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12th Annual Report to Congress
for Fiscal Year 1988

Electric and Hybrid Vehicles Program

U.S. Department of Energy
Assistant Secretary, Conservation and Renewable Energy
Office of Transportation Systems

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Washington, D.C.

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PREFACE

This twelfth 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), 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 1988, significant progress was made toward fulfilling the intent of the Congress in the Act. There has been continuing interest shown by both the automobile manufacturing and supply sectors of our economy in electric and hybrid vehicles. The three major domestic automobile manufacturers are all 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

In March 1987 the Secretary of Energy submitted a Report to the President of the United States, "Energy Security," which was a review of our energy-related national security interests. This Report stated: "Energy-efficiency improvements and the use of alternative fuels for transportation offer great potential for stemming the trend towards increasing dependence on insecure supplies of petroleum. In particular, the potential should be carefully explored for alternative fuel systems-including such possibilities as methanol, compressed natural gas, electricity, ethanol, gasoline-alcohol mixtures, synthetic oil products, and hydrogen." The Department's Electric and Hybrid Vehicles Program is conducting research, development, testing and evaluation activities to assess the use of electricity as an alternative fuel system for transportation.

The transportation sector consumed about 22% more oil than the total domestic oil production in 1988. Transportation's share of petroleum consumption has increased dramatically, as other industry sectors have found alternatives, from 51% in 1973 to almost 63% in 1988 (see Figure 1). However, the production of electricity over this same period has been relatively constant, but the fraction of electricity generated from petroleum has dropped from 17.7% in 1973 to 4.6% in 1988. Therefore, electric and hybrid vehicles present a

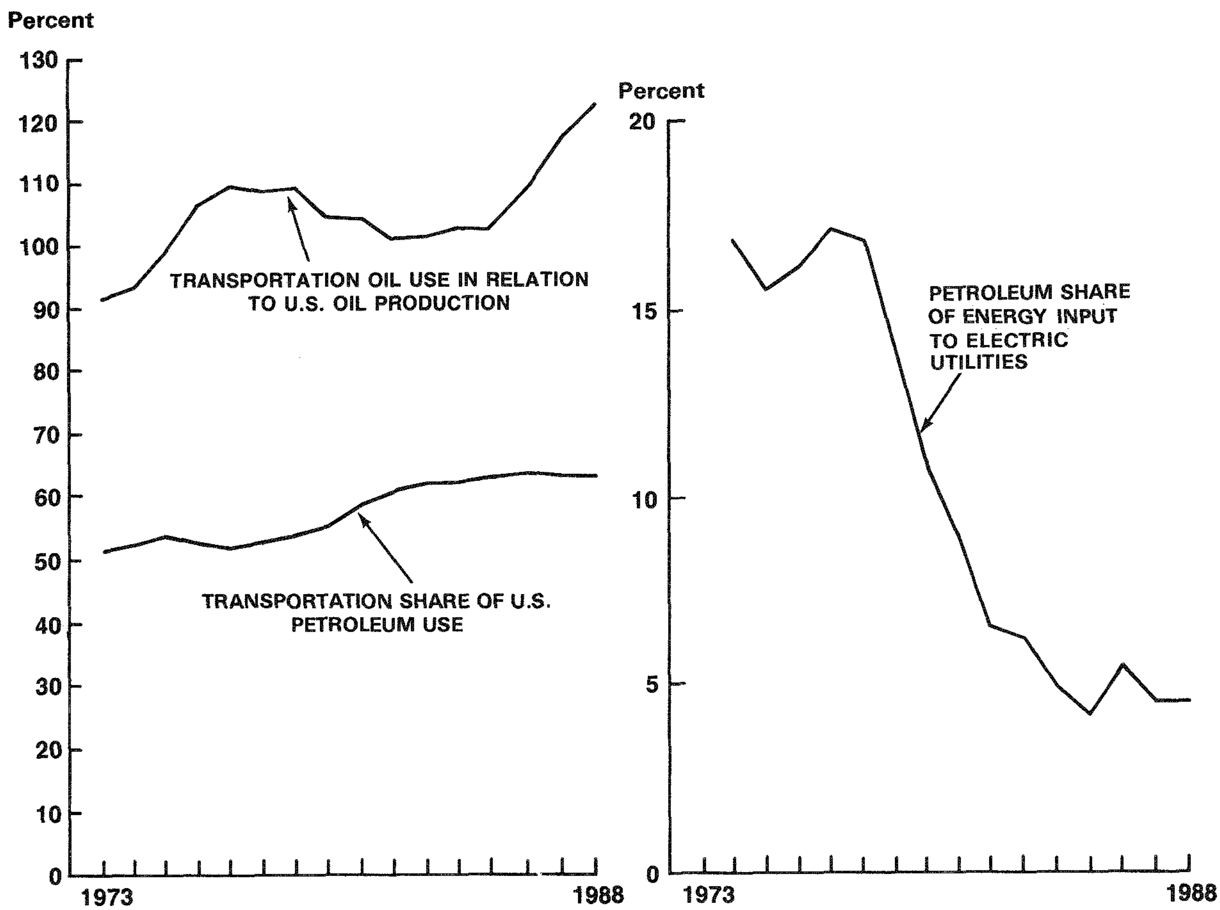

Figure 1. U.S. Transportation and Petroleum Use

link between low petroleum electricity generation and the large transportation sector user of petroleum. Dependence on petroleum in transportation could be reduced by shifting to other energy sources through electricity and electric and hybrid vehicles.

Cognizant of the fuel flexibility inherent in electric vehicles and having just gone through the energy crisis of 1973, Congress passed Public Law 94-413, the Electric and Hybrid Vehicle Research, Development and Demonstration Act of 1976. The Act was to "...encourage and support accelerated research into, and development of, electric and hybrid vehicle technologies...". The Congress and the Administration continued to support this effort with the FY 1988 appropriation for the Electric and Hybrid Vehicles Program of $14.1 million; the FY 1987 appropriation was $13.275 million.

The Act requires that an organizational entity be established to manage the Electric and Hybrid Vehicles Program. The Electric and Hybrid Propulsion Division was established within the DOE Office of Transportation Systems to conduct the assigned management responsibilities. 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 2.

The major participants in the Electric and Hybrid Vehicles Program are listed in Table 1. They include major automotive companies, battery, 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

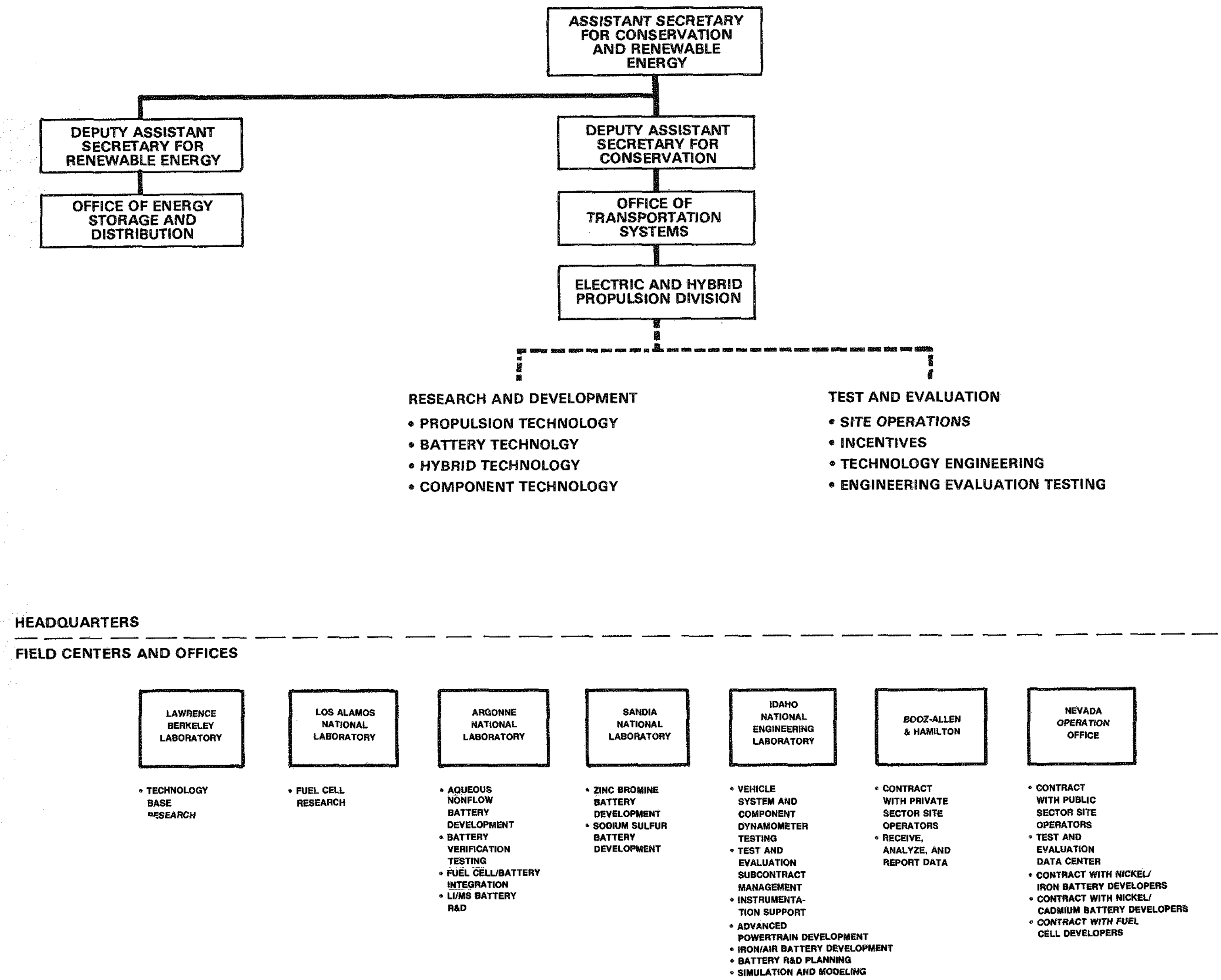

Figure 2. EHV Program Structure

Table 1

Major Participants in the Electric and Hybrid Vehicles Program

	Cost Share of Contract*
Automotive Companies	
Ford Motor Company	5%
Component and Propulsion System Companies	
Booz-Allen & Hamilton	32%
Eaton Corporation	5%
Energy Research Corporation	27%
General Electric	5%
Battery Companies	
Chloride Silent Power	19%
Eagle-Picher Industries	25%
Johnson Controls, Inc.	25%
Westinghouse	8%
Universities	
Georgetown University	14%
Massachusetts Institute of Technology	
University of Alabama	
Virginia Polytechnic Institute	
University of Florida	
Fleet Testing Site Operators[1]	
GTE	73%
Long Island Lighting Co.	60%
Detroit Edison	60%
Northrop Corporation**	34%
Arizona Public Service	42%
University of Hawaii	38%
City of Alexandria, Virginia	50%
City of Huntsville, Alabama**	57%
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 1988

sharing commitment of the participants is also given. Figure 3 is a milestone chart of major programmatic efforts completed and planned under each of the program elements.

The thrust of the Electric and Hybrid Vehicles Program in FY 1988 continued to be on battery and propulsion subsystems development up to the level of the testing and evaluation of proof-of-concept vehicles. The progress being made in developing electric and hybrid vehicle technologies will be described beginning with highlights of recent accomplishments in FY 1988. Detailed descriptions of the program activities during FY 1988 will be given on battery and propulsion systems development 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.

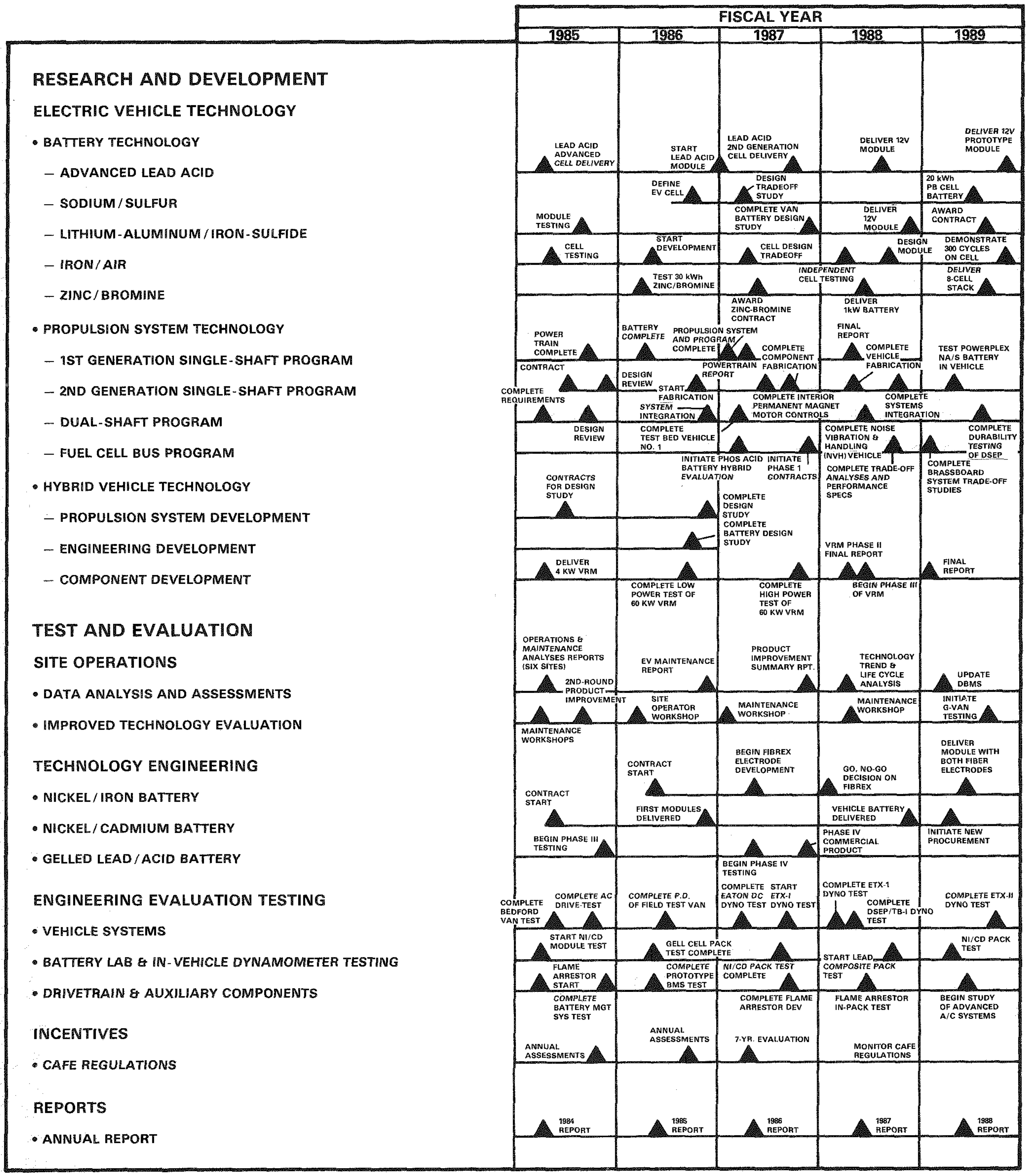

Figure 3. Milestone Chart

2. FY 1988 ACCOMPLISHMENTS

Significant progress occurred in each of the Electric and Hybrid Vehicles (EHV) Program areas during FY 1988. The following are highlights of those achievements.

Research and Development

- Johnson Controls, Inc., constructed a full-size, 12-volt, lead-acid module based on the flow-by design concept during FY 1988. This is the first multicell module fabricated in the flow-by configuration, and represents the logical progression in the technology from the cell level to the module level. This module also demonstrates for the first time a practical design for the integration of the basic cell components and the necessary subsystems required to achieve the desired electrolyte flow. The module is being evaluated to determine its performance and life, and to evaluate the interactive effects among the six series-connected cells when operated under simulated electric vehicle conditions.
- A 36-volt lithium-iron sulfide battery was assembled at Argonne National Laboratory (ANL) from 12-V modules fabricated by Westinghouse Oceanic Division and an improved insulated case fabricated by Meyer Tool and Manufacturing, Inc. Shakedown testing was completed and a test program is scheduled to begin in early FY 1989.
- A new concept of charge control for lithium-iron sulfide batteries that uses an inherent electrochemical process for overcharge protection was demonstrated at Argonne National Laboratory. This eliminates the need for external wires to each cell, increases battery reliability, and reduces battery and charger complexity and cost.
- Under its five-year contract with the Idaho National Engineering Laboratory (INEL), Westinghouse Electric Corporation fabricated and delivered three full-size iron-air cells, employing 400 cm^2 electrodes, for independent evaluation. The first of these cells operated for 113 cycles during a performance characterization test program at ANL. Testing of the second cell was initiated late in FY 1988 and it will be evaluated under SFUDS79 drive cycle conditions. Westinghouse, also, scaled this technology to the five-cell module level, as the next step in optimizing the cell design and studying cell-to-cell interactions.
- The development of the sodium-sulfur technology for electric vehicle applications is continuing at Chloride Silent Power, Ltd., (CSPL). CSPL has interfaced with Ford Research to establish mutually acceptable design criteria and specifications for a sodium-sulfur battery that is compatible with the ETX-II experimental vehicle. The battery is being designed to fit into a prescribed space under the vehicle. However, its performance will be initially evaluated while placed in the cargo area of the vehicle.
- The effort to develop the zinc-bromine battery technology continued at Johnson Controls, Inc., (JCI). During FY 1988, the ETX-II battery requirements were adopted as the program goal. JCI designed a new electrode and flow-frame configuration especially for the EV application. These changes will result in a low-profile stack that is also amenable to vibration welding.
- Road and chassis dynamometer testing of the first test bed vehicle (TB-1) for the

Dual-Shaft Electric Propulsion (DSEP) System Technology Development Program was completed. The test results of this first proof-of-concept system showed performance comparable to that of internal combustion engine powered vehicles.

- The second test bed vehicle (NVH) for the Dual-Shaft Electric Propulsion (DSEP) System Technology Development Program was completed. This vehicle is a more refined version of the first proof-of-concept TB-1 vehicle and offers substantial improvements in subsystem design and performance over the TB-1 system. Durability testing of the NVH vehicle to demonstrate system reliability and compatibility to urban delivery missions in all weather conditions was initiated.
- All subsystems of the Second Generation Single-Shaft Electric Propulsion System (ETX-II) Technology Development Program were completed, bench tested and fully characterized. This advanced propulsion system utilizes new magnetic materials in an interior permanent magnet motor. The motor and transaxle are fully integrated into a single package which contributes to large volume cost reduction and producibility. The small volume package also provides more flexibility in vehicle design, as the motor/transaxle is amenable to an unsprung rear wheel drive, or a sprung front wheel drive configuration.
- The major subsystems developed in the Second Generation Single-Shaft Electric Propulsion System (ETX-II) Technology Development Program were successfully integrated, first on a component dynamometer and then in the test bed vehicle. Development of the sophisticated vehicle and motor control algorithms that are necessary to provide the proper vehicle response from driver inputs (acceleration, braking, etc.) was initiated and is nearing completion. Outstanding characteristics of this advanced system include nearly uninterrupted torque transmission during both transaxle gear upshifts and downshifts and blending of regenerative and friction braking for optimum vehicle driveability and minimum net energy consumption.
- A sodium-sulfur battery developed for electric vehicle application has been incorporated into the Second Generation Single-Shaft Electric Propulsion System (ETX-II) Technology Development Program. The fabrication of the battery and the development and fabrication of a suitable microprocessor based battery controller was completed. The battery controller governs all aspects of battery management including thermal control, over voltage protection and over discharge protection. This controller is in constant communication with the vehicle system controller providing information and direction that will optimize the life and performance of this advanced technology battery subsystem.
- The team of Booz-Allen & Hamilton/Chrysler/Engelhard completed the design of a liquid-cooled phosphoric acid fuel cell/battery powered bus system. Tradeoff studies and economic analysis were performed to establish the detailed design for the fuel cell/battery power source and propulsion system for an urban bus application. Specifications were developed for a 55-kW brassboard system (25-kW fuel cell & 30-kW battery) which will be constructed and evaluated in FY 1989.
- The team of Energy Research Corporation(ERC)/Los Alamos National Laboratory/Bus Manufacturing, Inc., completed the design of an air-cooled phosphoric acid fuel cell/battery power source and propulsion system for an urban bus. ERC built and tested a one-eighth scale breadboard system consisting of a 7.5-kW air-cooled atmospheric-pressure fuel cell stack and a 4-kWh nickel-cadmium battery with appropriate interface controls. ERC also developed specifications for a 55-kW brassboard system (32-kW fuel cell and 23-kW battery) which will be constructed and evaluated in FY 1989.
- The mission-directed electric/hybrid vehicle analysis software program (MARVEL) developed by ANL was modified and improved during FY 1988. Battery and vehicle datasets contained in the software package were created and/or updated to

reflect an improved understanding of the battery and vehicle technologies, and to respond to the needs of the electric vehicle development community. A battery performance software package (DIANE) was developed at ANL for predicting the range and accelerative performance of candidate battery systems used in electric vehicles.

- INEL initiated the development of a multi-year battery R&D program plan for DOE. This is a technically-based program plan, utilizing the results of the mission-directed battery assessment. Multi-year R&D programs, directed at resolving the critical technical issues for each technology, are being formulated as part of this plan. It will provide guidance in the future structuring and funding of advanced battery R&D programs for EV applications. This plan will be submitted to DOE during the first quarter of FY 1989.

Test and Evaluation

- Arizona Public Service (APS) took delivery of three Ford Escorts converted for electric vehicle applications by Soleq Corporation. The EVCORTS are equipped with inverter driven air conditioning, a vehicle heater, a temperature compensated dc/dc converter and regenerative braking. The vehicles are performing well including the air conditioning system which maintained the interior temperature at 72 degrees with ambient temperatures of 100 degrees Fahrenheit.
- The test period for the six GM Griffon vans located at Detroit Edison (DECO) has been extended until 1989. During the past four years, the vans have been employed in a variety of missions including commuting, demonstrations, delivery and special testing using an on-board vehicle data acquisition system. DECO reported that the vans have performed well consistently and accumulated 23,137 miles during the year.
- The Johnson Controls Inc., Phase IV Gel/Cell battery is being tested at DECO and GTE. Phase IV batteries were installed on one GM Griffon at DECO and on seven Jet 750 pick-ups at GTE. The Phase IV incorporates an optimized battery case design and has improved energy density, longer life and reduced manufacturing cost over the Phase III. The battery pack at DECO that was placed on a Griffon van has been operating for one year and is near end of life. DECO reported that the battery saves approximately 15 minutes per month on maintenance time and averaged a distance of 30 miles per charge.
- Arizona Public Service (APS) has redesigned the electronics of the Turbo Electric Battery Pack Warning Device and the On-Board Battery Monitor as well as the Lester Smart Charger. In addition to the redesign which includes updated electronics, one circuit board is utilized for all three devices. The combined unit which occupies a smaller volume and saves on manufacturing costs has been operating for a year with no failures. APS is constructing 12 combined units for use in its vehicle fleet.
- Northrop, who is testing the recased nickel-iron battery, decided not to extend its subcontract upon completion of present contractural obligations. However, Northrop agreed to donate three nickel-iron powered South Coast Technology Rabbits to other DOE test and evaluation sites. INEL will receive two pickups and the University of Hawaii will receive a sedan. Northrop vehicles have logged over 87,258 miles during their involvement in the DOE program. The nickel-iron batteries have operated consistently since recasing over a year ago and are still performing at or near capacity.
- The University of Alabama (UAH) continued to successfully test a microprocessor based charging system in a roadable vehicle equipped with Gell/Cell batteries. The system insures an even charge and minimal gassing on a module level where previous systems viewed the multi-module battery pack as a single unit. UAH has also developed a single wire data collection system to support the charging system, greatly simplifying the earlier one wire per module system.

- The Energy Research Corporation (ERC) continued the development of rollbonded electrode technology for nickel-cadmium traction batteries. An analysis of the electrodes by Rutgers University determined that the diffusion rate limitation of the electrolyte into the electrode decreases battery performance at high current demands.
- The development of the dual battery van by Soleq is showing promising performance with an automatic transmission modified to match the speed and torque characteristics of the electric motor. The van also incorporates a DC-DC converter that eliminates the need for a 12-volt auxiliary battery entirely.
- Eagle Picher's R&D effort on Ni/Fe with support from National Standard and Rutgers University is showing improvements based on the nickel fiber electrode. In comparison with the standard sintered plague technology the new electrode is showing a longer life, greater capacity, better cycling characteristics and a potential for lower cost. Eagle Picher is extending this technology to the iron electrode in an attempt to reduce reliance on imported materials.
- Argonne National Laboratory (ANL) continued to support the EV Battery and R&D activities. Tests were conducted on full size nickel-iron modules, zinc-bromine batteries, sodium-sulfur cells, lithium-metal sulfide batteries and cells; and flow-by lead-acid cells.
- Johnson Controls Inc., (JCI) under contract to INEL, completed development of flame attenuation hardware capable of inhibiting or mitigating the force of a hydrogen ignition in either nickel-iron or lead-acid batteries. Testing of modified nickel-iron batteries demonstrated a clear reduction in the level of damage incurred from hydrogen ignition in batteries incorporating this hardware. JCI was subsequently granted two patents based on this technology development.
- An assessment of auxiliary power system requirements for electric vehicles performed by INEL determined that the best current dc/dc converter technology is capable of meeting the needs of present and near-term future vehicles, provided that it is packaged in a modular fashion to supply widely varying vehicle loads.
- The first of two Eagle Picher nickel-iron battery systems was procured by INEL for the Chrysler Pentastar-developed TEVAN in a cooperative effort between DOE and the Electric Power Research Institute. These batteries are a high-energy version of a design originally developed for the Dual-Shaft Electric Propulsion Program.
- As a follow-on to previous state-of-charge meter development performed by the Jet Propulsion Laboratory, INEL evaluated the performance of four methods of estimating propulsion battery state-of-charge using actual battery discharge data. Two of the methods were found to yield accuracies of about 10 percent under common EV operating conditions and to be suitable for moderate cost implementation based on current microcomputer technology.
- INEL completed an extensive series of performance tests on the Ford ETX-I Single-Shaft AC Propulsion System test bed vehicle, which demonstrated a powertrain DC energy consumption of about 0.2 KWh/km on the Federal Urban Driving Schedule and acceleration from 0 to 80 km/hr in about 21 seconds. The tubular lead-acid battery system developed for this vehicle by Chloride Silent Power Ltd., achieved a high specific energy of 32 Wh/kg.
- The Massachusetts Institute of Technology successfully tested a full size (60 kW) variable reluctance motor and inverter at the General Electric dynamometer test facility. Test results confirmed that high efficiency (95+ percent) can be maintained over the entire motor operating range by using a microcomputer-based control strategy which optimizes motor operating parameters at every operating point.

3. RESEARCH AND DEVELOPMENT

Research and Development activities (R&D) 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, Propulsion System Technology, Hybrid Vehicle Evaluation, and Component Development. The activities conducted in FY 1988 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 the DOE conducted research and development on flow-by lead-acid, lithium aluminum-iron sulfide, iron-air, sodium-sulfur, and zinc-bromine battery technologies during FY 1988. 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. The chart in Figure 4 provides the current status of these electric vehicle battery technologies.

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 (1988 $/kWh)	Cycle Life (Cycles to 80% DoD)**	Cost/Cycle/kWh (1988 $)
Flow-Thru Lead-Acid	JCI	C472	C	47	104		130***	
(Pb/A)			BG	56	79	72	450	0.16
Zinc/Bromine	JCI	J-1	B	55	88		142***	
(Zn/Br_2)			BG	75	79	75	600	0.12
Lithium Aluminum/ Iron Sulfide	ANL/ Westinghouse	36V	M	90	86		130	
(Li Al/FeS)			BG	100	106	91	600	0.15
Sodium/Sulfur	CSPL	PB	M	96	130		550	
(Na/S)			BG	100	106	91	600	0.15
Iron/Air	Westinghouse	W-3	M	70	50		> 120	
(Fe/Air)			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).

Figure 4. EV Battery R&D Technology Status

Advanced Lead-Acid Battery

R&D activity for the flow-by lead-acid battery is managed for DOE by Argonne National Laboratory (ANL). This activity includes battery technology R&D, experimental evaluation of development hardware, and battery application studies and assessments.

Johnson Controls, Inc., (JCI) continued the development of an advanced lead-acid battery in the third year of a four-year $3.3 million contract under 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 an innovative concept whereby the forced flow of electrolyte through the porous lead and lead dioxide electrodes is employed to achieve a dramatic increase (85%) in the utilization of these materials. During FY 1988, two prototype flow-by cells constructed by JCI were delivered to ANL for testing and evaluation. The most recently delivered cell displayed the best performance of any lead-acid battery to date, with a specific energy of 54 Wh/kg at the three-hour discharge rate in the ANL tests. When the cell was evaluated under the power demands of the Federal Urban Driving Schedule for an electric van, a simulated range of 87 miles was obtained, exceeding the performance goal of a 75-mile range capability for this technology. The cycle life of flow-by cells remains limited, however, with a life of only 130 cycles to date in the best cells at JCI. Present R&D efforts in the development program are aimed at improving the cycle life of the flow-by technology. During FY 1988, JCI also constructed a full-size, 12-volt, lead-acid module based on the flow-by design concept (See Figure 5). This is the first multicell module fabricated in the flow-by configuration, and represents the logical progression in the technology from the cell level to the module level. This 70-Ah module also demonstrates for the first time a practical design for the integration of the basic cell components and the necessary subsystems required to achieve the desired electrolyte flow. The module is being evaluated to determine its performance and life, and to evaluate the interactive effects among the six series-connected cells when operated under simulated electric vehicle conditions.

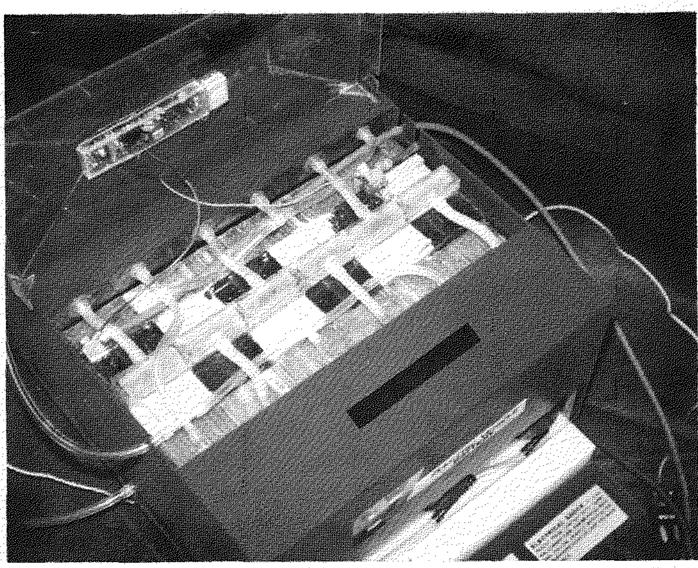

Figure 5. JCI 12-Volt, Flow-by-Lead-Acid Module

Lithium Aluminum-Iron Sulfide Battery

Development of a high-performance proof-of-concept lithium/iron sulfide van battery was continued at Argonne National Laboratory (ANL) in a program co-sponsored by DOE and the Electric Power Research Institute (EPRI). During FY 1988, a new concept of charge control was demonstrated in several cells at ANL in which an inherent electrochemical process ("lithium-shuttle") is employed to prevent overcharging the battery. Implementation of this concept in a battery will result in simplification and cost reduction of the charger. ANL has assembled a battery (Mark-II, 36-V) from 12-V modules fabricated by Westinghouse Oceanic Division (Chardon, Ohio) in an improved insulated case fabricated by Meyer Tool and Manufacturing, Inc., (Oak Lawn, IL). Shakedown testing of the Mark-II has been completed. A test program that includes performance evaluation under a computer-controlled van driving schedule, investigation of charging control, and life cycle evaluation is scheduled to begin early in FY 1989.

Iron-Air Battery

Idaho National Engineering Laboratory (INEL) manages and administers the engineering development of iron-air batteries at Westinghouse Electric Corporation. This five-year $5.5-million cost-shared (8%) contract was initiated in January 1987. It emphasizes air-electrode development and hardware scale-up to a full-size battery for evaluation in an electric van. During FY 1988 Westinghouse investigated methods of rigidizing the air electrode, while simultaneously increasing its power and life capabilities. Several promising options were identified for evaluation in full-size EV cells. Also, Westinghouse delivered three cells for independent evaluation and scaled the iron-air technology to five-cell modules (See Figure 6). With the increases being sought in air-electrode power and life, iron-air batteries could achieve the desired performance and operating characteristics for an EV power source, at a very attractive first cost.

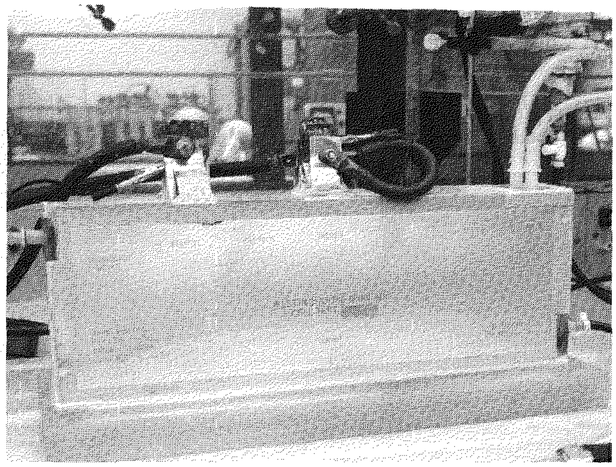

Figure 6. Westinghouse 5 Cell Stack (19½″ L × 6″ H)

Sodium-Sulfur Battery

In September of 1986, Sandia National Laboratories (SNL) placed a 19%, cost-shared contract with Chloride Silent Power, Ltd., (CSPL) to develop the sodium-sulfur (Na/S) technology for electric vehicle applications. SNL is responsible for the technical direction of the development contract and, in addition, performs material research, component evaluation, and environmental testing. The overall objective of this three-year, $1.5M effort is to complete the engineering development and evaluation of low-cost, long-life cells and proof-of-concept batteries that demonstrate high specific energy and high specific power. The contract was modified during FY 1988 to allow a sodium-sulfur battery to be designed specifically for the ETX-II experimental vehicle. The additional cost incurred by this modification is $500K. During the past year, CSPL has focused their efforts on the development of the insulated container and the evaluation of potential thermal management systems.

As part of Sandia's internal evaluation of the Na/S technology, 9 cells from CSPL and cells from Powerplex were tested. Parametric, simplified FUDS, and peak power tests were performed and successfully completed on a variety of these cells. A corrosion problem with the seal material on the CSPL cell was identified that contributed to a redesign of the seal; cells with the new seal are presently being tested. The first two Powerplex cells failed with less than 100 cycles. The latter four cells exhibited a strong capacity dependency on discharge rate.

During the process of identifying two candidate latent-heat-storage salts that could be used in a passive thermal management scheme, all practical aspects of using these salts were characterized including: preparation techniques, relevant physical properties, containment alternatives, and heat transfer properties. CSPL is currently using one of these salts in its conceptual passive system design for the ETX-II program.

Zinc-Bromine Battery

Sandia placed a three-year, $2.3M, 25%, cost-shared contract with Johnson Controls, Inc., (JCI) in December 1986, to design, fabricate, and evaluate an improved zinc-bromine battery system suitable for electric vehicle propulsion. Similar to the sodium-sulfur battery effort at CSPL, the JCI program has been restructured to address the ETX-II battery requirements. A battery design utilizing the new "V" stacks was reviewed and accepted. Engineering issues that were addressed in the new design included the injection molding of flow frames and establishing designs suitable for vibration welding. Fundamental work continued in the areas of cathode activation layer, electrolyte compositions, and material stability and durability. The performance of an early 8-cell module (See Figure 7) was evaluated at Sandia. The life-cycle testing was terminated after 88 cycles due to low efficiencies caused by poor electrolyte flow uniformity.

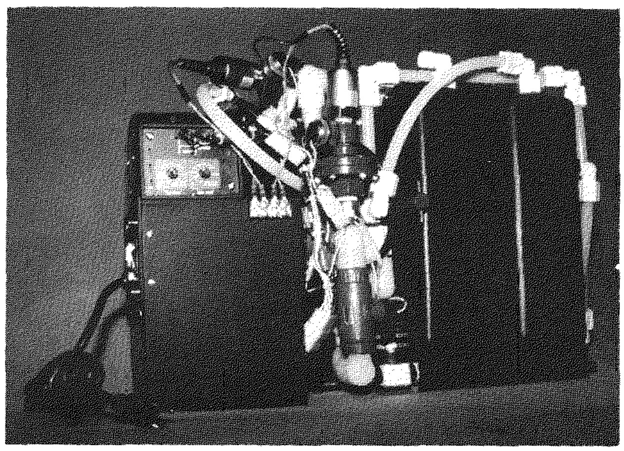

Figure 7. Automatic Test Station for 8-Cell Deliverable

Propulsion System Technology

The objective of the Propulsion System Technology Development Activity is to concurrently advance battery and powertrain technologies 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 should it become in their business interests to do so.

Dual-Shaft Electric Propulsion System Program (DSEP)

The Dual-Shaft Electric Propulsion (DSEP) System Technology Development Program is aimed at advancing electric propulsion technology through the integrated development of a nickel-iron battery, an AC motor and controls, and a two-speed automatic transaxle within a light weight van suitable for use in an urban/suburban environment (the motor and transaxle are arranged on two parallel axes, hence the term "dual-shaft"). The program is scheduled for completion in June 1989.

The DSEP program industrial research team includes Eaton Corporate Research and Development, Detroit 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 test vehicle modification and integration. This team is sharing 5% of the research cost.

The objectives of this 54-month program are to design, test and develop three advanced experimental proof-of-concept propulsion systems installed in vehicles. Two of these are to be thoroughly tested for performance, reliability and durability. The third complete vehicle/propulsion system—incorporating the technology developed under this program—is to be built, function-tested and delivered to the Government for further independent tests and evaluation. In its fourth year, the program has continued to make solid progress toward achieving those objectives.

All tests of the first test bed vehicle (TB-1) were satisfactorily completed in early 1988, the results exceeding most of the ambitious performance goals. Table 2 lists the goals against the actual measured performance of TB-1:

The second test bed vehicle, designated for noise, vibration and harshness tests, was converted to accept the electric powertrain. A DSEP system of a revised and improved design was installed and made ready for durability and noise, vibration, harshness tests at Chrysler Corporation's Chelsea (MI) Proving Grounds. The performance of this vehicle is expected to meet all goals. An endurance test plan for accelerated life testing was generated in cooperation with Chrysler engineering specialists. The plan provides for accumulation of the wear-and-tear equivalent of a lifetime of normal use in just a few months of testing at the proving grounds. The test commenced in August 1988. Figures 8 and 9 depict the installation of the battery pack and powertrain into the vehicle and Figure 10 shows the second vehicle on the test course.

The third vehicle (TB-2) of the DSEP program

Table 2

Acceleration:	**Goals**	**Actual**
0-80.4 km/h (50 mph)	20 sec.	20.5 sec.
0-48.3 km/h (30 mph)	10 sec.	8.0 sec.
Top Speed:	90.6 km/h (60 mph)	112 km/h (70 mph)
Gradeability:		
from rest	in excess of 20%	28%
maintain 88.5 km/h (55 mph)	on 3% grade	4%
Range:		
72.4 km/h (45 mph)	104.7 km (65 mi)	93.3 km (58 mi)

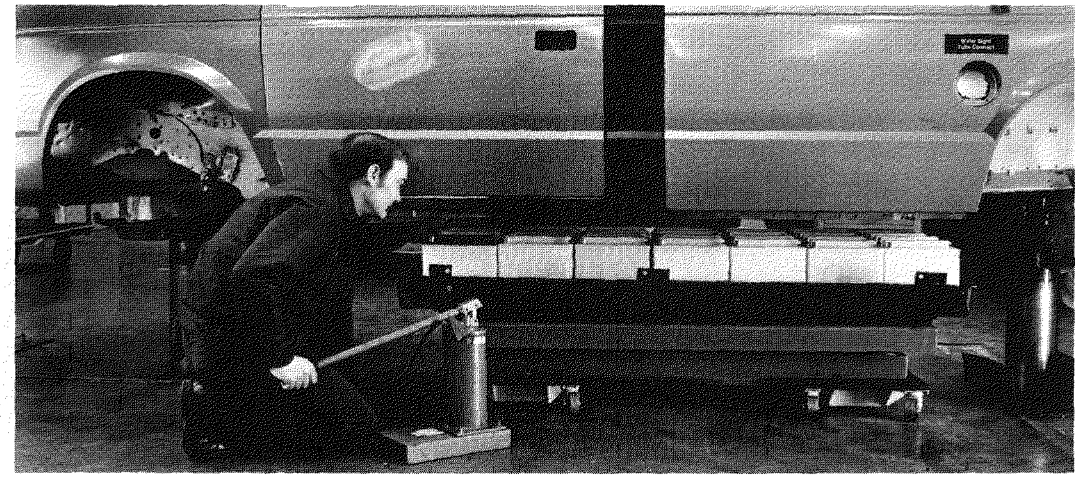

Figure 8. Installation of NI/FE Battery Pack in DSEP

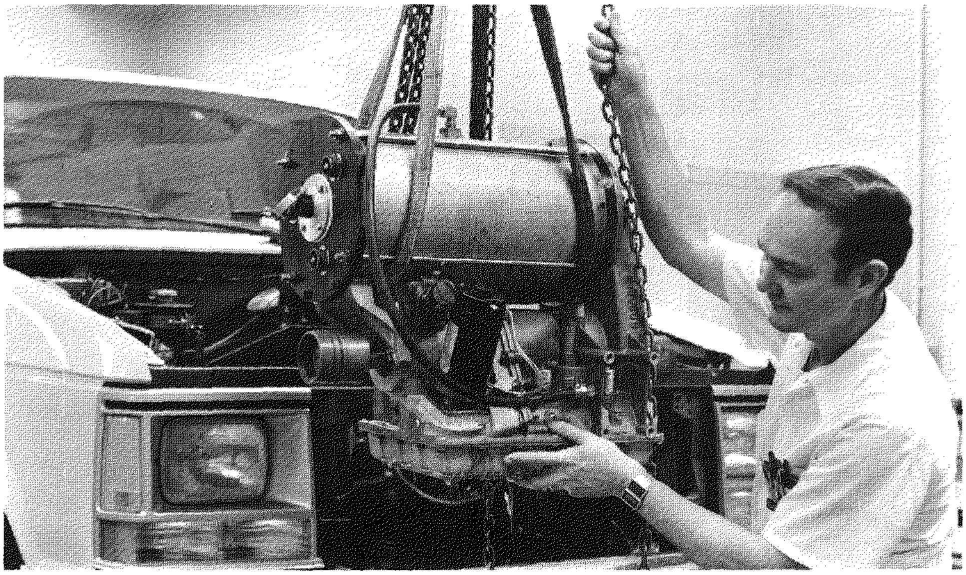

Figure 9. Installation of Powertrain in DSEP

Figure 10. DSEP Vehicle Operating on Test Track

is under construction. Further improvements in the overall system resulting from the durability tests of the second vehicle are expected to be incorporated in this TB-2 vehicle prior to delivery to the Government.

Life tests of the Ni/Fe battery subsystem were continued with two battery packs (at Argonne Labs and Eaton, respectively), and with one single module (at Eagle-Picher). Each of the two packs (nominally with 28 modules in each) have accumulated more than half of the 1200-cycle goal. The pack at Argonne has been subjected to accelerated life testing and suffered some accidental heavy overcharge. While the rest of the pack continues to test satisfactorily three modules have recently been removed due to inadequate performance. The single-module test was terminated just short of the goal, at 1060 cycles, for the same reason. Examination of all four removed modules indicates a prevalent, single assignable cause—a manufacturing quality control problem with the iron electrode. The deficiency has surfaced now, after prolonged testing. It is being addressed with the off-shore Swedish source. However, the manufacture of all six packs and spare modules required for the program was already completed before the material defect became perceptible. However, the battery packs in the test bed vehicles have performed satisfactorily in over-the-road and proving grounds tests enabling the vehicle to be fully characterized.

The task of the complete vehicle life cycle cost analysis and future planning for the product was addressed this year. The life cycle cost will focus on electric vs. gasoline-powered light delivery van comparison. A detailed manufacturing cost estimate is nearly completed for three different annual production quantities. Indications are that the DSEP program subcontractor for vehicle conversion, ASC Incorporated, may be interested in taking a lead role in overall vehicle responsibility in the commercialization of the product.

2nd Generation Single-Shaft Electric Propulsion System Program (ETX-II)

The ETX-II Program is advancing overall propulsion system technology through the integrated advancement of sodium-sulfur battery subsystem technology and single-shaft alternating-current powertrain technology. Ford Motor Company is the prime contractor and General Electric is a major subcontractor. General Electric is responsible for the electric subsystem, which includes the motor, its controls, and the inverter, including the power modules. Powerplex Technologies Inc., has also been added as major subcontractor and will supply the sodium-sulfur battery used in the program.

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. Many major technological advances will result from the ETX-II research program. Included among these are: 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. Figure 11 shows the ac motor/transaxle and inverter being installed in the ETX-II and the ETX-II vehicle on the test track at Ford. 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 of the system design trade-offs. In addition to Powerplex Technologies Inc., Chloride Silent Power Limited is also expected to supply a traction battery for test in the ETX-II propulsion system.

Major progress was made during FY-1988. The build and bench testing of all major subsystems has been completed. The transaxle has been operated on the dynamometer. Packaging of the subsystems in the test bed vehicle has been completed. All major components, with the exception of the traction battery, have been packaged in a location compatible with production considerations. The battery will be installed on the load floor for this program. The test vehicle, with all of the subsystems installed, has been operated on a chassis dynamometer and system integration and testing has been initiated.

Considerable work has also been done using the electric vehicle simulation program to evaluate the effects of design changes and to help design the subsystem control algorithms. These simulations have been expanded to include new features, such as the auxiliary loads, and have been used exten-

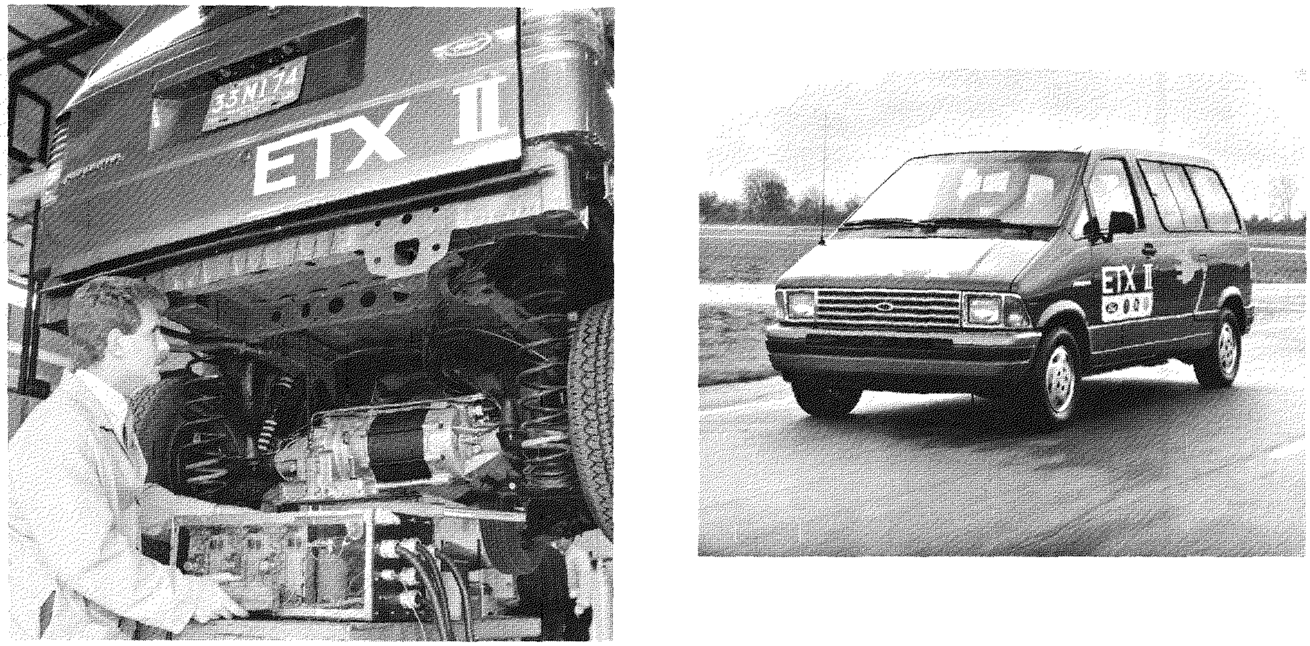

Figure 11. Installation of AC Motor/Transaxle and ETX-II on Test Track

sively to establish the design criteria for transmission shifting and to specify an optimized battery design. The simulation is also used to keep track of subsystem design status.

This program, which is approximately three-fourths complete, 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 initiated a Congressionally mandated program to conduct research, development, and demonstration of a Fuel Cell/Battery Powered Bus System Program in FY 1987. This effort is a joint program co-sponsored by DOE and the Department of Transportation/Urban Mass Transportation Administration (DOT/UMTA). Argonne National Laboratory provides the technical management for these activities, and Georgetown University provides additional support under a cost-sharing (14%) contract with DOE.

Fuel cells potentially can provide the range advantages of an internal combustion engine, but with clean and quiet operation using non-petroleum based fuels. The objectives of this program are to develop, evaluate, and show the feasibility of a methanol-fueled phosphoric acid fuel cell/battery technology aimed at proof-of-concept via a small urban test-bed bus; to advance the fuel cell/battery and control technologies in an integrated fashion for urban bus applications; to show the technology viability for urban bus applications; and to advance the technology so as to provide an alternative for diesel-powered buses.

During FY 1988, Phase I of a planned four-phase program was initiated. 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 definitions and trade-off analyses, and culminates with the fabrication and evaluation of a fuel cell/battery laboratory brassboard propulsion system. Phase II will encompass the development of the proof-of-concept fuel cell/battery power source and the power train components, and the integration of these into a test-bed bus. Track testing and field evaluation of this test-bed 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 small fleets of prototype buses in various urban applications. The results of Phase IV will provide the data and experience needed by industry to make commercialization decisions.

The fuel cell/battery hybrid propulsion technology being developed in this program must satisfy the requirements of the urban bus application, many of which are unique and new for fuel cell power sources. Evaluation of the state-of-development of the various fuel cell types led to the selection of the phosphoric acid fuel cell as being the only viable candidate for the bus application in the next few years. Furthermore, the continuous start-stop operating mode of an urban bus imposes wide power demand swings (peak to average power ratios of 3 to 1 or more) on the power source, along with rapid transient response requirements. For maximum energy efficiency the recovery of the bus kinetic energy through use of efficient regenerative braking is desirable. These performance considerations led to the selection of a fuel cell/battery hybrid power source as being the most compact, efficient and cost effective. The fuel cell can be sized to provide the average power requirement with the additional power required during acceleration supplied by the battery which can also readily accept the regenerative braking energy. This also eliminates the need to develop a fuel reformer with a rapid transient response. The battery must be capable of efficiently supplying the high acceleration power and accepting the high regenerative braking power while having an acceptable cost and life. Other technical considerations include a requirement for the use of methanol fuel, achievement of acceptable startup times, minimum power source size and weight, and meeting all safety and emission standards.

In FY 1988, the R&D team of Booz-Allen & Hamilton, Chrysler, and Engelhard began work on a two-year $2.1 million cost-shared (32%, negotiated up from an original proposal of 13%) contract to develop a liquid-cooled phosphoric acid fuel cell/battery brassboard system. Also in FY 1988, the R&D team of Energy Research Corporation (ERC), Bus Manufacturing USA, Inc., (BMI), and Los Alamos National Laboratory started work on a $2.5 million cost-shared (27%) contract to develop an air-cooled phosphoric acid fuel cell/battery brassboard system. After completion of the brassboard evaluations in Phase I, a decision will be made to select one technology for the Phase II effort. Figure 12 shows both the liquid-cooled and air-cooled fuel cell concepts being developed.

During FY 1988, the team of Booz-Allen & Hamilton/Chrysler/Engelhard completed the design of a liquid-cooled phosphoric acid fuel cell/battery powered bus system. Tradeoff studies and economic analysis were performed to establish the detailed design for the fuel cell/battery power source and propulsion system for a 27-ft, 20-passenger urban bus. Specifications were developed for a 55-kW brassboard system (25-kW fuel cell & 30-kW battery), which will be constructed and evaluated in FY 1989.

During FY 1988, the team of Energy Research Corporation/Los Alamos National Laboratory/Bus Manufacturing, Inc., completed the detailed design of an air-cooled phosphoric acid fuel cell/battery power source and propulsion system for an urban bus. ERC built and tested a one-eighth scale breadboard system consisting of a 7.5-kW air-cooled atmospheric pressure fuel cell stack and a 4-kWh nickel-cadmium battery with appropriate interface controls. ERC also developed specifications for a 55-kW brassboard system (32-kW fuel cell and 23-kW battery), which will be constructed and evaluated in FY 1989.

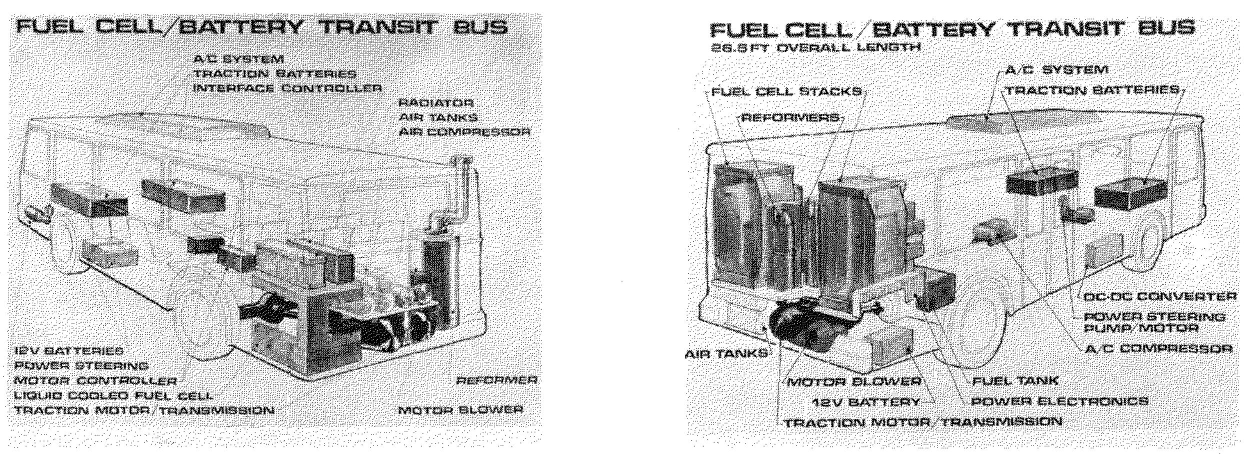

Figure 12. Fuel Cell Battery Powered Bus Systems

Hybrid Vehicle Evaluation

Although the hybrid vehicle program has not been funded since 1985 DOE is continuing a small in-house activity to keep abreast of current developments. The Electric Power Research Institute (EPRI) has signed a contract with Chloride EV Systems of Great Britain to conduct a design study of a range extender hybrid. The range extender is a separate engine/generator unit to be added temporarily to an electric vehicle for missions beyond the capacity of the battery. The design study is scheduled for completion in December 1988. There may be emission problems with the 6 to 7 KW portable power units considered for the range extender. Following completion of the design study EPRI plans to fund the construction of a proof-of-concept vehicle for field testing.

Volkswagen is developing both gasoline and diesel/electric hybrid systems utilizing the VW Golf vehicle. They will incorporate either lead-acid, sodium-sulfur or nickel-cadmium batteries with standard gasoline or diesel Golf engines. The unique design includes a novel motor/flywheel unit which is also used to start the engine. Possible production is being considered for the end of 1990.

Component Development

The motor construction and refinement portion of the Variable Reluctance Motor (VRM) project at the Massachusetts Institute of Technology (MIT) is complete. The final report on the high power testing of the motor and inverter at the General Electric Laboratories will be delivered to DOE during the first quarter of FY 1989. The industry cooperator in the construction phases of the project, Superior Electric, has a family of these motors now in their sales line for applications, such as robotics and material handling. The 65 kg (168 lb.), 60 kW (80 h.p.) motor is 20 cm (8 in.) in diameter and 30 cm (12 in.) in length. The motor weighs less than 2 pounds per horsepower compared with 5 pounds per horsepower for a current technology DC motor. This is made possible through its high efficiency (95%) and short effective flux paths. The moderate speed of the motor (12,500 rpm) will allow coupling directly with most conventional transmissions, avoiding large gear reductions which are common with high horsepower motors of small size.

The VRM program generated a method of determining motor-rotor position and direction of rotation without the aid of a shaft encoder. The microprocessor method of observation and control has been feasibility tested by both MIT and several major permanent magnet motor manufacturers and found to work equally well with that motor type. The VRM project will continue in the second quarter of FY 1989 with the development of a controls mapping technique.

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 Operations, Technology Engineering and Engineering Evaluation Testing. The activities conducted in FY 1988 within each of these T&E elements are described below.

Site Operations

During FY 1988, the emphasis of EV site operation activities was placed on improving vehicle utilization through more careful performance and mission correlation, and in analyzing field test data to obtain a more thorough understanding of the technical and economic issues associated with the current and projected electric vehicle (EV) technologies. A decision was also made to gradually deemphasize the upgrading of the older vehicles in the fleet and start integrating small quantities of newer technology vehicles as they become available.

The number of site operators was reduced from 10 at the end of FY 1987 to the current eight operators in 17 locations as vehicles were retired or phased out of the program. Included among the remaining sites are four private sector site operators and four public sector site operators including the U.S. Navy, which is the largest user of EVs with eight active site locations and approximately 220 vehicles. The U.S. Navy receives most of its vehicles from other site operators that have completed their contractual obligations. Table 3 shows the sites that are currently in the program.

Significant strides were made in the field test and evaluation of product improvement technologies during the past year in the areas of advanced batteries, new vehicles and maintenance and monitoring devices. A brief description of the test and evaluation programs that were conducted during FY 1988 is given below.

EVs are more attractive when their maintenance can be reduced or eliminated. Therefore, emphasis has been placed on the field testing of maintenance free, immobilized electrolyte batteries including the Johnson Controls Inc., and the Concorde Gel/Cell batteries. The Johnson Controls Inc., Phase IV Gel/Cell battery was tested at GTE and DECO during the year. Both sites have reported a significant decrease in battery maintenance without a substantial decrease in performance. The performance of the Concorde Gel/Cell battery was evaluated at GTE, LILCO, the University of Hawaii and Sandia National Laboratory. The test vehicles were driven on a regular basis throughout the year and performed well. The vehicles in the GTE fleet were utilized in missions with an average distance of 25 miles. Therefore, the maximum possible range attainable with the Concorde batteries was not obtained. However, the vehicles easily met the performance requirements for the missions to which they were assigned. The University of Hawaii achieved a vehicle range of over 50 miles on freeway driving with Concorde batteries in a Ford Escort (EVCORT).

The second area of new products in which testing continued during FY 1988 is in new vehicles. The GM Griffon van entered its fourth year of on the road testing at DECO. The results of the tests at DECO show that the GM Griffon van is a sturdy, reliable vehicle with performance characteristics well suited for the short haul service for which it was designed. During the year the vans were driven a total of 23,137 miles with an average energy consumption of 1.05 kWh/mile.

LILCO completed test and evaluation of the Grumman Kubvan and the Eagle-Picher Escort. The six Kubvans which operated over a three year period, were used for plant security and cargo transport. A few common problems were encountered, such as a broken shift lever and malfunction of the on-board 12-volt charger and logic module. LILCO reported that the vehicles performed well overall and were able to complete their assigned missions.

The six Eagle-Picher Escorts operating in the LILCO fleet were employed in inter-office

Table 3

Electric and Hybrid Vehicle Program Site Operators (Operating During FY 1988)

Private Site Operators

GTE Service Company
- Honolulu, Hawaii
- Pomona, California
- Tampa, Florida
- GTE Laboratories, Waltham, Massachusetts*

Long Island Lighting Company (LILCO)
Northrop Corporation*
Arizona Public Service Company (APS)
Detroit Edison Company (DECO)

Public Site Operators

Alexandria Virginia
Huntsville, Alabama*
Sandia National Laboratories
University of Hawaii

U.S. Navy

Naval Weapons Station
Concord, California*
Naval Air Station
Moffett Field, California
Pacific Missile Test Center
Point Mugu, California
Naval Facilities Engineering
Command, Pearl Harbor, Hawaii*
Mare Island Naval Shipyard
Vallejo, California
Navy Public Works Center
Norfolk, Virginia*
Naval Ordnance Station
Louisville, Kentucky
Naval Weapons Support Center
Crane, Indiana
Naval Air Station,
Bermuda
Naval Underwater Systems Center
Autec, Bahamas
Naval Supply Center
Pearl Harbor, Hawaii
Naval Academy
Annapolis, Maryland*
Puget Sound Naval Shipyard
Bremerton, Washingon*
Naval Construction Battalion
Port Hueneme, California*

*Operations completed in FY 1988.

transportation and as commuter vehicles between home and office. Aside from a few failures, which occurred to the vehicle motor controller and DC/DC converter, the Escorts provided reliable transportation to LILCO's employees.

GTE has installed sealed lead-acid batteries in all of the 29 vehicles remaining in its fleet. The JCI Phase IV Gel/Cell and the Concorde absorbed glass matt batteries are being fleet tested. GTE is also preparing to field test the Eaton dc Lynx vehicle, which has an automatic 3-speed transaxle. The vehicle will be utilized at the GTE Headquarters in Dallas, Texas to evaluate performance and driveability.

Three Ford Escorts converted by Soleq Corporation are being tested at Arizona Public Service (APS). The vehicles are equipped with advanced EV technologies, such as inverter driven air conditioning, an electric heater and regenerative braking. Initial tests of the air-conditioning system has shown that the vehicles are able to maintain comfortable interior temperatures of approximately 72 degrees at ambient temperatures of 100 degrees Fahrenheit. Cool down of the vehicle during recharge can be accomplished by operating the inverter driven air-conditioner from wall plug electricity.

Additional areas of new product technology that were tested during the year are maintenance and monitoring devices. Included among these products are:

Aeromed Battery Pro Module
Turbo Electric Battery Pack Blower Warning Device
Turbo Electric On-Board Battery Monitor
Lester Smart Chargers

The Aeromed module was developed for use with the Concorde Gel/Cell battery and allows the battery to be charged using ferroresonant chargers by limiting the charger voltage. In field and lab tests, it was determined that modifications of the unit would be necessary before it would receive widespread use by the DOE sites.

Turbo Electric designed and developed an on-board battery module for APS. As a result of problems encountered during initial testing and evaluation, APS redesigned and refabricated one unit upgrading the electronics of the unit from transistors to integrated circuits. The unit has been operating one year with no reported malfunctions.

APS also redesigned the Lester Smart Charger. The charger consists of a user programmable temperature compensated charging profile and a system of internal diagnostics for problem identification.

APS placed the three redesigned units on one circuit board and the combined unit has been operating with no malfunctions. APS reported that the combined unit occupies a significantly smaller volume and has lower manufacturing costs as compared to the total volume and manufacturing costs for the three separate units. Twelve combined units are currently being built for use in the APS vehicle fleet.

Additional activities conducted by Booz, Allen & Hamilton during FY 1988 include:

- Updating the EV Database Management System (EVDBMS) which contains critical performance parameters and mission characteristics derived from the site operations for effectively defining the EV duty cycle. Modifications to the database include integrating standard software packages, such as Lotus and dBase to enhance the database's user-friendliness.

- Development of a life cycle cost model that compares EV life cycle costs to competitive alternative fuel technologies, such as gasoline, methanol and CNG in 1988 and 1995. The study determined that light duty EVs are currently not cost competitive with gasoline powered vehicles, but may be by 1995 with the advent of new technology, such as sodium-sulphur batteries and ac drivetrains. Relative to CNG and methanol vehicles, EVs are cost competitive both in the near and long term. The EVDBMS provided the site operator fleet data from which the EVs life cycle cost were computed and actual fleet data from a number of sources was used for the computation of the CNG, methanol and gasoline vehicles life cycle costs.

- Completion of a database for the EV Technology Information System which documents current experience on various EVs and components that have been tested or are under development that could be field tested by Users Task Force members.

- Analysis of the Versatile Data Acquisition System (VDAS) data. A GM Griffon van at DECO and a VW pickups at Northrop and GTE equipped with VDAS have completed their special drive cycles and runs. The purpose of the data collection was to define mission and performance requirements of several EV operations including service runs, delivery operation and commuter duty cycles to aid in the understanding of field related influences on EV performance battery life. Analysis of the data indicated that approximately two weeks of runs at DECO produced statistically meaningful data. The development of VDAS as an ongoing tool for the evaluation of field data is a continuing effort.

- Development of an International EV Programs database which contains programmatic information on EV programs in the United Kingdom, Germany and Japan. The major EV associations, electric utilities, component manufacturers and automotive manufacturers were contacted for information. Responses have been received from the majority of organizations contacted and contain key program information, such as the program sponsor, program milestones and future plans. The information obtained thus far indicated that the overseas programs cover several areas, including new vehicle demonstrations, advanced battery development, such as the sodium-sulfur battery and EV system component development, such as AC drive motor systems.

Technology Engineering

Technology Engineering activities undertake the 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. The chart in Figure 13 provides the current status of electric vehicle battery technologies under this activity with battery goals shown for those batteries still under development. Improved controllers, battery chargers, battery monitoring instrumentation and EV safety issues also are evaluated when enhanced EV capabilities may result from incorporation of these technologies. Battery evaluation was conducted at the University of Alabama in Huntsville; Rutgers University Medical School in Piscataway, NJ; and Soleq Corporation in Chicago, Illinois.

ELECTRIC VEHICLE BATTERY TECHNOLOGY ENGINEERING STATUS

Battery	Company	Type/Model 6 Volt Module	Status	Specific Energy (Wh/kg)	Specific Pk Pwr @ 50% (DoD) (W/kg)	Projected OEM Cost, Vol Prod. (1988 $/kWH)	Cycle Life (Cycles to 80% DoD)	Cost/Cycle /kWh (1988 $)
Gel/Cell Lead Acid	JCI, Globe Battery	GC-6V-200 Traction	M BG	22 32	80 90	50	400 1000	0.05
Nickel/Iron	Eagle-Picher (EPI)	NIF 225	M BG	53 56	110 79	125	500 1125	0.13
Nickel/ Cadium	Energy Research (ERC)	EV 180	M BG	44 53	110 79	80	243 600	0.12

OEM = Original Equipment Manufacturer

DoD = Depth of Discharge

BG = Battery Goals

M = Battery Modules

Figure 13. EV Battery Engineering Status

The University of Alabama (UAH) began characterization of Ni/Cd rollbonded technology and continued life testing of gelled electrolyte lead-acid batteries. The wide temperature range testing plus microstructure analysis by Rutgers University Medical School's Dr. Alvin Salkind produced two discoveries. The life shortening swelling of the battery was caused by growth in the nickel-hydroxide crystal and the excessive temperature rise rate with discharge, capacity loss, and drooping voltage character were due to a severe diffusion limitation. Studies are continuing to determine if diffusion in the basic technology can be markedly improved to save the technology base.

UAH is continuing to life test Phase IV Gel/Cell batteries in a roadable vehicle using an in-house developed charging algorithm. The algorithm requires a small microprocessor but charges all modules in a battery pack uniformly. Previously, some modules would overcharge while some would remain undercharged. The new algorithm requires less overcharge for a complete charge so it is expected that it will extend battery life. The program in its 2nd year should reveal if the charging algorithm meets the needs of an aging battery pack and if it can improve vehicle range reliability as the battery modules age. A cost reduction adjunct to the testing is planned in FY 1989, to determine if the microprocessor controller can control the chargers on more than one vehicle simultaneously, thus reducing the cost of a fleet operator.

The dual battery van powertrain development included some major modifications to an automatic transmission which have made it competitive in efficiency with a manually shifted transmission, but retains its superior drive comfort characteristic. The shift points have been reset to match the speed and torque characteristics of the separately excited electric motor. The van also has a brass board DC-DC converter that can supply 12 volt auxiliary power without the necessity of an auxiliary battery. Elimination of the 12 volt auxiliary battery in an electric vehicle would remove a major failure item, reduce maintenance expense and improve reliability.

Sandia National Laboratories completed the outdoor laboratory retrofit and proof testing of the Phase IV Gel/Cell batteries in the small size pickup truck version of an electric vehicle. The test also included the test of a PMC controller with a chopping frequency above hearing range. Not only does this make the vehicle quieter but the high frequency uses the inductance of the electric motor more effectively as a filter and energy storage element, which in turn improves efficiency.

Technology engineering and research programs to develop the nickel-iron (Ni/Fe) and the nickel-cadmium (Ni/Cd) battery types to a higher state of the art continued. Eagle Picher's R&D effort on Ni/Fe with nickel fiber electrode support from National Standard and microstructural analysis from Rutgers University's Dr. Alvin Salkind has continued to improve. Compared with the standard sintered plaque technology, the nickel fiber structure shows a slower capacity loss in cycling; higher utilization of active material and therefore, more capacity in the same size case; and faster and more complete voltage recovery after a heavy current demand. The thin fiber electrode (0.055 inches) development has been successful so the program now goes into development of the double thickness which is a cost reduction effort in terms of both materials and processing labor. First attempts to make a fiber nickel active iron electrode is promising. The future growth in this development is a fiber iron structure with less of the active iron for lower material cost and greater compatibility in material and recycling potential. A parallel cost analysis is in process to determine the total cost reductions available with the fiber technology over the older sintered plaque technology.

The independent analysis and test program with the University of Alabama (UAH) and Rutgers University on the roll-bonded Ni/Cd technology being developed by ERC has shown that the battery has a severe diffusion limitation of electrolyte into the electrode at high current rates. Electrode analysis revealed the roll-bonded technology has only 40 to 48 percent porosity compared with 80 to 84 percent with sintered nickel and fiber nickel electrodes. Studies are in process to determine if additional solvent in electrode manufacturing or additional electrolyte concentration can reduce the severity. ERC has a nickel coated graphite fiber loaded material in process that may also increase the porosity of the electrode. The current low porosity only prevents the battery technology from being successful and useful in traction applications. It would still have potential for success in applications where the energy demand from the battery is slower than the two hour rate.

Argonne National Laboratory (ANL) continues to support the EV Battery and R&D Activities. Laboratory evaluations are conducted to assess the functional capability of batteries to perform the mission requirements of electric vehicles. Battery performance and life characteristics are evaluated under uniform test conditions that simulate driving cycle load profiles. Tests were conducted on full size nickel-iron modules, zinc-bromine batteries, sodiumsulfur cells, lithium metal-sulfide batteries and cells; and flow-by lead-acid cells. These evaluations provide a measure of the progress in the battery development efforts and provide insight for the direction the research programs should take.

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 Idaho National Engineering Laboratory (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 (FUDS). Battery laboratory capabilities were enhanced during FY 1988 to permit the testing of battery packs under vibration conditions typical of automotive operation, and modifications were begun to the INEL dynamometer to permit some testing of individual EV components, such as motors and transmissions while retaining the capability to test complete vehicles. Figure 14 shows batteries being tested in the environmental chamber and on the vibration table, respectively.

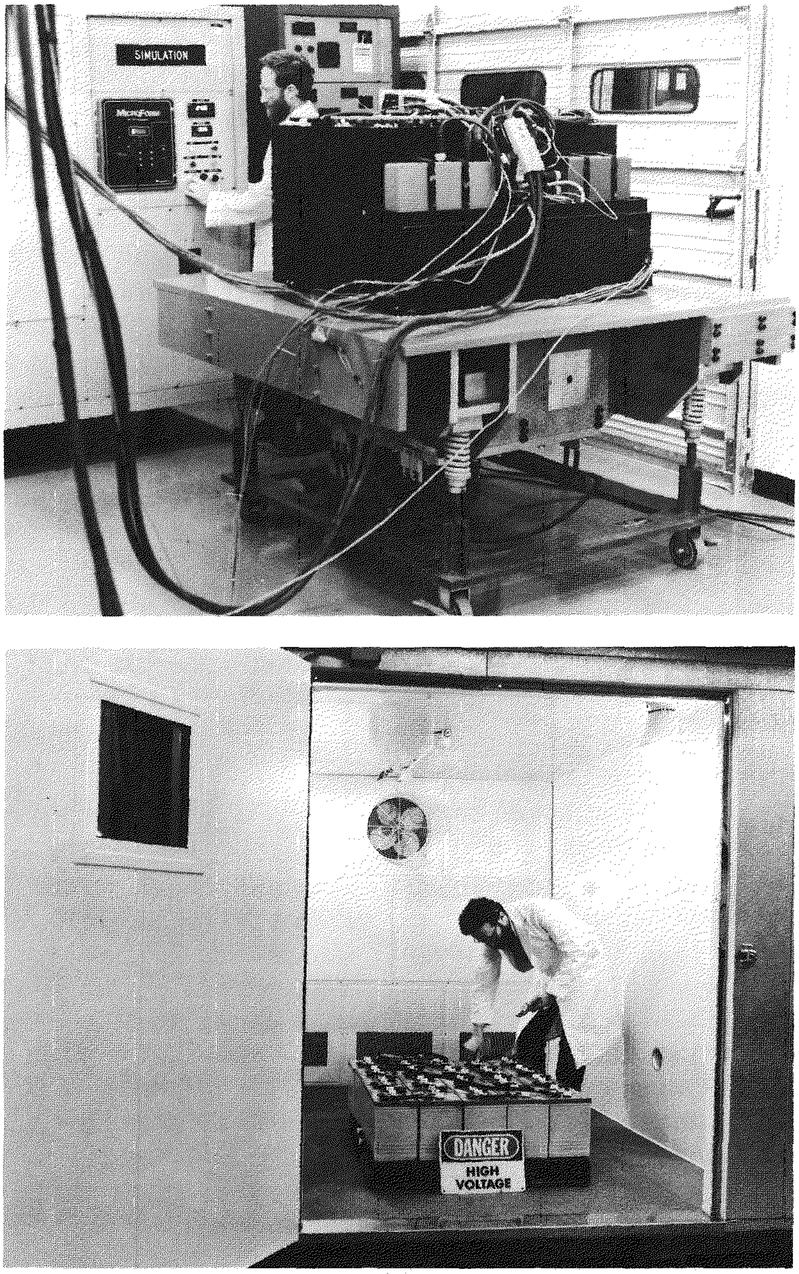

Figure 14. Environmental Chamber and Vibration Testing of Batteries

INEL dynamometer testing during FY 1988 focused on performance testing of electric propulsion systems developed under previous and ongoing DOE sponsored programs. An extensive series of dynamometer tests was completed on the ETX-I AC powertrain packaged in a test bed vehicle developed by the Ford Motor Company. Table 4 shows the results of this testing, which confirmed Ford's predicted and measured powertrain performance while identifying auxiliary and vehicle-related losses.

A limited series of dynamometer tests was performed on the first powertrain test bed vehicle (TB1) developed by the Eaton Corporation for the Dual-Shaft Electric Propulsion (DSEP) Program. These tests, done in preparation for FY 1989 testing of the final deliverable DSEP test bed vehicle (TB2), confirmed the generally excellent performance expected from the DSEP propulsion system in a small van (0-80 km/hr in 22 seconds, net DC energy consumption of 300 Wh/km on the FUDS cycle.) Areas of electromagnetic interference (EMI) were identified for future development concern.

Dynamometer and laboratory testing was also performed on the tubular lead-acid battery system developed by Lucas Chloride EV Systems for the ETX-I propulsion program as well as the nickel-iron battery system built by Eagle Picher for the DSEP program. The Lucas Chloride batteries demonstrated an excellent (for lead-acid) specific energy of 32 Wh/kg in spite of their 3-year age and intermittent use. Testing of the DSEP nickel-iron pack disclosed a declining capacity, which was later found to be due to iron electrode fabrication problems simultaneously discovered by other test laboratories.

Basic performance tests were performed on a new sealed lead-acid battery, which may be produced commercially by Johnson Controls Inc., (JCI). This gel/cell battery demonstrated overall performance comparable to other maintenance free lead-acid batteries previously tested while maintaining the highest specific peak power (over 100 W/kg) at 80% depth-of-discharge of any battery yet tested by INEL.

DOE and the Electric Power Research Institute

Table 4

FORD ETX-I SUMMARY TEST RESULTS

Test Type		Range (km)	Energy Consumption (Wh/km) AC Wall Plug Electricity
48 km/hr	Constant Speed	125.67	204
64 km/hr	Constant Speed	101.52	257
88 km/hr	Constant Speed	66.64	331
D-Cycle	Regeneration	59.47	334
D-Cycle	No Regen	52.76	381
C-Cycle	Regeneration	64.88	333
C-Cycle	No Regen	63.09	399
FUDS	Regeneration	61.88	381

ACCELERATION
(Average time in seconds vs. Battery State-of-Charge)

	100% SOC	54% SOC	33% SOC	11% SOC
0-48 km/hr	7.4	8.4	9.3	10.9
40-80 km/hr	16.0	17.9	20.8	33.4
0-80 km/hr	21.3	23.9	27.7	40.8
0-88 km/hr	29.8	33.5	39.7	59.5

(EPRI) continued their joint sponsorship of the design and fabrication of a half-ton van, intended to produce two operational prototype vehicles. Through a contract with INEL, Eagle Picher fabricated and delivered the first of two nickel-iron batteries, which will be incorporated in the vehicle under construction for EPRI by Chrysler Pentastar Electronics, Inc.

During FY 1988 INEL performed hydrogen ignition testing of nickel-iron batteries modified to incorporate flame attenuation hardware developed under contract by JCI. This testing demonstrated a clear reduction in the level of damage or risk to be expected from ignition of combustible gases in batteries using this hardware as shown in Figure 15. JCI delivered additional prototype hardware which was incorporated into a complete battery pack built by Eagle Picher for the DSEP program. This battery will undergo system-level testing by Eaton and INEL in FY 1989. JCI was granted two patents based on this development program.

Analytical activities during FY 1988 included an assessment of auxiliary power system requirements for electric vehicles. The study established that present dc/dc converter technology can meet the needs of current and near-term future EVs for low-voltage power for support systems (e.g. lights, electronics, passenger comfort) if converters are available in modular packages which can be combined to supply the wide variations in load demands for various EVs (30 to 100 amperes). A retrofit to the ETX-I propulsion test bed vehicle established a usable design approach to provide high reliability auxiliary power.

INEL also evaluated the performance of four methods of estimating traction battery state-of-charge using a common set of actual battery test data. Two of the simpler methods were found to yield a potential accuracy of 10 to 20 percent under common EV operating conditions, which is at least comparable to that achieved by the much more complex method developed by Gould for JPL. Testing will be performed in FY 1989 to establish the practicality of an implementation based on low-cost microcomputer technology.

Figure 15. Ignition Testing of NI/FE Battery at INEL

5. INCENTIVES

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

CAFE Regulations

Section 18 of the Chrysler Corporation Loan Guarantee Act of 1979 (Public Law 96-185) directed the Department of Energy (DOE)

> . . . to conduct a 7 year evaluation program of the inclusion of EVs in the calculation of average fuel economy to determine the value and implications of such inclusion as an incentive engineering development and initial commercialization of electric vehicles in the United States.

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

Planning Grants

There was no activity in this incentive program during FY 1988.

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 1988 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. To date, $870,000 have been recovered out of their $2,170,000 debt.

6. OTHER ACTIVITIES

Studies and Assessments

Impact Studies

Public Law 94-413, Section 13, 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 1988 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 1988.

EV Battery Assessment

During the first phase of an INEL project to produce a multi-year EV battery R&D program plan for DOE, Sheladia Associates, Inc., conducted a mission-directed assessment of all viable secondary batteries. With overall coordination from INEL, Sheladia's team of ten battery and EV consultants worked cooperatively with representatives from ANL, INEL, LANL, LBL, PNL, and SNL to evaluate battery design concepts for the Improved Dual-Shaft Electric Propulsion (IDSEP) van. In most cases industrial, academic, and government proponents of battery technologies responded to a Solicitation for Information by providing fully-integrated hardware design information on their battery technologies as power sources for this light-duty van. Utilizing explicit assessment criteria and an associated scoring system, the battery assessment team evaluated 42 battery design concepts and scored them in the areas of: cost, performance, ruggedness, resource availability, safety/environmental, and likelihood of success.

Twelve battery technologies were identified as possessing characteristics which could result in their successful development as traction batteries for this light-duty van. These batteries were judged to possess IDSEP-van range capabilities of 60-140 miles under SFUDS drive cycle conditions. Although some technologies possess range capabilities at the lower end of this scale, they presented less concerns to the assessment team in other important areas, e.g. cost and safety. The results of this assessment will be published in FY 1989.

EV Battery R&D Program Plan

Utilizing the results of the EV battery assessment as a technical basis, INEL initiated the development of a multi-year battery R&D program plan for DOE in May 1988. The plan is being generated to provide guidance relative to future structuring and funding of EV battery R&D programs and to provide DOE with a basis for exercising technology-based decisions regarding the development of competitive battery technologies.

Multi-year R&D programs are being formulated for the development of the most promising battery candidates for the EV application. These technical plans incorporate technology specific information on: background, projected capabilities, goals, status, critical issues, and R&D schedules-including milestones and tasks. Levels of R&D effort and funding estimates are established for advancing these technologies to the point where industry can make quality decisions regarding their commercial development.

Battery Test Working Task Force

The EHP Battery Test Working Task Force was formed in 1983 to coordinate the battery evaluation work at several DOE-funded laboratories and other government agencies. Member labs in FY 1988 were ANL, INEL, SNL, and TVA. The Task Force met twice in FY 1988 to discuss battery testing procedures, results, reporting methods, and special techniques. Over the years, several new evaluation procedures have been developed, tested, and implemented. Improved data reporting techniques have also been suggested and implemented.

During FY 1988, a significant accomplishment of the Task Force was the publication of a final report describing the simplified FUDS battery test procedure. This procedure was developed by the group in prior years to provide a realistic EV battery test regime. The report documents the methodology used to develop the test. It contains the necessary specifications for other labs to implement and use the procedure. The test should provide more accurate data regarding battery performance and life for the EV application compared to constant current methods used in the past.

Another Task Force activity nearing completion was the Glossary of Battery Testing Terms. This glossary was developed and edited during the last several years for the purpose of clarifying the terminology used to describe battery tests and results. The glossary was in the final publication stages at the end of FY 1988.

The Task Force reviewed INEL's concept for a computerized data base for battery test results. Several suggestions for improving the data base were made by the group and accepted. A continuing activity is to identify specific data from the member laboratories which should be incorporated into the INEL data base.

A new activity begun in FY 1988 was the effort to document and standardize battery test procedures. Two years ago, a standard battery capacity test procedure was developed by the Task Force and implemented by the members labs. This work identified some of the differences in the evaluation methods used by each lab. During FY 1988, these methods were reviewed by the Task Force and it was agreed that the members would exchange test procedure documentation.

In the next year, the test procedure documentation will be analyzed and an attempt will be made to develop a standard set of test procedures. Also, the group will continue its task of coordinating the diverse battery testing activities of member labs to insure accurate results and avoid duplication of effort.

Computer Modeling

In support of the DOE Electric and Hybrid Propulsion Program, Argonne National Laboratory (ANL) developed software packages for technical analysis and modeling of batteries and electric vehicles. During FY 1988, 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, analysis of proposed battery R&D efforts, development of mission-directed goals for battery research. During FY 1988, MARVEL was used in a scoping analysis on the possible impacts of using a hypothetical superconducting motor in a DSEP-type electric van. In addition, MARVEL was used to evaluate the range capabilty of the GM Griffon (Bedford) electric van using state-of-the-art (EV-5T) and advanced (3ET205) tubular-plate lead-acid batteries. The range predicted by MARVEL was in good agreement with that from track test results. A study was also carried out to evaluate the suitability and future prospects of sodium-metal chloride batteries for electric vehicle applications. 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 developed a preliminary version 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 any type of battery usage. A formalized procedure was developed to derive parameter values used in the model from laboratory test data. The algorithms that form the basis for the DIANE formulation have been thoroughly evaluated by comparing the results of calculations with the algorithms against known battery performance. Graphical capability was also added to improve data presentation.

Database Development

ANL developed a battery technology database using the dBASE III Plus data management system. Input records were created for all of the battery technologies being developed in the DOE/EHP R&D program. The database was delivered to DOE and successfully installed on several microcomputers. This database provides facile access to programmatic data and technical status information on the various battery systems.

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 7.0, 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 the Act."

No further vehicle purchases are being made under the provisions of Section 7.0 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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