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Electric and Hybrid Vehicles Program

13th Annual Report to Congress for Fiscal Year 1989

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Assistant Secretary, Conservation and Renewable Energy
Office of Transportation Systems
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PREFACE

This thirteenth annual report on the implementation of the Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976 (Public Law 94-413), referred to 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.

During FY 1989, significant progress was made in this program. There has been continuing interest shown by both the automobile manufacturers and supply sectors of our economy in electric and hybrid vehicles. The three major domestic automobile manufacturers all are devoting some effort towards electric vehicles. Their participation includes cost-shared contracts with the Department of Energy and the Electric Power Research Institute as well as independently funded activities. Research and development efforts in batteries and propulsion components continue to achieve significant progress in providing industry with technology options that will result in vehicles that will be more economically competitive and more acceptable to the public.

1. 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.

The transportation sector is the single, largest user of petroleum; it consumed 63% of all petroleum used last year. Only a small fraction (5%) of electricity is generated from petroleum. Electric vehicles (EV), which are themselves virtually pollution-free, present an excellent link between low petroleum electricity generation and the high use of petroleum by the transporation sector. Electric vehicles could play a key role in helping to reduce our severe urban pollution problems and dependence on petroleum, particularly imports. It is the program's goal to develop the technology in cooperation with industry that will lead to the production and introduction of pollution-free electric vehicles into the Nation's transportation fleet and substitute cleaner 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...". Congress provided an appropriation for the Electric and Hybrid Vehicles Program of $13.9 million in FY 1989. The FY 1988 appropriation for this program was $14.1 million.

The Electric and Hybrid Propulsion Division within the Office of Transportation Systems is assigned to manage the program. Some supporting battery research has been conducted by the Office of Energy Storage and Distribution. 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 are listed in Table 1. They include major automotive companies, battery companies, component and propulsion system companies, universities, and electric vehicle users from private firms, utilities, the U.S. Navy and State and local government agencies. On Table 1 the cost sharing commitment of the participants is also given. Figure 2 is a milestone chart of major programmatic efforts completed and planned under each of the program elements.

The emphasis of the Electric and Hybrid Vehicles Program in FY 1989 continued to be on battery and propulsion systems development up to the level of the testing and evaluation of proof-of-concept vehicles in the laboratory and in fleet operations. The progress being made in developing electric and hybrid vehicle technologies will be described, beginning with highlights of recent accomplishments in FY 1989. Detailed descriptions of the program activities during FY 1989 will be given on battery and propulsion systems developments and the testing and evaluation of new technology in fleet site operations and laboratory testing. In accordance with the reporting requirements of the Act, the 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.

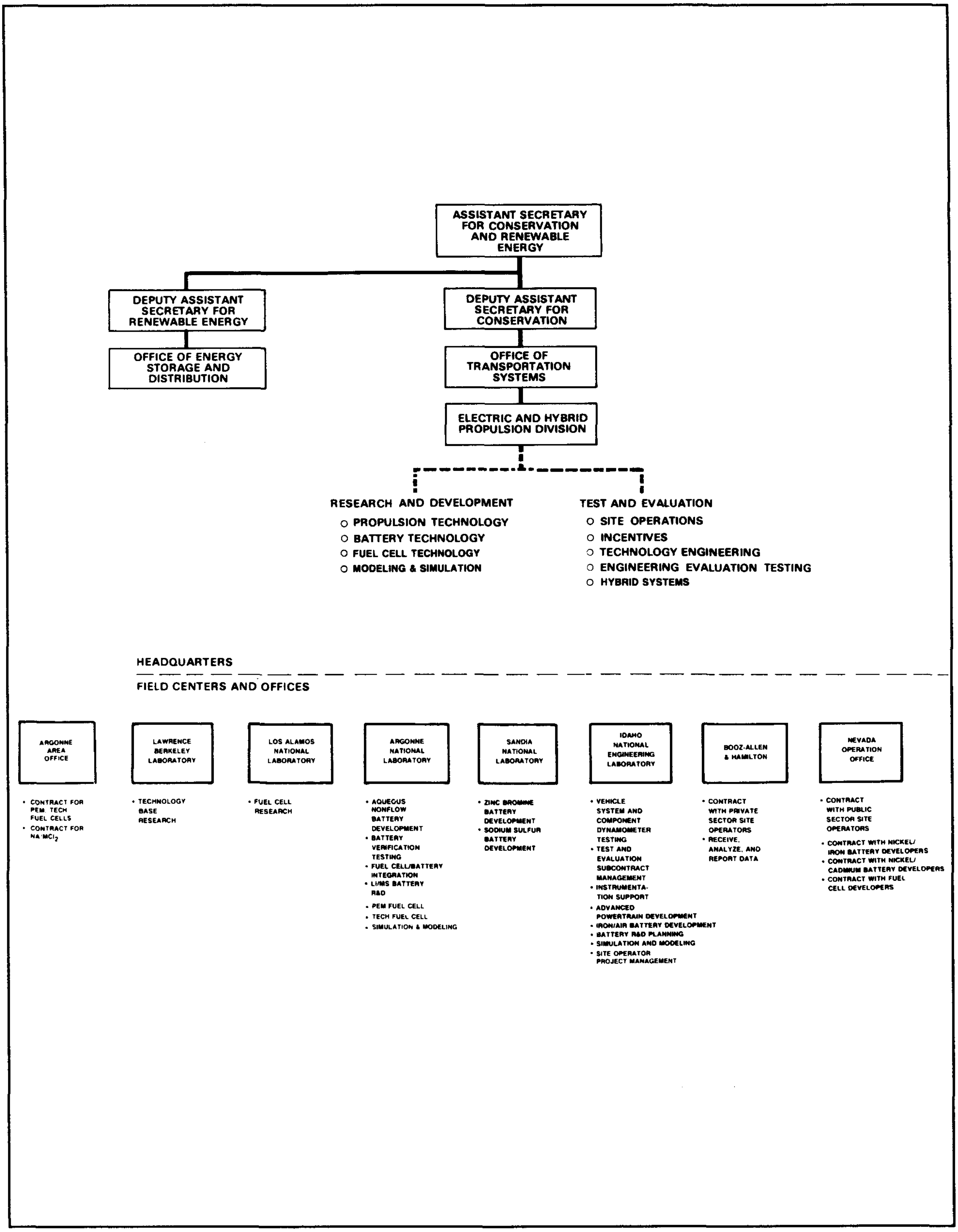

Figure 1: EHV Program Structure

Table 1

Major Participants in the Electric and Hybrid Vehicles Program

Automotive Companies	**Cost Share of Contract***
Ford Motor Company	5%
Component and Propulsion System Companies	
Delco/GM	50%
Booz-Allen & Hamilton (BA&H)	32%
Eaton Corporation	5%
Energy Research Corporation (ERC)	27%
General Electric (GE)	5%
Battery Companies	
Beta Power, Inc.	25%
Chloride Silent Power Limited (CSPL)	19%
Eagle-Picher Industries (EPI)	5%
Johnson Controls, Inc. (JCI)	25%
Westinghouse	8%
Universities	
Georgetown University (GU)	14%
Massachusetts Institute of Technology (MIT)	
University of Alabama (UAH)	
Virginia Polytechnic Institute (VPI)	
University of Florida	
Fleet Testing Site Operators 1/	
GTE	73%
Long Island Lighting Co.** (LILCO)	60%
Detroit Edison (DECO)	60%
Arizona Public Service (APS)	42%
University of Hawaii	38%
City of Alexandria, Virginia**	50%
United States Navy	80%

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 1989

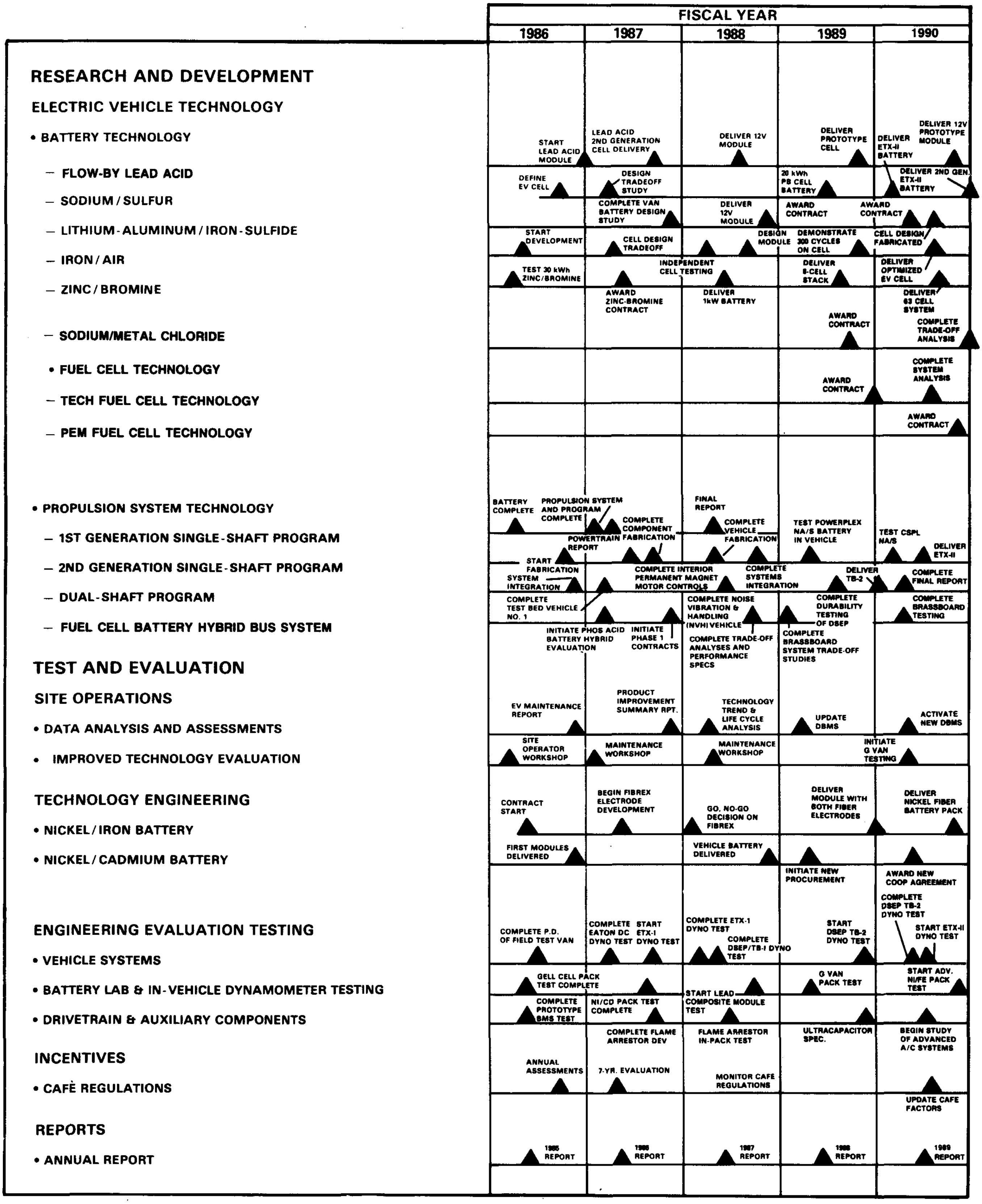

Figure 2: Milestone chart

2. FY 1989 Accomplishments

Significant progress was made in each of the Electric and Hybrid Vehicles (EHV) Program areas during FY 1989. The following are highlights of achievements.

Research and Development

- Johnson Controls, Inc. (JCI) fabricated and delivered two flow-by cells and a 6-volt flow-by module based on the use of a forced electrolyte flow. Test results obtained at Argonne National Laboratory (ANL) indicated that the performance of these cells are able to meet the peak power requirements of the Simplified Federal Urban Driving Schedule (SFUDS) at up to 96% depth-of-discharge.

- Testing of a 36-volt lithium/iron sulfide module manufactured by Westinghouse Ocean Systems Division and a vacuum-insulated case developed by Meyer Tool and Manufacturing, Inc. was completed at Argonne National Laboratory.

- DOE initiated a joint program with the Electric Power Research Institute (EPRI) to complete the development and evaluation of a full-scale proof-of-concept lithium-alloy/iron sulfide battery for an electric van.

- Westinghouse Electric Corporation directed its iron-air battery research and development (R&D) efforts at increasing the power and extending the cycle life of practical bifunctional air electrodes. Cycle life was doubled from 150 to 300 for 40 cm^2 air electrodes operating at constant current in half-cell tests.

- A 64-volt, sodium-sulfur EV battery fabricated by Chloride Silent Power Limited (CSPL) successfully completed over 200 test cycles at ANL. Results of simulated electric vehicle driving tests indicate a projected range of 148 miles for an electric van on the Federal Urban Driving Schedule.

- Johnson Controls, Inc., continued the engineering design of the zinc-bromine battery and began the fabrication of a flow frame specific for EV applications. The R&D program encompassed the development of almost every component of the battery and included studying efficient means of battery packaging for an EV.

- A cost-shared, one-year contract for a design study of high-performance sodium/metal chloride batteries for electric vehicles was awarded in August 1989 by DOE to Beta Power Inc.

- DOE awarded a two-year, 50% cost-shared, contract in September 1989 to the Delco Remy and Hughes Divisions of General Motors for the development of a thermoelectrochemical (TECH) system for transportation applications.

- The electric vehicle analysis software package (MARVEL) developed by ANL was upgraded with additional battery and vehicle datasets to reflect recent progress attained in battery and EV technologies.

- The second Dual-Shaft Electric Propulsion (DSEP) vehicle successfully underwent limited durability and system reliability and compatibility testing in all weather conditions at the Chrysler Chelsea Proving Grounds in Chelsea, MI. Also, the vehicle either met or exceeded the program goals during performance testing.

- The third vehicle in the DSEP Technology Development Program was completed and delivered to Idaho National Engineering Laboratory (INEL) for extensive test and evaluation. The completion and delivery of TB-2 marked the end of the 64-month development effort with Eaton Corporation.

- All subsystems developed in the Single-Shaft Electric Propulsion System (ETX-II) Technology Development Program were integrated into the testbed Aerostar mini-van and extensive control software development was initiated.

- A sodium-sulfur battery developed for electric vehicle application was evaluated successfully in the ETX-II testbed vehicle. Chassis dynamometer tests indicate that this battery (in combination with the energy efficient powertrain) will provide a range of over 160 km (100 miles) on the Federal Urban Driving Schedule (FUDS).

- The team of Booz-Allen & Hamilton, Chrysler Pentastar Electronics, and Fuji Electric completed the design and fabricated a brassboard system of a liquid-cooled phosphoric acid fuel cell/battery propulsion system for an urban bus.

- The team of Energy Research Corporation (ERC), Los Alamos National Laboratory, and Bus Manufacturing, Inc. completed the design and fabrication of a brassboard system of an air-cooled phosphoric acid fuel cell/battery propulsion system for an urban bus.

Test and Evaluation

- Project and contract management of the Site Operator Program was moved from Booz-Allen and Hamilton Inc., to Idaho National Engineering Laboratory. Each of the Site Operators was issued a new contract with E.G.& G. Idaho to continue their fleet testing of electric vehicles.

- New software was developed by DOE for the Site Operator field test data. The software places the actual database in the hands of each fleet manager for entry and access of data. INEL will maintain a master file to be used for analysis.

- The test period for the six GM Griffon vans located at Detroit Edison was extended to 1991. The vans continue to operate reliably in a variety of missions including commuting, demonstrations, delivery and special testing. Detroit Edison also completed the testing of the Chloride EV Systems Indirect Battery Heating System and the Aachen Range Prediction Device.

- The Energy Research Corporation completed the DOE contract to develop and build an electric vehicle sized nickel-cadmium battery based on their roll-bonded technology. Two battery modules were delivered for testing and a final report was submitted to INEL.

- The University of Alabama at Huntsville (UAH) successfully tested a single wire data collection system to replace a multi-wire harness used by the charge controller to monitor module voltages and the ability of their system to control the simultaneous charge of multiple vehicles.

- Experimental nickel-iron batteries constructed by Eagle-Picher Industries (EPI) with fiber electrodes successfully completed over 800 cycles in tests conducted at Argonne National Laboratory.

- INEL conducted a series of performance tests on a DC powertrain in an electric passenger car, incorporating an inverter driven air conditioner and electric heater/defroster. The vehicle was built by the Soleq Corporation and purchased for use in the Site Operator Program by Arizona Public Service.

- A series of acoustic noise tests conducted by INEL determined that interior and exterior noise levels in an electric passenger vehicle were noticeably lower than a comparable internal combustion engine (ICE) vehicle during acceleration and idle conditions, while essentially equivalent at constant speeds.

- INEL conducted a series of performance tests on a DC propulsion system developed by the Soleq Corporation with partial DOE sponsorship and installed in a full size van. The system incorporated two parallel battery packs for enhanced reliability and a modified automatic transmission with no torque converter.

- The INEL battery laboratory tested a number of near-term or commercially available batteries to determine their suitability for electric vehicle applications, including sealed lead-acid batteries built by Johnson Controls, Concorde and Sonnenschein.

3. Research and Development

Research and Development activities are conducted to advance the technology to the point that transfer to the automobile industry for application-oriented R&D becomes feasible. The functions are carried out in the following elements: Battery Technology, Fuel Cell Technology, and Propulsion System Technology. The activities conducted in FY 1989 within each of these R&D elements are described below.

Battery Technology

The objective of the Battery Technology Research and Development Activity is to advance promising battery technologies to levels of maturity that will allow industry to make quality decisions regarding their potential viability as foundation technologies for commercial product development. To this end, research and development was conducted on flow-by lead-acid, lithium aluminum/iron sulfide, sodium/metal chloride, sodium/sulfur, zinc/bromine and iron/air battery technologies during FY 1989. Major R&D contracts have been awarded to industrial developers of these batteries for electric propulsion. Each of these contracts will culminate with the fabrication and delivery of full-size battery systems for evaluation and testing in electric vans. Table 2 provides the current status of these electric vehicle battery technologies. Additional battery development and testing efforts are described in Section 4.0 under Technology Engineering.

Table 2

Electric Vehicle Battery R&D Technology Status

Battery	Developer	Designation	Status*	Specific Energy (Wh/kg)	Specific Peak Power at 50% DoD (W/kg)	Projected OEM Cost (1989 $/kWh)	Cycle Life (Cycles to 80% DoD)**	Cost/Cycle/kWh (1989$)
Flow-By Lead-Acid (Pb/A)	JCI	C472	M	53	104		130***	
			BG	56	79	72	450	0.16
Zinc/Bromine (Zn/Br_2)	JCI	J-1	M	55	88		142***	
			BG	75	79	75	600	0.12
Lithium Aluminum/ Iron Sulfide (Li Al/FeS)	ANL/ Westinghouse	36V	M	90	86		130***	
			BG	100	106	91	600	0.15
Sodium/Sulfur (Na/S)	CSPL	PB	M	96	130		261***	
			BG	100	106	91	600	0.15
				65[a]	70[a]			
Iron/Air (Fe/Air)	Westinghouse	W-3	C	70	50		200-300[a]***	
			BG	100	106	91	600	0.15

*Status: C, Cells; M, Modules; B, Battery
**Depth of Discharge.
***Current R&D Core Program is Aimed at Improving Cycle Life While Maintaining Specific Energy & Power.
BG: Mission Directed Goals for EV Battery R&D Based on IDSEP Van and Tested Under Simplified Federal Urban Driving Schedule (SFUDS).

Note: a - Projected from 40cm^2 cells operating at 25 mA/cm^2 to full-size cells operating on SFUDS.

Advanced Lead-Acid Battery

Johnson Controls, Inc., continued the development of an advanced lead-acid battery under a $3.3 million contract in which JCI provides a 25% cost-share. The objective of the R&D effort is to improve the performance and life of lead-acid batteries to meet the mission requirements of electric vans. The work is based on the concept of a forced flow of electrolyte by the porous lead and lead dioxide electrodes to achieve an increased utilization of these materials. During FY 1989, two flow-by cells and a 6-volt flow-by module were constructed by JCI and delivered to Argonne National Laboratory (ANL) for testing and evaluation. Test results at ANL revealed that the performance of these cells is unique among lead-acid batteries in that the cells, as a result of the flowing electrolyte, are able to meet the peak power requirements of the Simplified Federal Urban Driving Schedule (SFUDS) at up to 96% depth-of-discharge, whereas most lead-acid batteries fail to meet the power requirements beyond 75-80% depth-of-discharge. Also during FY 1989, JCI delivered a 6-volt, flow-by, advanced lead-acid module to ANL for evaluation. This was the first multi-cell module delivered under the development contract, and represents the logical progression in the technology from the cell level to the module level. This 70-Ah module demonstrated that a practical design could be developed for the integration of the basic cell components and the subsystems required for the desired electrolyte flow. The module was evaluated at ANL to determine its performance and life, and to evaluate the interactive effects among the three series-connected cells when operated under simulated electric vehicle conditions. In the ANL tests, the module displayed a simulated range of 68 miles for an electric vehicle on the SFUDS, thereby achieving over 90% of the development goal of 75 miles range. The cycle life of these cells remains limited, however, with a life of only 130 cycles to date in the best cells at JCI. R&D efforts in the development program are aimed at improving the cycle life of the technology.

Lithium Aluminum-Iron Sulfide Battery

Development of a high-performance proof-of-concept lithium/iron sulfide van battery was continued at ANL in a program co-sponsored by DOE and the Electric Power Research Institute (EPRI). During FY 1989, the testing of a 36-V lithium aluminum-iron sulfide module (See Figure 3) was completed at ANL. The module, designated the Mark-II and comprised of cells manufactured by Westinghouse Ocean Systems Division (Chardon, OH) and a vacuum-insulated case developed by F. Meyer Tool and Manufacturing, Inc. (Oak Lawn, IL), was the first lithium aluminum-iron sulfide module designed to meet the weight and packaging requirements for an electric van. The tests showed that the cells in a module array developed the required energy and power needed to propel an electric van, however, the first cell failure was experienced after 79 cycles. Further testing showed that the module could continue to be cycled normally, except for a loss of about 2 V per failed cell, without thermal control problems.

During FY 1989, DOE also established a joint program with EPRI to complete the development and evaluation of a full-scale proof-of-concept lithium-alloy/iron sulfide battery for an electric van. A Request-for-Proposals was issued in FY 1989, and an evaluation of the proposals received is underway; a cost-shared R&D contract is expected to be awarded in early FY 1990.

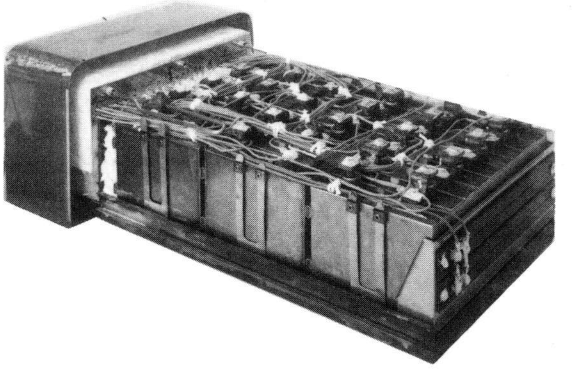

Figure 3: 36-V Lithium/Aluminum-iron sulfide Module

Sodium/Metal Chloride Battery

A cost-shared contract for a design study of high-performance sodium/metal chloride batteries for electric vehicles was awarded in August 1989 by DOE to Beta Power, Inc., (Salt Lake City, UT). Sodium/metal chloride batteries are expected to offer the same high performance as sodium/sulfur batteries, but they are also expected to have the additional benefits of a lower operating temperature and inherently greater safety. The objectives of this one-year contract are to (1) define and evaluate conceptual designs for low cost, high-performance (150 Wh/kg, 200 W/kg) sodium/metal chloride batteries for electric vehicles, (2) conduct battery cost estimates for assumed production levels of 1,000, 10,000 and 100,000 full-sized batteries per year, (3) identify R&D needs, and (4) prepare a plan for developing modules and full-size batteries.

Iron-Air Battery

INEL manages and administers the engineering development of iron-air batteries at Westinghouse Electric Corporation. This $5.5 million cost-shared (8%) contract was initiated in January 1987. A no-cost modification executed during FY 1989 extended the period of performance of this contract by two years through September 1993. This modified contract emphasizes the development of high performance, long-lived, bifunctional air electrodes and hardware scale-up to a full-size laboratory EV battery. During FY 1989 Westinghouse developed and refined a comprehensive empirical model of its air electrode. This knowledge-refinement model relates fabrication processing parameters to the performance and life characteristics of the air electrode (see Figure 4). This model has been used to help guide the experimental R&D effort, which successfully increased the cycle life of 40 cm^2 electrodes from 150-180 cycles to 300-325 cycles. This improved technology is being scaled to the 400 cm^2 size for evaluation, under simulated drive cycle conditions, in prototype EV cells; while model refinement and small-electrode development continue in an effort to improve performance and cycle life further. If the performance and cycle life characteristics of the bifunctional air electrodes can be increased to acceptable levels, then the iron-air battery could become an attractive low-cost power source for personal-use EV applications.

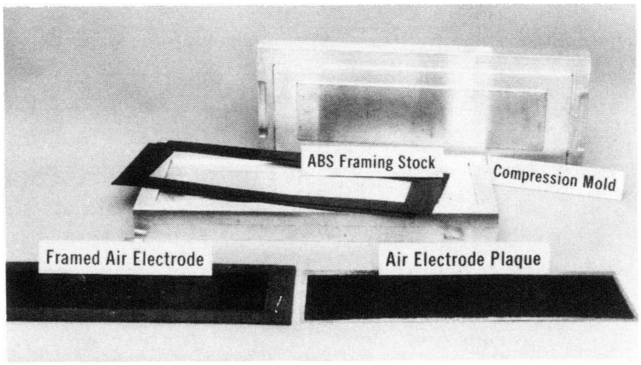

Figure 4: Flexible air electrodes supported by compression molded ABS plastic frame

Sodium-Sulfur Battery

A cost-shared contract was placed by Sandia National Laboratories (SNL) with Chloride Silent Power Ltd., (CSPL) in September 1986 to advance the sodium-sulfur battery technology specific to EV applications. This three-year program was modified in 1987 to allow the final contract deliverable to be a full-scale proof-of-concept battery, which will be designed specifically for the Ford ETX-II vehicle. FY 1989 tasks included (1) formulation of final battery specifications, (2) initial fabrication of the battery, (3) supporting thermal, mechanical, and electrical evaluations, and (4) development of the following systems and components:thermal management and electronic system controls, cell/battery interconnections, and evacuated thermal enclosures. Although the ETX-II battery is designed for underfloor mounting, it will be evaluated while located in the cargo bay because of the current lack of required mechanical and electrical support systems. To determine the expected performance of the system, an intermediate scale battery (~1/3 capacity) was fabricated and delivered to ANL for testing (see Figure 5). This sub-battery performed as expected, yielding excellent results for over 200 cycles. Improved lifetime characteristics for the cells being used in the ETX-II battery should allow at least 400-500 cycles to be obtained with it. Additionally, thermal analyses have confirmed that the 50-kWh ETX-II battery should be capable of sustaining a 35-kW discharge rate for the currently specified time of 40 minutes. At the end of FY 1989, all components for the ETX-II battery had been designed and fabricated. The battery will be assembled, qualified, and delivered to Ford Motor Co. in December 1989. In order to determine definitively the feasibility of the sodium-sulfur technology for use in actual EV applications, the contract with CSPL is being extended for an additional year. During FY 1990, a second-generation ETX-II battery will be designed, qualified, and fabricated. This battery will have a reduced weight, no active thermal management, and improved battery auxiliaries. The cells for this battery will be produced at a new pilot-plant facility. Further improvement in cell reliability characteristics is expected to yield a battery with a lifetime greater than 500 cycles. As part of Sandia's internal evaluation of the sodium-sulfur technology, nine individual cells and two four-cell strings from CSPL as well as several cells from Powerplex were tested. Parametric, SFUDS, peak power, and constant power tests were performed and successfully completed on a variety of these cells. A charge polarization phenomenon was identified with the CSPL cells which led to the testing of an additional six cells and two four-cell strings. These new cells are equipped with a sodium protection tube and are being evaluated. Powerplex cells have experienced shorter than normal cell life; however, two cells have accumulated 400 and 1100 cycles, respectively, and will continue to be tested. During FY 1989, two supporting development activities activities also were performed at SNL. The first consisted of the identification and qualification of latent-heat-storage materials for use in passive thermal management systems. This effort was successful in that a ternary eutectic salt with a very high heat-of-fusion value (~100 cal/gm) and a desirable melting temperature was found. This material may enable passive systems to be feasible. Detailed characterization evaluations are continuing to determine corrosion behavior, stability, heat-transfer properties, and any freeze/thaw-induced mechanical problems. The second SNL activity involved the design of thermal cut-off fuses that will absolutely prevent internal short-circuiting in the worst-case situation when major cell failures occur. Specific accomplishments included the selection of zinc as the fusible material, the design of devices that are inexpensive and highly reliable, and finally, the experimental characterization of actual performance. A key development has been the use of inexpensive Sol-Gel coatings to prevent the oxidation of the zinc. The initial results are promising. If ultimately proven successful during FY 1990, this technique could considerably reduce the fuse cost and thus, allow these devices to be used.

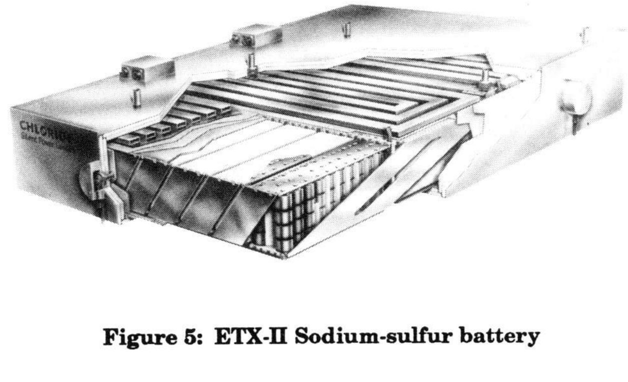

Figure 5: ETX-II Sodium-sulfur battery

Zinc-Bromine Battery

Sandia placed a three-year, \$2.3M, 18% cost-shared contract with Johnson Controls, Inc., in December 1986, to design, fabricate, and evaluate an improved zinc-bromine battery system suitable for EV propulsion The new "V" design, which utilizes vibration-welded flow frames, has undergone extensive review and design modifications. The "V" battery stack is a welded polymer unit which will eliminate any nuisance bromine leaks or odors (see Figure 6). Through a core technology improvement program directed at extending battery life and increasing energy efficiency, JCI has addressed flow frame and electrode material composition, separator development, cathode activation layer

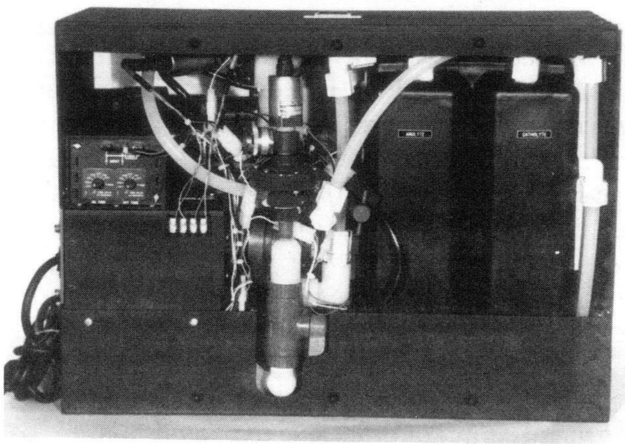

Figure 6: "V" Design zinc-bromine battery

improvement, supporting electrolyte composition, and zinc bromide concentration. In addition to hermetically sealing the battery stack and addressing safety concerns, such as electrolyte containment, JCI has demonstrated that the battery stack and its auxiliaries can be packaged into a simple, compact design. For an 8-cell battery, total battery volume and weight have been reduced 70% and 23%, respectively, as compared to the previous battery generation ("Z" design).

EV Battery R&D Evaluations

Laboratory evaluations were conducted at ANL in support of the EV Battery R&D Activities to assess the functional capability of developmental batteries to perform the mission requirements of electric vehicles. Battery performance and life characterizations were performed under uniform test conditions that simulate driving cycle load profiles. Evaluations were conducted on a 1/3 full-size sodium-sulfur battery and developmental hardware from the advanced lead-acid battery R&D program. The results of these evaluations provided a measure of the success of the battery development efforts and provided insights into the direction the research programs should take.

As a precursor to evaluation of a full-size sodium-sulfur battery in the Ford ETX-II vehicle, a one-third sized EV battery was fabricated by CSPL and evaluated for over 200 test cycles at ANL. This 300-Ah, 64-V battery came complete with charger and thermal management system. It contained 960 cells configured into 8 series-connected banks. A bank consists of 30 parallel-connected strings, each with 4 series-connected cells. Each cell is hermetically sealed in a chromized steel case and has a rated capacity of 10 Ah. The battery underwent performance characterization and life testing. It achieved a maximum capacity of 306-Ah (18.7-kWh) and a specific energy of 81 Wh/kg at the 3-h discharge rate. It provided a peak-power of 98 W/kg at 50% depth-of-discharge (DOD). Results of driving profile discharges indicated ranges of 148 miles for the DSEP van on a SFUDS79 driving schedule and 182 miles for the IETV-1 car on a SAE J227a D schedule. During these driving profile discharges, the thermal management system satisfactorily maintained the battery within an operating temperature range of 330-360°C. The operating temperature limit of 370°C was reached only after conducting a continuous 1.2 hour hill-climbing power discharge of 50 W/kg.

The CSPL Na/S battery was operated for a total of 241 cycles. Cycles were performed with driving profile discharges (SFUDS) to 100% DOD. After about 130 cycles, a cell (or cells) failed which resulted in a capacity loss of about 5%. The battery, however, continued to operate satisfactorily and exhibited the same gradual decline in capacity (0.03%/ cycle rate) that was present before the cell failure. The capacity declined to 80% of its initial level after 225 cycles. Operation was continued for another 15 cycles (10% capacity decline) to verify proper thermal management and performance during end-of-life. Throughout the ANL tests, the individual bank capacities remained matched to within 1% (3 Ah) as determined by the bank voltages at the end of charge and discharge.

Fuel Cell Technology

Fuel cells offer great promise as a potential replacement of internal combustion engines in transportation. Recent advances and several assessments gave indication that proton exchange membrane (PEM) and high-temperature ceramic fuel cells could provide the high power densities needed to meet transportation requirements. This effort will accelerate the development and proof of concept of the PEM fuel cell technologies for transportation applications. The program would move the technology through the research and development phases to laboratory evaluation of the fuel cell system.

Proton Exchange Membrane (PEM)

The PEM fuel cell, when fully developed, may offer significant advantages over the phosphoric acid fuel cell for transportation applications. These include reduced size and weight, faster start-up, better transient response, increased reliability and potentially lower cost. The DOE program goal is to develop, analyze and evaluate the PEM fuel cell system, thus providing data and information for industry to make decisions on the merits of developing the PEM fuel cell power source as a future commercial product for transportation applications.

A major new initiative for the development of the PEM fuel cell for transportation applications is being undertaken by DOE. A competitive procurement for this effort is being prepared by DOE. An announcement of DOE's intent to solicit potential sources for this effort was published in the Commerce Business Daily in September 1989. Contractor selection and award of a cost-sharing contract is expected in FY 1990.

The overall program will be divided into four phases with a go/no-go decision between each phase. Phase I, Feasibility Evaluation, will lead to the demonstration of a 5-kW breadboard system. Phase II, Proof-of-Feasibility, will be directed at proving feasibility by means of a 25-kW brassboard system. Phase III, System Scale-Up, will result in the laboratory evaluation of a full-scale 50-kW propulsion system. In Phase IV, Proof-of-Concept, this full-scale system will be installed and evaluated in a test-bed vehicle.

The objective of Phase I of this project is to evaluate the feasibility of the PEM fuel cell technology for vehicle applications. The technical efforts of the Phase I work will include (1) development of a conceptual propulsion system design, based on trade-off studies and economic analyses, to establish the component specifications required for transportation applications and to identify the limiting components, (2) R&D on limiting components to advance the technology to meet system needs, (3) development and fabrication of controls and interface systems, and (4) integration of a complete 5-kW subscale breadboard system and its evaluation as a potential power source for transportation applications. A 2-year period for Phase I is contemplated. The desired outcome of the Phase I work is an evaluation of the feasibility of an electric propulsion system based on a PEM fuel cell system and an identification of the critical problems that must be resolved in system scale-up and integration into a vehicle.

Thermo-electrochemical (TECH)

This fuel cell program was initiated in FY 1989 for the development of a TECH system for transportation applications. The TECH system uses a cation-exchange-membrane in an electrochemical cell with thermally regenerative reactants to convert methanol fuel or heat into electrical power for propulsion. In September 1989, DOE awarded a two-year, 50% cost-shared, contract to the Delco Remy and Hughes Divisions of General Motors for the development of the TECH system for transportation applications. A two-year program is planned to establish system feasibility and to conduct a laboratory-scale demonstration of the TECH system. The initial activities will include a conceptual design of a TECH system for transportation applications, and cost and design tradeoff studies. Additional activites will include development and the design, fabrication, and evaluation of a 1- to 5-kW demonstration unit. This unit will demonstrate the feasibility of the system and supply information necessary for engineering assessment of overall system efficiency and scale-up requirements. A major emphasis in this development effort will be on demonstrating high efficiency at a reasonable projected cost for the system.

Propulsion System Technology

The objective of the Propulsion System Technology Development Activity is to advance battery and powertrain technologies concurrently in a mission-oriented, integrated fashion within the context of a total propulsion system perspective. These technologies are to be advanced to levels of maturity that will allow industry to make quality decisions regarding their potential viability as foundation technologies for the development of commercial products suitable for electric vehicle applications. In order to enhance the transfer of these technologies to potential manufacturers of derivative commercial products, contracts for development of the technologies have been placed with industrial teams that not only have the necessary development expertise but also have the capability to manufacture related products.

Dual-Shaft Electric Propulsion System Program (DSEP)

The Dual-Shaft Electric Propulsion (DSEP) System Technology Development Program was successfully completed on September 30, 1989. It was aimed at advancing electric propulsion technology through integrated development of a nickel-iron battery, an AC motor and controls, and an automatic, two-speed transaxle within a light-weight van suited for use in an urban/suburban environment.

The DSEP program's industrial research team was comprised of Eaton Corporation's R&D Center, Southfield, MI, the prime contractor, with responsibilities for powertrain technologies and propulsion system integration; Eagle-Picher Industries, Joplin, MO, responsible for battery technology; and ASC, Inc., Southgate, MI, responsible for vehicle modification.

The 64-month program effort designed, developed, sequentially built, and evaluated three advanced proof-of-concept propulsion systems installed in vehicles. The first vehicle system was used for testbed evaluation, the second for performance testing, and the third for delivery to the Department of Energy as a demonstration vehicle for further testing, evaluation and site placement.

Table 3

		Actual Results	
	Goals	DSEP-1 Vehicle	DSEP-2 Vehicle
Acceleration			
0-80.4 km/h (50 mph)	20 sec.	20.5 sec.	18.6 sec.
0-48.3 km/h (30 mph)	10 sec.	8 sec.	7 sec.
Top Speed	90.6 km/h (60 mph)	112 km/h (70 mph)	117 km/h (73 mph)
Gradeability			
from rest	greater than 20%	28%	32%
maintain 88.5 km/h (55 mph)	on 3% grade	4%	4%
Range at 72.4 km/h (45 mph)	104.7 km (65 mi)	109.4 km ** (68 mi)	117.6 km ** (73.5 mi)

** with the battery capacity at its nominal 170 ampere-hour rating

The program achieved all its objectives, with the exception of anticipated battery life. Vehicle performance reached and surpassed all initial goals. Table 3 shows performance goals and actual test results from the first two DSEP test vehicles. The improvements achieved between the first and second DSEP systems were a result of advances made in intensive propulsion system technology development.

The DSEP-2 successfully underwent limited durability testing at the Chrysler Chelsea Proving Grounds in Chelsea, Michigan. One mile of proving ground tests is equivalent to 10 miles of normal driving. The tests were designed to check the vehicle's system reliability, basic functionality and structual soundness in mixed road, weather and driving conditions. The vehicle ride and handling characteristics also were evaluated by expert Chrysler Corporation engineering personnel and found to be of acceptable commercial quality in both respects. The vehicle accumulated a total of 465 miles of proving ground tests.

The DSEP program scope was modified in March 1989 with regard to the number of deliverable vehicles. Instead of providing for only one deliverable vehicle (DSEP-3), the revised objectives called for delivery of DSEP-2 and DSEP-3 which will better serve DOE's needs for further independent testing and/or site operation. Figure 7 is a photo of all three vehicles built on the DSEP program. Therefore, the originally planned extensive durability testing of the second DSEP vehicle was revised to a reduced test schedule to enable the vehicle to be transferred to the Detroit Edison Company for site operation and evaluation beginning in October 1989.

Installation and checkout of the propulsion system in the third DSEP vehicle was completed. The vehicle underwent shakedown and limited performance tests before delivery to Idaho National Engineering Laboratory in August 1989 for evaluation and characterization testing.

Figure 7: Three final DSEP vehicles

The nickel-iron batteries demonstrated and met the performance goals for power at 80% depth of discharge and energy storage capacity in vehicle tests. The goal for cycle life fell short of the expected 1200 cycles as life cycle battery tests at ANL and at Eaton Corporate R&D Detroit Center were terminated at 650 and 900 cycles, respectively. Although the life goal of 1200 cycles was not achieved, the failure mode was determined to be caused by the defective manufacture of the iron electrode and is expected to be solved with improved quality control of the manufacturing process for future battery development.

A life cycle cost estimate of the entire DSEP vehicle/powertrain system was completed; it indicates a disadvantage relative to a gasoline-powered vehicle. Several factors contribute to this, namely, the initial cost of the system, the shorter-than-expected battery life, and the unavailability of "gliders", e.g. vehicle chassis minus the conventional powertrain. Another development phase for the system aimed at reducing the cost of some subsystems and establishing the durability of others is believed necessary in order to enhance prospects for successful commercialization.

Second Generation Single-Shaft Electric Propulsion System Program (ETX-II)

The Ford ETX-II research effort is concentrating on technologies that will adapt the ETX concept to a small commercial van and take the major subsystems a step closer to production. As in the ETX-I program, General Electric is a major subcontractor and is responsible for the electric subsystem, which includes the motor, its controls, and the inverter, including the power modules. Powerplex Technologies, Inc., is also a major subcontractor and has supplied the sodium-sulfur battery used in the program. Major technological advances that have been accomplished include; a new interior permanent magnet (IPM) motor for the transaxle assembly, which is integrated into the rear axle of the van, development of the control algorithms required for control of the interior permanent magnet motor, further development of the unique power modules, improvements to the inverter to reduce its size and weight, and integration of the vehicle controls and the electric subsystem controls to provide a system controller that is in command of the entire propulsion system. In addition, specification and integration of an advanced sodium-sulfur battery is included in the program to assure that this important portion of the propulsion system is included in all system trade-offs. In addition to Powerplex Technologies, Inc., Chloride Silent Power Limited will also supply a sodium-sulfur battery, developed under a separate contract with DOE, for test in the ETX-II propulsion system.

FY 1989 has been used for system integration, development, test and demonstration. The vehicle was shown publicly for the first time at the Ninth International Electric Vehicle Symposium (EVS-9) in Toronto and then was tested at Powerplex in Toronto with two B-11 sodium-sulfur batteries installed on the cargo floor and operated on a chassis dynamometer (See Figure 8). After initial testing was completed the vehicle was delivered to Dearborn, Michigan for test at the Ford facility. The vehicle was operated on the FUDS and successfully achieved over 160 km (100 miles). The vehicle was also shown publicly and demonstrated in Washington, D.C. in conjunction with a Ford Alternate Fuels press conference in April.

Major achievements for the year include the integration and refinement of the closed loop upshift control algorithms and the design, development and test of the lube pump controller. Several sequences on sodium-sulfur batteries from Powerplex and ABB (the European joint venture company ASEA, Brown and Boveri) have shown that the propulsion system has 160 km (100 mile) capability when operated on the FUDS. Measurements taken during these tests indicate that the propulsion system can be expected to meet its goals of energy consumption less than .25 kWh/km and acceleration to 80 km/h in less than 20 seconds. In addition to propulsion system development, two electric power steering systems have been procured and tested.

Figure 8: ETX-II With two B-11 sodium sulfur batteries

In FY 1989 the ETX-II program was expanded to include the installation and testing of an additional sodium-sulfur battery from Chloride Silent Power Limited and an MCT inverter from General Electric Company. The CSPL battery is being built to ETX-II specifications under a separate DOE contract with Sandia. The MCT inverter from GE utilizes the MOS-(Metal Oxide Semiconductor) Controlled-Thyristor (MCT) technology developed at GE, and a high voltage multi-layer ceramic (MLC) capacitor available from Olean Advanced Products, and will be "plug-compatible" with the base program ETX-II inverter. The MCT power devices provide important advantages over the present technology by eliminating the bulky power driver circuits and the power supplies that are required for bipolar switching devices, by eliminating bulky snubber circuits, and by offering a reduction in operating losses permitting greater power efficiency and better thermal management. The use of the ceramic capacitor permits a large reduction in required volume for the DC bus capacitor and a reduction in energy loss as heat. The new inverter design, therefore, will result in a significant reduction in hardware volume. This program, which will be completed next year, will result in a propulsion system suitable for a light commercial van. The propulsion system will be the most advanced system built to date, and one whose features will enhance the probability of such a system being a viable commercial product.

Fuel Cell/Battery Powered Bus System Development

DOE continued a Congressionally-mandated program to conduct research, development, and demonstration of a Fuel Cell/Battery Powered Bus System Program which was initiated in FY 1987. This effort is a joint program co-sponsored by DOE, the Department of Transportation/Urban Mass Transportation Administration (DOT/UMTA), and the California South Coast Air Quality Management District (SCAQMD). Argonne National Laboratory provides the technical management for these activities, and Georgetown University provides additional support under a cost-sharing (14%) contract with DOE. Booz-Allen & Hamilton continued work on a two-year $2.1 million cost-shared (32%) contract to develop a liquid-cooled phosphoric acid fuel cell/battery system; and Energy Research Corporation continued work on a $2.5 million cost-shared (27%) contract to develop an air-cooled phosphoric acid fuel cell/battery system.

The objective of this program is to develop a methanol-fueled, phosphoric acid fuel cell/battery propulsion system for a 30-ft urban bus. Fuel cells, operating on non-petroleum fuels, can potentially provide a propulsion system alternative with nearly twice the fuel economy and greatly reduced emissions compared with the internal combustion engine.

During FY 1989, work was continued on Phase I of this four-phased program. Phase I is a two-year effort directed at demonstrating proof-of feasibility of a phosphoric acid fuel cell/battery system as the prime source of power for an urban bus. Phase I is a system design and integration effort that includes system trade-off analyses, cost projections, and culminates with the fabrication and laboratory evaluation of a half-size fuel cell/battery brassboard power source. Figure 9 shows both the air-cooled and liquid-cooled brassboard systems. Phase II will encompass the integration of a full-size fuel cell/battery propulsion system into a testbed bus to demonstrate proof-of-concept. Track testing and field evaluation of this testbed bus will be accomplished in Phase III. Phases I through III will provide the technology development and demonstration needed to proceed to Phase IV, which encompasses field testing of a small fleet of prototype buses. The results of Phase IV will provide the data and experience needed by industry to make commercialization decisions.

During FY 1989, the team of Booz-Allen & Hamilton, Chrysler Pentastar Electronics, and Fuji Electric completed the design of a liquid-cooled phosphoric acid fuel cell/battery propulsion system for an urban bus. A fuel cell/battery hybrid power source and electric drive system that is one-half the size planned for the bus was fabricated to demonstrate proof-of-feasibility for the concept. Laboratory evaluation of this 68-kW brassboard system (25-kW fuel cell and 43-kW lead-acid battery) was initiated in late FY 1989 and will be completed during early FY 1990.

The team of Energy Research Corporation, Los Alamos National Laboratory, and Bus Manufacturing, Inc., completed the design of an air-cooled phosphoric acid fuel cell/battery propulsion system for an urban bus. ERC constructed a fuel cell/battery hybrid power source system that is one-half the size planned for the bus. Laboratory evaluation of this 62-kW brassboard system (32-kW fuel cell and 30-kW nickel/cadmium battery) was initiated in late FY 1989 and will be completed during early FY 1990.

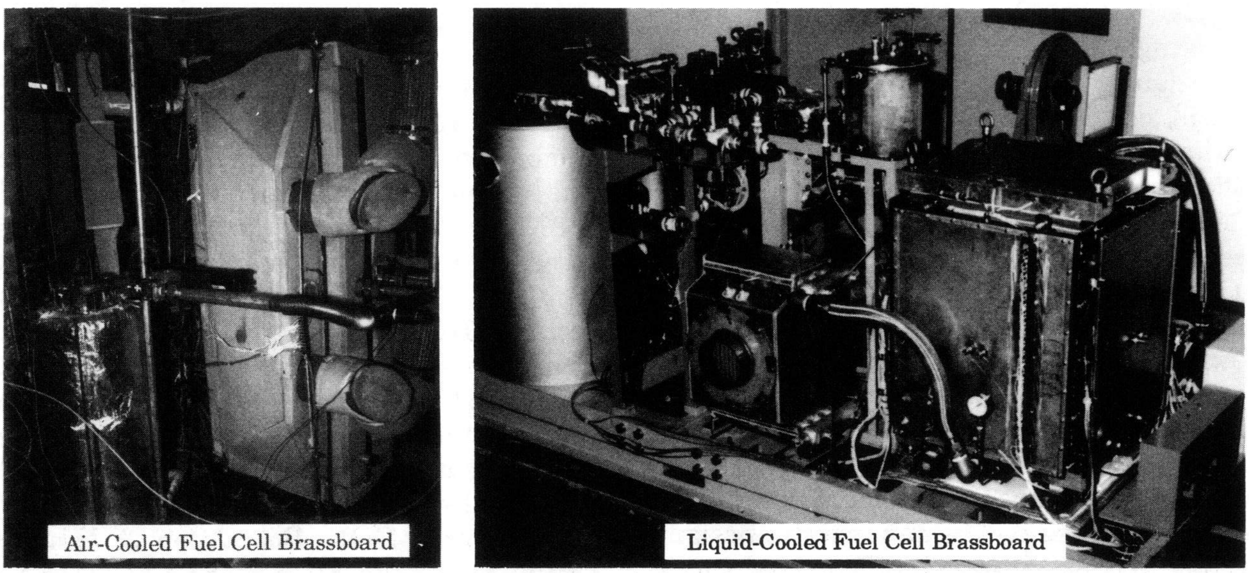

Figure 9: Fuel cell brassboards

4. Test and Evaluation

Test and Evaluation (T&E) activities are performed on newly developed and existing technologies to characterize their performance potential in laboratory and field environments. The functions are carried out in three separate elements: Site Operators, Technology Engineering and Engineering Evaluation Testing. The activities conducted in FY 1989 within each of these T&E elements are described below.

Site Operators

During FY 1989 management of the Site Operators Program was transferred from Booz, Allen and Hamilton to the INEL. This was done to provide closer contact and better coordination between the site operators and ongoing laboratory testing and other activities (e.g. propulsion system R&D) conducted or managed by INEL. Existing subcontracts with the private sector operators were closed out and new subcontracts were placed by INEL. In conjunction with this, the public sector contracts and cooperative agreements were transferred from the Nevada Operations Office to Idaho. This transfer of responsibility will also provide closer support for the industry sponsored User Task Force.

The Site Operator Program is concentrating on identifying new technology vehicles and other components (especially batteries) for field testing, and on tailoring the data collection activities to focus on these newer vehicles and components.

A new, more user friendly computer database has been established for the collection, retention and retrieval of drivers' log and maintenance data. The program uses standard formats for collection of routine data, allowing the site operators to input data directly into a computer readable format. This data is sent to INEL on a monthly schedule where it is compiled into the master database. The master database is organized to allow retrieval of selected data based on one or more variables, such as specific site, vehicle type, and/or battery type. This permits rapid retrieval of data for the evaluation of performance parameters and trends. Use of this program will begin in FY 1990 with four private sector and three public sector participants. These are shown in Table 4.

The program continues to work toward improved EV acceptability through careful matching of vehicle capabilities with mission requirements. This has been made possible to some extent by the familiarity with, and data collected on, the current generation of vehicles and batteries. There is also a renewed effort to introduce the EV into areas where internal combustion engine vehicles (ICEs) have previously provided the only option. Several program participants have organized activities to temporarily replace ICEs in fleet operations with EVs chosen for their ability to perform specific missions. This serves a dual purpose in allowing fleet operators to gain experience with the use and capabilities of the EV, while also providing test data and user evaluation for the vehicles under actual service conditions.

FY 1990 activities will include the introduction of a new generation of vehicles and new batteries for testing. Prototypes of the General Motors G-Van will be delivered shortly after the beginning of the fiscal year, with early production vehicles scheduled for delivery later in the year. The G-Van is an electric powered version of the GM Vandura van. It is manufactured cooperatively by the General Motors Corporation, Vehma International Inc., (a subsidary of Magna International Inc.), and Chloride EV Systems. The vehicle has a top speed of over 50 mph with a range of about 60 miles. It is available in either cargo or passenger configurations, with available payloads of approximately 1500 and 1000 pounds, respectively.

Table 4

Electric and Hybrid Vehicle Program Site Operators (Operating During FY-89)

Private Site Operators

GTE Service Company Honolulu, Hawaii Pomona, California Irving, Texas	Arizona Public Service Company (APS) Detroit Edison Company (DECO) Long Island Lighting Company (LILCO)* Southern California Edison Company (SCE)**

Public Site Operators

Sandia National Laboratories	University of Hawaii

U.S. Navy

Naval Underwater Systems Center Autec, Bahamas	Naval Weapons Support Center Crane, Indiana
Naval Air Station Moffett Field, California	Naval Air Station Bermuda
Naval Ordinance Station Louisville, Kentucky	Pacific Missile Test Center Point Mugu, California
Naval Supply Center Pearl Harbor, Hawaii	Naval Shipyard Mare Island, California

* Operations completed in FY 1989.,
** New site operator added in FY 1989

Standard equipment includes power steering and brakes, with air conditioning available as an option. It is estimated that the G-Van has the capacity to replace 60,000 ICE fleet vehicles in the Los Angeles area alone.

Two Eaton developed Dual-Shaft Electric Propulsion vans have been delivered to DOE and are currently undergoing preliminary testing. These vans incorporate new generation propulsion systems with AC traction motors, a new nickel-iron (Ni/Fe) battery design, and state-of-the-art controls, manufactured using the body and chassis of the Chrysler T-115 Mini-Van. One of the vehicles is at the INEL where it will undergo laboratory testing in FY 1990 prior to being made available for field use. The other has been delivered to Detroit Edison Company, one of the Site Operators, for on-the-road test and evaluation.

Results of preliminary testing on the Sonnenschein 6V160, sealed cell lead-acid battery, indicate that it may provide a solution to problems with short life experienced by other sealed lead-acid batteries. The University of Hawaii has installed these batteries in an Evcort (electric Ford Escort) with good results to date. The vehicle is providing approximately a 40 mile range with an overall energy use of 0.34 kWh/mile.

Arizona Public Service (APS) has increased the size of their EV fleet through the addition of three Jet Escort sedans transferred from LILCO and three SCT VW Rabbit pickups transferred from Northrop Corporation in Los Angeles. This brings the fleet to eighteen vehicles, including a 1915 Detroit Electric, possibly the oldest EV currently in use in the country. It is used in a variety of public awareness programs, including parades and displays, throughout Arizona. The remaining vehicles in the fleet are loaned to various operating organizations within the company for evaluation as to suitability for a variety of missions. They also provide routine transportation for personnel within the EV program. Data is collected on significant operating parameters and maintenance activities.

APS has also participated in the testing of "Smart Chargers" and state of charge instrumentation. The APS Smart Charging system monitors individual module voltages within a battery pack so that the entire pack is charged to the same potential. State of charge instrumentation informs the vehicle operator when any of the modules drop below operating voltage, allowing the driver to take the necessary actions to prevent damage to the batteries through over discharge.

Detroit Edision Company (DECO) continues its over the road evaluation of the GM Griffon Electric Van. This effort provides a basis for comparison with the new GM G-Vans scheduled for delivery starting in FY 1990. Since the beginning of the evaluation seven vehicles have been used in both commercial and commuting applications. Collectively they have been driven over 125,000 miles, ranging from a low of 1400 miles to a high of 43,000 miles per vehicle. They have averaged 28 miles/charge and 0.98 kWh/mile, and have demonstrated the ability to replace ICE vehicles for a range of applications. During the past year testing was completed on a battery heating system designed to allow the lead-acid batteries in the Griffon vehicles to operate at low ambient temperatures. The system demonstrated the ability to extend the useful operating temperature of the vehicles to around 15°F.

These vehicles will be retrofitted with several new components in FY 1990, including a new generation of battery chargers, traction motors, motor controllers, and a second generation battery heating system. The vehicles will continue operation with these components. During the coming year DECO will also operate two G-Vans and one of the DSEP prototypes. This provides the opportunity to evaluate three electric van technologies in a side by side comparison.

GTE continues its participation in the program with an Eaton Lynx in Texas and fleet operations in California and Hawaii. The Lynx is a current technology design featuring an advanced DC powertrain and two speed automatic transmission. The vehicle is performing well in a daily commuting capacity. Fleet operations in California and Hawaii continue to concentrate on battery test and evaluation. GTE is currently in the initial stages of testing five new battery types, including two gelled and three flooded-electrolyte types. Preliminary results on one of the gelled electrolyte types indicate a much longer life expectancy than has been observed in the past.

Long Island Lighting Company (LILCO) completed the work covered by their subcontract with the Site Operators Program during FY 1989. For internal budgetary reasons company management made the decision not to continue the program and the contract was not renewed. LILCO has donated the vehicles and equipment from their operation to Arizona Public Service, the University of Alabama in Huntsville, York Technical College in South Carolina, and the U.S. Navy.

Southern California Edison (SCE) joined the program at the end of FY 1989 with a subcontract to test and evaluate fifteen preproduction prototype G-Vans which are scheduled for delivery early in FY 1990. SCE will use these for both routine operations within their own fleet and as demonstration vehicles on loan to outside organizations in the Los Angeles area.

Sandia National Laboratories currently operates a fleet of eleven Jet Electrica sedans. All eleven 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 reasonable reliability. The vehicles have replaced ICE vehicles and demonstrated a capability to perform an assigned mission and provide operator satisfaction.

The EV program at the University of Hawaii continues to focus on 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 and a moderate climate.

The U.S. Navy continues to operate a large fleet of vehicles at bases from Hawaii to Bermuda. As has been the case in past years, this fleet is primarily composed of vehicles which have been declared surplus from commercial fleets. Work has begun on the installation of a solar powered EV battery charging station at the base on Bermuda, thus combining two inherently clean energy technologies. The system is scheduled to be in operation during early FY 1990.

In addition to the present program participants, the Los Angeles Department of Water and Power (LADWP) has expressed an interest in becoming a site operator. They have joined the EV Users Task Force and are participating in task force activities.

Technology Engineering

Technology Engineering activities undertake the development and evaluation of improved-technology components that are likely to enhance the capabilities of early state of the art EVs in site-operated fleets. These components are evaluated in laboratories; on test tracks in vehicles; and in sheltered (outdoor laboratory) on-the-road vehicles to verify their suitability for incorporation into site-operated EVs. Factors, such as temperature, road shock, moisture, electromagnetic interferences, durability and safety, are evaluated along with the actual performance measurements for the component under test. Battery technology improvements discovered through integrated independent testing of new process components offer the greatest opportunity for enhancing EV performance. Improved controllers, battery chargers, battery monitoring instrumentation, auxillary systems (air conditioning, heating and lighting) and EV safety issues also are evaluated when enhanced EV capabilities may result from incorporation of these technologies.

The University of Alabama completed the characterization of Energy Research Corporation's roll-bonded Ni/Cd battery. The final analysis, supported by testing at Rutgers University Medical School by Dr. Alvin Salkind, showed that this particular battery technology cannot provide the high currents required in traction service. The problem is a diffusion limitation or the ability of the electrolyte to reach the active material in the plates at a rate fast enough to maintain a workable voltage level while producing high current. The Rutgers University analysis showed a 40 to 48 percent porosity compared to 80 percent and higher for standard traction batteries. Concluding research by ERC did not improve the power capabilities of the roll-bonded technology; however, the battery has proven to be useful in applications where the energy demand is slower than the two hour rate. In concluding the DOE contract, ERC produced a final report describing the four year development effort. The Ni/Cd program will continue with a new solicitation designed to cooperatively develop a sealed or very low maintenance battery based on the nickel fiber technology showing success in the nickel-iron battery program.

UAH is continuing the life testing of the Johnson Controls Phase IV Gell/Cell batteries using an inhouse developed charging algorithm. The charging system uses a microprocessor to continuously monitor the status of each battery module in the vehicle, providing a uniform charge to the entire battery pack (18 modules per pack). The battery pack under test has accumulated over 100 charge/discharge cycles while maintaining a balanced charge throughout the pack, in comparison to field tests with standard chargers which typically require module replacement within 50 cycles due to charge imbalance. The system has also proven the operation of a greatly simplified data collection system, necessary to monitor the voltage of individual modules, and the ability of the central processor to control two chargers simultaneously, reducing the cost of the system to the fleet operator.

A project was initiated with the NAVY to install a Solar Photovoltaic (PV) charging station in Bermuda. The station will consist of a 13.5 kw PV array that will feed power to a large storage battery during the day which will in turn, charge five electric vehicles at night. Three of the vehicles will be charged by conventional means and the other two will use the system developed by UAH. Initial operation of the site is expected late in FY 1990.

A research program to advance the development of nickel-iron (Ni/Fe) batteries for electric vehicles was continued during FY 1989 by Eagle-Picher Industries, Inc., under a 4-year, $2.1 million cost-shared contract. The effort at EPI is directed toward reducing the cost of improved nickel-iron batteries. The work is focused on the development of fiber-type nickel electrodes. Because nickel metal is the major cost driver in the manufacture of nickel-iron batteries, the lower nickel requirements of the fiber-type approach is expected to provide significant cost reductions potential for future nickel-iron batteries. During FY 1989, EPI continued to make steady progress in the development of fiber-based nickel electrodes and fabricated full-size, fiber-based Ni/Fe modules for evaluation.

Recent nickel-iron batteries have experienced reduced lifetimes due to the deteriorated quality of iron electrodes obtained from SAB Ni/Fe of Sweden. The problem may have been related to a relocation of equipment and the assignment of new personnel in Sweden. Since EPI has a license from SAB NIFE for rights to the technology, EPI is proceeding with a plan to acquire, with support from DOE and EPRI, the equipment necessary to begin fabrication of iron electrodes at their Joplin, MO facility. This capability will allow EPI to have direct control over the iron plates produced. Installation of the pilot line for iron electrode fabrication is scheduled to be completed in late FY 1990.

Evaluation of developmental nickel-iron modules fabricated by EPI is performed by ANL. During FY 1989, a full-size fiber-based module achieved over 800 cycles in testing at ANL. In other developments, test results indicate that a post-impregnation addition of a surface film of cobalt hydroxide on the nickel electrodes may ameliorate the iron poisoning of nickel electrodes caused by iron plates of poor quality; a full/size NIF-220 module with cobalt hydroxide is maintaining its full rated capacity of 220 Ah after 150 cycles to date at ANL.

The ruggedness and long life of nickel-iron batteries developed under this program continued to be confirmed in in-vehicle tests. Nickel-iron batteries performed well after seven years in commercial fleet operations at industrial sites. A complete nickel-iron battery system has powered an electric vehicle for over 47,000 actual miles of operation to date at Electrotek's Electric Vehicle Test Facility in Chattanooga, TN.

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 on a dynamometer and in test bed vehicles; (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.

DOE selected the INEL in FY 1984 to perform these testing activities, and dynamometer and battery test laboratories were established for this purpose. The present laboratory facilities permit the testing of vehicles and complete battery subsystems under simulated load conditions which closely approximate the demands of EV operation, including the performance of the Federal Urban Driving Schedule. Modifications were made to the INEL dynamometer in FY 1989 to permit the performance characterization of individual components, such as motors and transmissions within the 30 kW continuous, 53 kW peak power limits of the dynamometer, while retaining the capability to test complete vehicle systems. Figure 10 shows the chassis dynamometer modified for testing of an electric vehicle motor. Some modifications were also made to the battery laboratory to permit the testing of fuel cell/battery hybrid power sources, such as those now under development for the DOE/DOT fuel cell bus program.

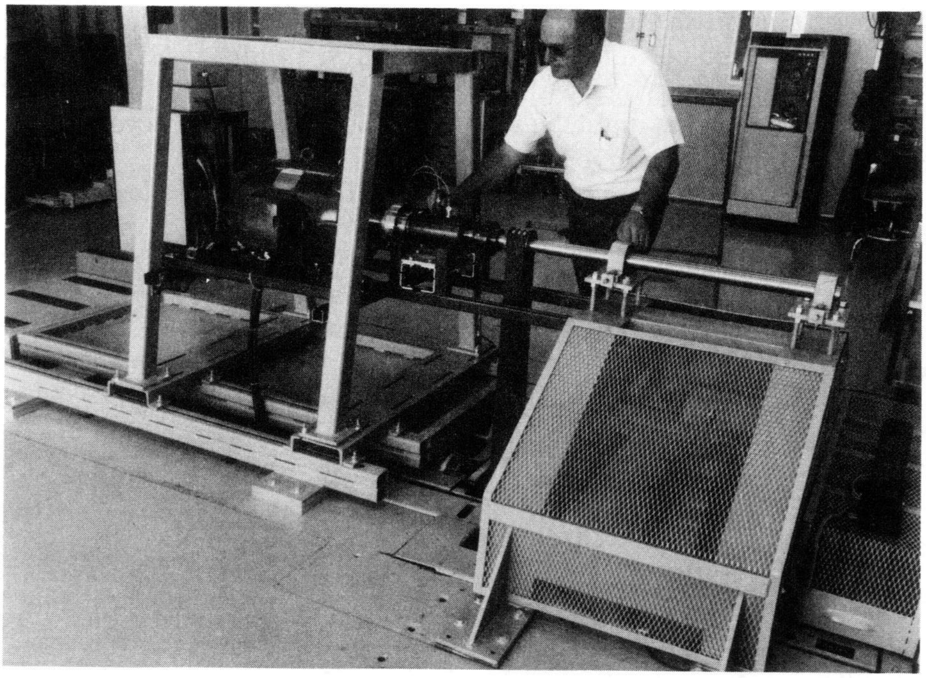

Figure 10: Component test setup on dyno

INEL dynamometer testing during FY 1989 focused on performance testing of electric propulsion systems in near-term electric vehicles using currently available technology in contrast to the more advanced vehicles from DOE propulsion system R&D programs to be tested in FY 1990. Figure 11 is a collage of the steps in electric vehicle testing exemplified by the Soleq dual battery van. The major stages shown are: A. Battery conditioning and preparation; B. Track gradeability testing; C. Coastdown operation for dynamometer set-up data; D. Power train sensor connections for dynamometer data acquisition; and finally E. Chassis dynamometer testing. In addition to basic vehicle and powertrain performance, attention was devoted to other factors which influence user acceptance such as air conditioning and heater/defroster performance and acoustic noise levels. Table 5 summarizes the results of the powertrain and vehicle tests conducted by INEL in FY 1989.

A series of track and dynamometer performance tests were conducted on a DC powertrain in an electric Ford Escort (Evcort) testbed vehicle built by Soleq Corporation for site operator Arizona Public Service (APS). The Evcort propulsion system efficiency under many conditions was found to be comparable to the Chrysler/GE-developed ETV-1, which is one of the most efficient propulsion systems built. The

Evcort DC energy consumption on the FUDS was 212 Wh/km, while its acceleration from 0 to 80 km/hr in 25 seconds was comparable on a power-to-weight basis to any vehicle tested to date. The Evcort also incorporated an inverter-driven air conditioner and heater/defroster, all powered from the traction battery pack. Use of the modest-size air conditioner increased energy consumption by 25% or more under some conditions, with corresponding reductions in vehicle range. This testbed vehicle was later equipped by INEL with a new-generation on-board Versatile Data Acquisition System (VDAS) to collect extended engineering data on vehicle and air conditioning performance in the field during its use by APS in Phoenix.

A series of comparative acoustic noise tests were also conducted on the Evcort vehicle and a similar internal combustion engine (ICE) vehicle under various operating conditions at Chrysler's Arizona Proving Grounds. Measurements of interior and exterior (drive-by) acoustic noise indicated that the electric vehicle was noticeably quieter under acceleration and idle conditions. Under constant speed operation the two vehicles exhibited essentially equivalent interior noise levels; at higher (constant) speeds this noise level tends to be dominated by road and wind noise and can also be affected by vehicle trim level.

A series of dynamometer and track performance tests was conducted on an 80 kW (107 hp) DC propulsion system installed in a full-size Dodge van, built with DOE assistance by the Soleq Corporation in FY 1988 to investigate the performance of a dual parallel battery pack configuration and the behavior of various transmission options based on commercially available hardware. The final configuration incorporated two quasi-independent battery packs for a reliable "limp-home" capability, an externally pumped automatic transmission with no torque converter for higher efficiency, and a DC/DC converter which required no auxiliary battery for accessory power. The van's DC energy consumption on the FUDS was 470 Wh/km, and it accelerated from 0 to 80 km/hr in about 24 seconds; both of these represent good

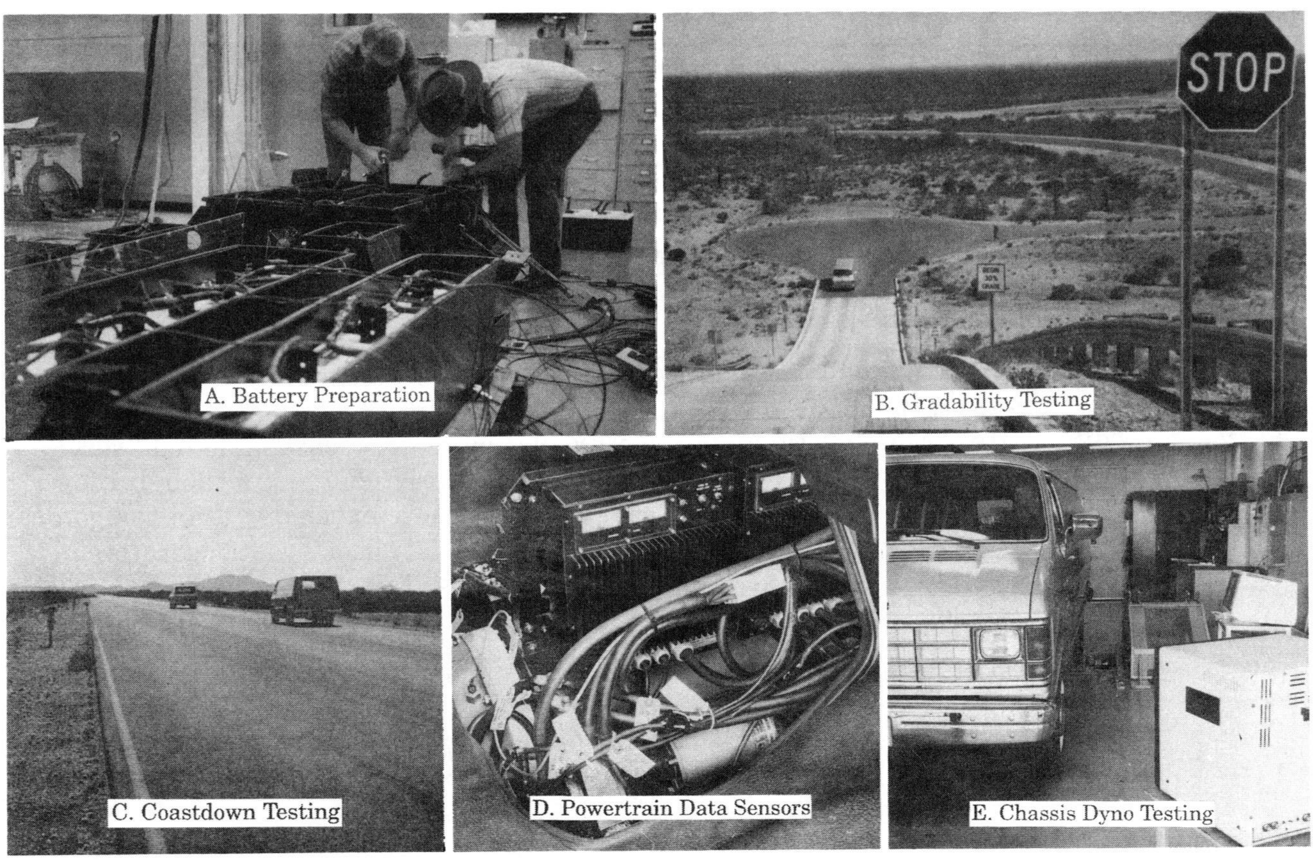

Figure 11: Stages in electric vehicle testing

Table 5

Vehicle & Powertrain Engineering Evaluation Testing Results

	Chrysler/GE ETV-1 (for reference only)	Soleq Evcort	Soleq Dual Battery Van
Vehicle Type	Passenger Car	Passenger Car	Full Size Van
Test Weight (kg)	1723	1968	3713
Battery Mass Fraction	0.31	0.34	0.32
Battery Manufacturer/Type	JCI Phase 3 Gel/Cell Sealed Lead-Acid	Concorde 6250 Sealed Lead-Acid	JCI Phase 4 Gell/Cell Sealed Lead-Acid
Transmission (No. Speeds)	Single	Five (Use only 3)	Three
Road Load Power Required at 88 Km/h (kw)	9.6	12.5	23.8
Acceleration, 0-80 km/h (seconds)	23.6	25.6	24.0
Net DC Energy Consumption: Federal Urban Driving Schedule (FUDS) (Wh/km)	174	212	471
48 km/h (Wh/km)	94	119	235
88 km/h (Wh/km)	129	160	361
Powertrain System Efficiency at 88 km/h	84%	84%	75%

performance for a 3700 kg full size vehicle. This testing also demonstrated noticeable efficiency improvements from the use of modern low-rolling-resistance radial tires, compared to conventional light truck tires. The range of the vehicle was substantially compromised by the older sealed lead-acid batteries used with it; however, these batteries served to identify potential concerns in maintaining balanced pack conditions in a dual battery configuration.

As part of a continuing effort to monitor the state of near-term battery development for DOE site operators and other potential EV users, the INEL battery laboratory tested a number of commercially available lead-acid batteries for potential EV application, along with several other batteries which are not yet being manufactured. Table 6 summarizes the results of the batteries tested by INEL in FY 1989. Sealed lead-acid batteries from Johnson Controls, Concorde and Sonnenschein, along with an improved tubular lead-acid battery from Chloride, all proved to have good (for lead-acid) initial performance. The Concorde battery deteriorated rapidly in use and was determined to be unsuitable for EV use without further design refinement. The Sonnenschein and Chloride batteries are mature designs which are expected to give reasonable field service if they are properly charged, although they are significantly more expensive than the golf car batteries typically used by site operators in the past. Availability of suitably flexible charging systems for EV use is an area of concern for all batteries tested recently except for the Chloride batteries, which were designed as part of a complete battery system for the G-Van and are scheduled to be available in the U.S. during 1990.

An advanced lead-acid battery using a privately-developed materials technology by Electrosource was tested in full-size EV modules, which proved to have high energy density and good power performance; however, process problems have prevented the attainment of a useful life for these batteries to date. Fabrication limitations are also believed to be a principal cause for the very short life achieved by privately-developed zinc-air cells by DEMI which were tested in FY 1989.

Improvements in INEL computer networking capability permitted the implementation of enhanced methods for handling both test and simulation results. This enhanced capability was used for several investigations, including a comparison of AC and DC powertrain performance based on various testbed vehicles, an evaluation of the expected performance of several advanced batteries now under development for new-generation vehicles, and the development of an approach for characterizing power and velocity profiles of EVs based on field and road test data. The AC vs DC comparison illustrated that AC propulsion systems tested to date have not yet achieved the high efficiency of the best DC systems (which have a much longer history of development), although their performance is comparable in other respects and superior in some. Further improvements in efficiency are projected for newer generation AC systems which have not yet been tested.

Table 6

Battery Evaluation Summary Test Results

Battery Description	Battery Type	Module Weight (Kg)	Battery Capacity 3Hr Rate (Ah)	Specific Energy 3Hr Rate (Wh/Kg)	Volumetric Energy Density (Wh/L)	Peak Pwr 50% DOD 15s (W/Kg)	Battery Coulombic Efficiency (%)	Battery Energy Efficiency (%)
Lucas Chloride 6ETX-100	Tubular Lead-Acid	32.3	90	32.3	72.06	107	80	66
Eagle Picher NIF-170-5	Nickel-Iron	24.1	158	40.3	69.39	119	76.5	58
Johnson Controls GC-2	Sealed Lead-Acid	28.1	115	24.0	54.86	129	95.6	82
Concorde GP 6250	Sealed Lead-Acid	38.2	173	26.9	83.19		92.5	75
Sonnenschein 6V180	Sealed Lead-Acid	31.8	150	28.0	73.80	125	95.7	84
Chloride 3ET 205	Tubular Lead-Acid	32.5	176	31.4	76.63	90	84.9	71

5. Incentives

The major incentives-related activities included the Corporate Average Fuel Economy (CAFE) and Loan Guarantee activities.

CAFE Regulations

Section 13(c)(1) of Public Law 94-413 directed the Department 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 inclusions as an incentive for early initiation of industrial engineering development and initial commercialization of electric vehicles in the United States.

This 7-year evaulation 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 update the factors that are necessary for calculating the CAFE credits for electric vehicles published in 10 CFR 474, dated April 21, 1981. When completed, the new factors will be published in the Federal Register.

Planning Grants

There was no activity in this incentive program during FY 1989.

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, ten formal applications were provided to DOE and two loan guarantees were issued, both of which were terminated due to default. The assets of one company were liquidated in 1982 recovering approximately $83,000, which resulted in a 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.

In FY 1989 Jet Industries continued their efforts to sell the real estate and pay off the remaining balance of the loan but an acceptable offer has not been obtained.

6. Other Activities

Studies and Assessments

Impact Studies

Section 13 of Public Law 94-413 requires a continuing assessment of material demand and pollution effects from electric and hybrid vehicles (EHVs). No new studies of material demand were conducted in FY 1989 because earlier studies indicated that the availability and production of materials for EHV production could be readily increased to meet any plausible level of EHV production during this century.

Section 13 of the Act also requires a statement of activities related to research on incentives to promote broader consumer acceptance of EHVs. No new activities were initiated in this area during FY 1989.

Hybrid Vehicle Evaluation

The Department of Energy continues to monitor domestic and foreign developments in hybrid vehicles. Improvements in batteries, powertrains, engines, motors, and computer modeling, etc. are monitored for possible effective use toward consideration of future hybrid systems.

Volkswagen (VW) is proceeding with plans to fabricate two pre-production prototypes of their diesel/electric hybrid vehicle, designed around the VW Golf, in 1990 with fifty more to follow in 1991. Field testing of the prototype vehicles will be conducted in Zurich, Switzerland with support provided by the Swiss Government.

Contractors' Coordination Meeting

The Electric and Hybrid Vehicles Program Contractors' Coordination Meeting was held on September 6-8, 1989, at INEL. Some 120 people were in attendance to exchange technical information on the development of electric vehicle technologies, participate in the ride and drive of various electric vehicles and to tour the INEL facility.

EV Battery R&D Program Plan

Utilizing the results of DOE's 1988 EV battery assessment study, INEL generated a multi-year battery R&D program plan for DOE during FY 1989. Technical plans were established for each of the nine most-promising advanced-battery technologies, as identified in the battery assessment. The technical plans incorporate technology-specific information in the areas of: technology background, projected capabilities, goals, status, critical issues, and R&D schedules which include major milestones and tasks.

Estimates of R&D effort and funding were developed for advancing these technologies to an advanced engineering level, referred to as the refined engineering battery. Industry should be in the position to make quality decisions regarding commercial product development based on analyses and evaluation of refined engineering batteries. The R&D funding estimates form part of the implementation plan, which establishes a technology-based decision-tree process for use in implementing a prioritization of EV battery technologies for DOE sponsorship. Technologies offering the highest probability of impacting early EV markets and personal-use EV markets are recommended for consideration as top-priority candidates.

Battery Test Working Task Force

The EHV Battery Test Working Task Force was formed in 1983 to coordinate the battery evaluation work at several DOE and EPRI funded laboratories. Present member laboratories are ANL, INEL, LANL, SNL, and Electrotec. The group has met twice each year since then to discuss testing procedures, results, reporting methods, and special techniques. Several new evaluation procedures have been developed, tested and implemented. The task force has recommended improvements in testing procedures used at each represented laboratory, and most have been accepted.

During FY 1989, a key accomplishment of the task force was the completion and publication of a glossary of battery testing terms developed by the task force. It provides a set of carefully written definitions for use by all who need to understand and interpret battery test results.

Task force members are submitting raw point by point data to INEL to be incorporated into the Electric Vehicle and Battery Test Database. This database format was developed at INEL in cooperation with the task force to serve as the central repository for test results of selected batteries based on maturity of development and significance.

Future activities include developing additional standard testing procedures and further work on the testing database. Also, the group will continue its important task of coordinating the diverse battery testing activities of member laboratories to insure accurate results and avoid duplication of effort.

Computer Modeling

In support of the DOE Electric and Hybrid Propulsion (EHP) Program, ANL developed software packages for technical analysis and modeling of batteries and electric vehicles. During FY 1989, the software package named MARVEL was improved to increase its effectiveness as an analytical tool. MARVEL examines the allowable battery design tradeoffs and derives the characteristics of an EV battery which provides the least-cost optimization for any specified electric or hybrid vehicle and for any specified mission. ANL performed selected battery analyses and comparative evaluations in support of the DOE/EHP Division programs using the simulation models. These have included evaluation of candidate batteries for specific end-uses and development of mission-directed goals for battery research. During FY 1989, MARVEL was used to evaluate the range capability and user costs for various electric vans (ETX-II, DSEP, G-Van) with state-of-the-art and advanced batteries being developed in the DOE program. MARVEL, which is a user-friendly system available for the IBM-PC, has been distributed to many different battery developers, EV developers, and EV users for their use.

ANL also continued development of a battery software package named DIANE which enables the accurate prediction of EV performance by modeling the battery's second-by-second current/voltage relationship as a function of battery age and usage. This model also operates on a personal computer, and it is structured with interactive capability. The accuracy of the updated model was validated by comparing the results of the model calculations against measured data obtained for 3 different battery types, 3 different electric vehicles, and 3 different driving profiles; in all cases, the DIANE range predictions matched measured test results to within less than 6%. A plotting menu which allows the user to select the desired graphical output of results was also added to improve data presentation.

Database Development

INEL developed a battery R&D database using the dBase IV data management system. The objective of this project is to consolidate EV battery R&D information, from a variety of sources, into a single easily-accessible database. It is organized into eight (8) information modules, each containing different battery R&D information: (1) Programmatic Information, (2) Projections, (3) Technology Status, (4) Battery Goals, (5) Battery Assessment, (6) Reference Information, (7) Test Results, and (8) Battery R&D Program Plan. Consolidation of the battery R&D information into a single database will facilitate locating relevant information on any major EV battery technology. Also, it will facilitate the updating of battery R&D information.

The relational features planned for this database will allow an authorized user to access information from several different information modules without the need to return to the Master Access Module for transferring from one to the other. A compiled demonstration version of this database was delivered to DOE in mid-year to obtain feedback concerning its content and functionality.

Use of Foreign Components

Section 14 (2) of Public Law 94-413 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 purposes of this Act."

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.

7. Recommendations for Initiatives

The Department of Energy is not considering any new legislative initiatives to further the purpose of the Act. The current legislation is sufficient to stimulate the advancement of EHV technologies to the point where the private sector can determine their viability as transportation options and continue their development into marketable products.

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