt work on the solar-powered, battery-charging station on Bermuda. The equipment will be dismantled and shipped to the University of South Florida for inclusion in their Site Operator Program. During FY 1990 the Navy purchased three G-Vans for use at the Long Beach Naval Shipyard.

Los Angeles Department of Water and Power (LADWP) currently operates a fleet of six preproduction G-Vans which are used both by Department personnel and on loan to outside organizations. LADWP is also doing a long-term evaluation of one of the Dual Shaft Electric Propulsion (DSEP) vehicles built by Eaton Corp. for DOE. The DSEP vehicle has developed a few minor problems typical of a prototype vehicle, but overall performance has been very good. LADWP reports the vehicle has much better performance for both acceleration and range than any of the other vehicles they have tested.

6.3 Engineering Evaluation Testing

Under the Engineering Evaluation Testing activity, dynamometer and laboratory tests are conducted to evaluate technology outputs in circumstances that duplicate or simulate actual EV operation and environments under repeatable and well defined conditions. For this reason, 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.

The Department of Energy selected the Idaho National Engineering Laboratory in FY 1984 to perform these testing activities, and dynamometer and battery test laboratories were established for this purpose. The laboratory facilities permit the testing of vehicles and complete battery subsystems under simulated load conditions that closely approximate the demands of EV operations. Typical standard driving profiles on which vehicles are routinely tested are the Society of Automotive Engineers (SAE) electric vehicle driving cycles (SAE J227a) and the SFUDS. Special tests are also developed and performed, depending upon the need. In the past, special tests were 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 1990, the INEL chassis dynamometer was extensively overhauled. A new- generation dynamometer system controller was installed in FY 1991. In addition to the new chassis dynamometer system controller, the data acquisition processing and display capabilities of the dynamometer laboratory were enhanced with the installation of an integrated laboratory data acquisition system. The Laboratory Data Acquisition System (LDAS) is based on the Imagination Systems Inc., Autonet Data Acquisition System software in conjunction with a Neff System 470 data acquisition unit and a 32-bit Intel 80386-based workstation. The operating system provides a real-time, multi-user, multi-tasking, and networkable operating environment. The LDAS acquires and logs data, monitors for alarms, and displays "real time" and/or historical data via high-resolution graphic displays. The capabilities of the system to support dynamometer tests are shown in Table 10.

Table 10. Capabilities of the Dynamometer Laboratory Data Acquisition System

- Samples up to 96 analog input channels at +/- 10mv to +/- 10 volt full scale;
- Samples 18 input pulse channels (0-50 khz);
- Two analog output channels which may be programmed to reproduce input parameters;
- Eight relay outputs for process control;
- Data logging routines that allow the operator to pre-establish data logging rates;
- Event-based data logging at a maximum aggregate rate of 10,000 samples per second;
- File transfer to other CPU systems;
- Logs actual channel values and "calculated values"; and
- Remote video monitors used by the vehicle driver to maintain cyclic driving patterns and observe pertinent vehicle-measurement parameters.

The new laboratory data system substantially increases the reliability and automation of data processing and analysis activities. Improved measurement equipment and methods will continue to be developed to provide the capability required for testing state-of-the-art AC electric propulsion systems such as the one found in the Ford ETX-II vehicle.

In FY 1989, a component test capability was added to the existing chassis dynamometer, which permits the performance characterization of certain types of EV components such as motors, transmissions, etc., while preserving the ability to test complete vehicle systems. In FY 1990, component dynamometer functional tests were conducted to test their capabilities. Components within the power limitations of the dynamometer can now be evaluated for their suitability in electric drive train use.

In the last quarter of FY 1990 and continuing into FY 1991, an extensive series of track and dynamometer performance tests were conducted on the final test-bed vehicles (TB-2 and NVH) delivered to the DOE by the Eaton Corporation at the completion of the DSEP program. These tests confirmed the excellent performance projected for the DSEP propulsion system in a small van. The test program included a series of SFUDS cycles, constant-speed tests, SAE J227a C and D cycles, and acceleration tests on the chassis dynamometer. Track tests included coastdowns, gradeability, acceleration, constant speed, and brake performance tests (tested both with and without regeneration). A summary of the test results is presented in Table 11.

Due to the significant amount of time required to perform the installation and verification testing of the new chassis dynamometer system controller, and the laboratory data acquisition system upgrade, the INEL Electric Hybrid Vehicle Program was unable to complete the performance testing of the Ford ETX-II test-bed vehicle and CSPL sodium-sulfur battery in FY 1991. However, testing of the ETX-II test bed is expected to be completed by the end of the first quarter of FY 1992. Preliminary results indicate that the vehicle meets or exceeds the established DOE goals for the ETX-II Propulsion System Program.

Table 11. DSEP Performance versus Program Goals

	DOE Goal	Actual Performance
Acceleration (0-80 km/h)	20 sec.	18 sec.
Gradeability @ 88 km/h	3%	4%
Gradeability limit	30%	32%
Top Speed	96 km/h	120 km/h
Payload	545 kg	545 kg
SFUDS Energy Consumption	280 Wh/km	296 Wh/km
Range of SFUDS	80 km	*50 km

* Battery at less than 60% of rated capacity

6.4 EV Air-Conditioning Study

The Arthur D. Little study of advanced technology for air conditioning and heating of electric vehicles was completed, and a report entitled "Study of Long Term Options for Electric Vehicle Air Conditioning" (EGG-EP-9831, July 1991) was issued. The study showed that a significant improvement in the vehicle range reduction due to climate control energy demands could be achieved by utilizing improved insulation, glazing properties, and ventilation in the vehicle design. Evaluation of various advanced cooling approaches, such as evaporative cooling, air-cycle heat pumps, and magnetic refrigeration, indicated that improved conventional systems utilizing low chlorofluorocarbon refrigerants offered the best potential for cost-effective, efficient heating and cooling of electric vehicles.

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.

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 seven-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 1989. A new method for calculating the electric-vehicle, CAFE-equivalent fuel economy will be ready for proposed rulemaking in the spring of 1992.

Planning Grants

There was no activity in this incentive program during FY 1991.

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).

Since inception of this program in FY 1979, 10 formal applications were provided to DOE, and two loan guarantees were issued, but both were later terminated due to default. The assets of one company were liquidated in 1982, recovering approximately $83,000, but resulting in a net loss to the Government of $2,363,000. A workout agreement was negotiated in January 1983 with the second company (Jet Industries), providing for full payment of the $2,170,000 principal outstanding pending liquidation of real estate and other assets. The workout agreement provision that gave Jet Industries the exclusive right to sell the real estate expired on September 1, 1990. DOE is currently working with the General Services Administration to dispose of the property and recover the assets.

8.0 STUDIES AND ASSESSMENTS

8.1 Hybrid Vehicle Evaluation

During FY 1991, DOE began a study of the viability of a Range Extender Vehicle (REV). The purpose of this study is to provide an initial evaluation of the REV concept, primarily through a comparative analysis with EVs and ICE vehicles. In this analysis, a series of baseline conceptual REV designs (passenger car, truck, and minivan) are included, as are conceptual designs of comparable EVs. The study takes a near-term approach for the REVs, focusing upon how the first (next) REVs introduced might be configured and operated. The analysis focuses upon range (the primary impetus for the REV), but also includes other performance and cost comparisons. A survey of existing and planned electric and hybrid vehicles, systems, and components is being performed to provide the data for the designs.

In addition to the baseline designs, the comparative analyses extend to different operating strategies and substitution of various components. This is done to identify the impact of these changes upon the baseline REV, especially in the area of future component technologies (such as engines for generator sets and batteries).

The results of this study will be presented in a final report, which is due to be completed in FY 1992.

8.2 Battery Test Task Force

The EHP Battery Test (Working) Task Force was formed in 1983 to coordinate the battery evaluation work at DOE- and EPRI-funded laboratories. Present member laboratories are ANL, INEL, LANL, SNL, and Electrotek. The group has met approximately twice each year since its formation to discuss testing procedures, results, reporting methods, and special techniques.

During FY 1991, the key accomplishments of this group were the agreement among the DOE laboratories on a general test plan for characterizing electric vehicle batteries and the adoption of the SFUDS battery-discharge profile for cycle life testing.

8.3 Data Base Development

INEL continued the development of a PC-based data base for storing the physical characteristics and charge/discharge data for the various batteries that have been tested for EV applications at DOE laboratories.

Programming of the menu system for the INEL battery test database was completed during the second quarter of FY 1991, and Version 1.0 of the Electric and Hybrid Vehicle Program Battery Test Data Database was released to DOE on April 30, 1991. Version 1.0 is a stand-alone computer database contained in compressed files on a single floppy disk. The database includes test data summary tables for over 40 battery packs. However, no detailed test data were included because the large volume of data was impractical to include on floppy disks.

A computer demonstration of the database software was presented to the Battery Working Test Task Force at a June 4, 1991, meeting at INEL. The version demonstrated was enhanced to include access to the detailed test data files. The demonstration was well received, and considerable interest was shown by Task Force members in possible network and dial-in telephone access to the database. Development of a network capability version is currently in progress.

INEL continued development of the PC-based electric vehicle simulation program, SIMPLEV. The capability of the program was extended to include advanced batteries and an on-board auxiliary power unit for range extension. Further work was done to include detailed treatment of ultra capacitors and pulse batteries to load-level the traction battery in the electric vehicle propulsion system.

8.4 Environmental Impact

The National Renewable Energy Laboratory (NREL), formerly SERI, is conducting environmental, health, and safety (EH&S) assessments of advanced batteries for electric vehicles. The focus of these assessments for FY 1991 was on sodium-sulfur batteries, particularly the EH&S issues relevant to cell and battery design, shipping, in-vehicle use, and recycling and disposal. Reports on these four EH&S aspects of sodium-sulfur batteries will be published in FY 1992.

In conducting the EH&S analyses of sodium-sulfur cell and battery design, NREL examined the literature on inherent material hazards, cell components and failure modes, and cell and battery safety testing. Cell components considered critical to safety were the beta-alumina electrolyte, the alpha alumina-beta alumina glass seal, the metal-to-alpha alumina seal, and the cell container-sulfur electrode. Cell safety testing issues examined were life testing, failure testing, and thermal (freeze-thaw) cycling. Battery safety issues considered included mechanical and electrical interconnection of cells, electrical and thermal insulation, thermal management, failure propagation, and integrity of the battery enclosure. Also analyzed were safety testing of prototype batteries under mechanical shock, physical deformation of the outer container, external short-circuiting, inversion, vibration, and exposure to fire and high temperatures.

For shipping sodium-beta (sodium-sulfur and sodium metal-chloride) cells and batteries, NREL reviewed U.S. shipping regulations for hazardous materials and recent revisions to these regulations promulgated by the Department of Transportation (DOT). NREL is working with ANL to review the shipping requirements for sodium and sulfur and the process for obtaining general exemptions from DOT, and a new regulation through the DOT-UN rulemaking process. For in-vehicle safety, NREL reviewed the Federal Motor Vehicle Safety Standards (FMVSS) as well as potentially applicable standards issued by such organizations as the Society of Automotive Engineers and the National Electrical Manufacturers Association. NREL is working with INEL to conduct this study. For recycling and disposal, NREL and SNL are reviewing recent EPA regulations controlling the recycling and disposal of sodium-sulfur batteries and studying cost-effective chemical processing options.

A study of the impact of electric vehicles on CO_2 emissions was started with Arthur D. Little. This study will evaluate the effect of various electric vehicle, power generation, and alternative fuel technologies on total greenhouse gas emissions from various types of vehicles for several commercialization scenarios in the time period 2000-2025.

Also during FY 1991, NREL initiated an environmental assessment of fuel cell technologies to identify critical environmental, safety, and health issues involved in the use of fuel cells for transportation applications.

8.5 EV Battery Readiness Working Group

The EV Battery Readiness Working Group was convened in May 1990 to initiate a government-industry effort to identify regulatory issues associated with the safe shipment, in-vehicle use, and recycling/disposal of sodium-beta batteries. The mission of the Working Group is to assist in the development of Federal regulations to address EH&S issues in these three areas. The Working Group consists primarily of representatives from battery developers, automobile manufacturers, Federal agencies, and national laboratories. At the May 1990 meeting, sub-working groups on shipping, in-vehicle safety, and recycling were formed to develop implementation plans to address the most important regulatory issues in these three areas.

The second meeting of the Working Group was held in May 1991, after a meeting scheduled in January 1991 was canceled due to the restrictions and precautions on air travel instituted during the Persian Gulf crisis. In the second meeting, the sub-working groups finalized implementation plans and established task schedules based on an anticipated time frame for commercial-scale use of sodium-beta batteries in electric vehicles. The third meeting of the Working Group is scheduled to be held in January 1993.

The Shipping Sub-Working Group will carry out several activities: provide organizational and technical support as needed to facilitate collection of needed information for regulatory applications; facilitate the preparation and submission of regulatory applications for general exemptions and for DOT regulations; identify and secure an official sponsoring organization; establish the scope of ruling(s) sought; identify potential hazards posed during shipment; develop and conduct standard tests to demonstrate that these hazards are acceptably low; prepare and submit applications for new regulations based on the results of the hazard tests.

The In-Vehicle Safety Sub-Working Group will work with industry to analyze hazards associated with batteries in electric vehicle propulsion, with battery-specific emphasis on sodium-beta technologies. The objective of this analysis is to develop a comprehensive framework for safety testing and demonstration of Na/S batteries and Na/S-powered EVs. It is expected that such a framework will help establish a testing program to meet the FMVSS and address public perception of safety of both Na/S batteries and Na/S-powered EVs.

The Recycling/Disposal Sub-Working Group will work with EPA's Office of Solid Waste to provide a simplified definition of disposal requirements that takes into account expected regulations at the end of the decade and information on interim storage and demonstration-phase process licensing. The Sub-Working Group will also analyze the technical, regulatory, and institutional issues involved in recycling Na/beta batteries and the feasibility of recycling as an alternative to disposal that will also avoid regulation under the Resource Conservation and Recovery Act.

8.6 Direct Electrochemical Oxidation of Methanol

There are two approaches one can take to achieve reformerless fuel cell operation in vehicles. The first is to reform fossil-based fuels off-board to produce hydrogen. The second approach is to develop a direct methanol-air fuel cell (DMFC) capable of electrochemically oxidizing methanol to carbon dioxide at the anode. The advantages of the DMFC-powered vehicle are similar to those of the off-board reformer concept. It will eliminate the need for the reformer and the selective oxidizer on-board the vehicle, resulting in a weight and volume reduction of approximately 30% and an efficiency improvement of 10%. In addition, the DMFC approach eliminates the need for cost-effective hydrogen storage technologies. These benefits will only be realized, however, if a DMFC demonstrates performance capabilities comparable to those of the PEMFC operating on reformat with similar life-cycle costs. Such a DMFC does not exist at present.

A workshop was held on May 14 through May 16, 1990, to discuss the feasibility of developing a viable DMFC and to prioritize research and development issues that must be undertaken to accomplish such a goal. This international workshop attracted approximately 50 participants from academic institutions, industry and government laboratories, reflecting strong, worldwide interest in DMFC technology.

The workshop concluded that a targeted program to develop DMFCs for transportation program is warranted. The primary emphasis of such a program on DMFCs must be on:

- Developing new high-performance and cost-effective catalysts for methanol oxidation.
- Identifying an appropriate electrolyte for the DMFC system.

Progress in these two areas is essential before the stacks can be tested and evaluated and some of the pertinent systems issues addressed.

8.7 Ambient-Temperature Rechargeable Lithium Batteries

The lithium-solid polymer electrolyte electrochemical system offers great promise as an electric-vehicle battery. It is, however, in the early stage of development, with only small coin-type cells and other basic electrochemical designs available for characterization. At the request of the Electric and Hybrid Propulsion Division of the Department of Energy, Sandia National Laboratories conducted a technology assessment of ambient-temperature rechargeable lithium batteries for EV application. During FY 1991, the technology evaluation was completed and the assessment report, SAND 91-0938, was published.

9.0 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.

10.0 RECOMMENDATIONS FOR INITIATIVES

The Department of Energy is not considering any new legislative initiatives to further the purpose of the Act. The current legislation provides sufficient flexibility to the program to stimulate the advancement of EHV technologies to the point at which the private sector can determine their viability as transportation options and continue their development into marketable products. The President's FY 1992 budget request incorporates the restructured Electric and Hybrid Vehicles R&D Program, with a significant increase in funding (and a further increase planned for FY 1993), but no new legislation will be needed to accomplish this.

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