MASTER

ENGINEERING DEVELOPMENT OF LITHIUM/METAL SULFIDE BATTERY TECHNOLOGY FOR VEHICLE PROPULSION

Summary Report**October 1977—September 1978****by**

**D. L. Barney, A. A. Chilenskas, W. H. DeLuca,
E. R. Hayes, F. Hornstra, M. K. Farahat,
J. A. E. Graae, and S. Box**

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ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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Chemical Engineering Division

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* Private consultant to ANL.

† Student from the University of Oklahoma.

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ABSTRACT

This report describes the research, development, and management activities done in preparation for in-vehicle testing of engineering-scale lithium/metal sulfide batteries. These activities were carried out at Argonne National Laboratory (ANL) from October 1977 to September 1978.

Over the past year, lead-acid batteries were tested both in the laboratory and in a Renault automobile. The data obtained from these tests will be used to assess the performance of lithium/metal sulfide batteries. Testing of a 40 kW-hr lithium/metal sulfide battery in a vehicle is planned for early 1979. The equipment needed to evaluate the performance of this battery has been designed and fabricated. Testing of this equipment is expected to begin at the end of 1978.

In order to carry out the above in-vehicle test, the lithium/metal sulfide battery must have a thermally efficient case and a charger. Eagle-Picher Industries, Inc. has been contracted by ANL to develop and fabricate the case for this battery; construction of the case is in progress. Based on a charger/equalizer design developed by TRW Systems, ANL has fabricated a portable charger/equalizer that has the capability of charging up to six lithium/metal sulfide cells.

I. INTRODUCTION

The lithium/metal sulfide (Li/MS_x) battery program at ANL has the dual objective of developing rechargeable batteries for use as power sources for electric vehicles and as stationary energy-storage (SES) devices for load-leveling on electric utility systems. The widespread use of electric vehicles would decrease the consumption of petroleum fuels, since the energy required for charging batteries could be produced by coal, nuclear, hydroelectric, or other sources. Load-leveling batteries could also save petroleum by reducing

* Private consultant to ANL.

† Student from the University of Oklahoma.

the need for gas turbines to meet peak power demands. Stationary energy-storage batteries may also find application in conjunction with solar, wind, or other cyclic or intermittent sources of energy. This report describes the work done at Argonne National Laboratory from October 1977 to September 1978 in preparation for in-vehicle testing of lithium-aluminum/metal sulfide batteries.*

Program goals that have been developed by ANL for electric-vehicle batteries are shown in Table 1. Eagle-Picher Industries, Inc. was contracted to design and fabricate a 40 kW-hr battery, designated Mark IA, to be tested

Table 1. Program Goals for Li/MS_x Electric-Vehicle Batteries

	Mark I ^a	Mark II	Mark III	Long Range
Specific Energy, ^b W-hr/kg				
Cell (average)	100	125	160	200
Battery	75	100	130	155
Energy Density, ^b W-hr/L				
Cell (average)	320	400	525	650
Battery	100	187	300	375
Specific Power, W/kg ^c				
Cell (average)	100	125	160	250
Battery	75	100	130	200
Heat Loss through Jacket, W	300	150	125	75-125
Lifetime				
Equivalent Full Discharges	400	500	1000	1000
Equivalent Distance, km	60,000	100,000	200,000	300,000
Target Dates				
Battery Tests	1979	1983	1986	--

^aGeneral goals for Mark I series batteries; the goals for the Mark IA battery are somewhat less stringent.

^bCalculated at the 4-hr discharge rate.

^cPeak power sustained during 15 s pulse at 50% depth of discharge.

in the laboratory and in an electric van at ANL in 1979. The Mark IA will be the first full-scale Li/MS_x battery ever produced. The Mark IA performance goals are given in Table 2. The Mark II battery will have higher performance

*Funded by the Division of Transportation Energy Conservation in the Department of Energy.

and will be tested in a car or van in 1983. The Mark II battery requirements include cost-related specifications that require manufacture of the battery with low-cost materials. The Mark III battery will be designed for installation and testing in a passenger car in 1986. The "long range" column in Table 1

Table 2. Performance Goals for the Mark IA Battery

Criteria	Goal
Cycle life ^a	200
Energy Storage, kW-hr ^b	40
Power, ^c kW	30
Specific Energy, ^b W-hr/kg	60
Heat Loss, W	400
Nominal Battery Voltage, V	144
Battery Volume, L	400

^aTo 20% loss of the design capacity; minimum of four months in-vehicle usage.

^bDischarge to 1.0 V/cell at the 4-hr rate.

^cFifteen-second pulse at 50% depth of discharge.

refers to the estimated performance and lifetime that can ultimately be achieved with this type of battery system.

A Renault electric automobile presently powered by twelve 6 V (1.8 kW-hr) lead-acid batteries was obtained for use in the first in-vehicle test of a Li/MS_x battery. For this test, one of the 6 V lead-acid batteries will be replaced by a 6 V Li/MS_x battery fabricated by Eagle-Picher Industries, Inc. For in-vehicle testing of the 40 kW-hr battery (Mark IA), a volkswagen van powered by lead-acid batteries will be obtained, and equipped with on-board apparatus to measure and record vehicle and battery performance. The reliability of the in-vehicle testing equipment will be determined by road-testing the van with lead-acid batteries. After preliminary testing in the laboratory, the Mark IA battery will then be installed in the electric van and road tested. Baseline data, obtained by road testing the van with lead-acid batteries, will then be used to assess the performance of the Mark IA.

In order to carry out the above in-vehicle tests, the lithium/metal sulfide battery must have a thermally efficient case and a reliable charge/equalizer. Therefore, Eagle-Picher was contracted to design, develop, and fabricate battery cases for the 6 V and 40 kW-hr electric-vehicle batteries; and TRW Systems was contracted to conduct a design and cost study for a battery charger. Using information provided in the study by TRW Systems, ANL designed and fabricated a six-cell battery charger, which is currently being tested.

II. DEVELOPMENT OF TESTING PROCEDURES FOR ELECTRIC-VEHICLE BATTERIES

Lead-acid batteries are being tested in the laboratory and in a test vehicle to obtain baseline data prior to testing of lithium/metal sulfide batteries. Instrumentation for measuring battery and vehicle performance is being designed.

A. Testing of Lead-Acid Batteries

The 6 V lead-acid batteries used for testing purposes are commercially available, and designed for use in electric golf carts. This 6 V battery (manufacturer's rated capacity, 132 A-hr at the 1.8-hr rate) weighs 28.6 kg and is 16.8 x 23.5 x 24.8 cm.

1. Laboratory Tests (E. R. Hayes)

The laboratory testing facilities use a computer-controlled 1000-A Robicon* cycler, and can be programmed to charge and discharge the battery under simulated driving conditions, e.g., various rates of acceleration and selected distances driven at constant or variable speeds. A 6 V lead-acid battery was tested in this laboratory to determine the peak power as a function of depth of discharge (DOD), internal resistance as a function of DOD, capacity as a function of constant-power discharge, and specific energy and specific power at various discharge rates. In the above performance parameters, constant-power discharge was chosen in preference to constant-current discharge for two reasons: vehicle use requires constant power during constant speed driving, and acceleration conditions are closely approximated by constant-power profiles in some vehicles.

The battery was tested according to the following procedure. The battery was charged to approximately 125% of its rated capacity, and underwent conditioning cycles until the capacity was within 10% of the manufacturer's rating. The fully charged battery was then discharged at a high current rate to determine if any unusually high power dissipations were present at the terminals; this procedure assured low-resistance electrical connections. At this time, the electrolyte temperature and specific gravity for each cell were measured to make certain that the battery was operating properly. The battery was then charged and all cells equalized.

Once the battery was charged, tests were conducted to determine the peak power sustainable for 15 s as a function of DOD. To make this determination we discharged the battery at a constant power to 80% DOD and recorded the energy removed from the battery during each of nine 15-s power pulses. The power pulses were followed by an inactive period of 100 s. A data-acquisition system recorded the duration of the pulse and the energy removed from the battery; a regression analysis of the data for the nine pulses was then undertaken to establish the internal resistance at 80% DOD. This same procedure was repeated at 60, 40, 20, and 5% DOD. The peak power (P_p) was

*Manufactured by Robicon Corp., Pittsburgh, PA.

calculated from the internal resistance using the equation $P_p = E^2/4R_i$, where E is the voltage during the pulse and R_i is the internal resistance.

The results of the power-pulse tests for the lead-acid battery are shown in Figs. 1 and 2. The plot shown in Fig. 1 gives the measured battery resistance during a 15-s power pulse as a function of DOD; as shown in this figure, the battery resistance increased from only 2.5 to 3.5 m Ω during the first half of discharge, but increased from 3.5 to 8.0 m Ω during the next 30% of discharge. The plot shown on Fig. 2 gives the calculated specific power as a function of DOD; the battery tested had a specific power of about 100 W/kg at a 50% DOD.

Fig. 1. Battery Resistance as Measured During Peak Power Production of Lead-Acid Battery

After the power pulse tests were completed, the capacity of the battery was measured at various constant-power discharges. Power levels were chosen so that the battery would be completely discharged after approximately 2, 4, and 6 hr. These discharge rates correspond to powers of 380, 250, and 155 W, respectively. Voltage of the battery at 100% charge was 6.8 V, or approximately 2.25 V per cell. The voltage vs. capacity curves for the three constant powers are given in Fig. 3. At the 380 W rate (1.8-hr discharge rate), the capacity obtained was 152 A-hr. Decreasing the power discharge to 155 W

Fig. 2. Peak Power as a Function of Battery Depth of Discharge for a Lead-Acid Battery

increased the capacity to 180 A-hr. Finally, the specific energies of the battery were measured at 1.75-, 4.25-, and 6.0-hr discharge rates. The results of this test are given in Table 3.

Table 3. Specific Energy of a 6 V Lead-Acid Battery at a Constant-Power Discharge (5.1 V cut-off; smoothed values)

Discharge Rate, hr	Specific Energy, W-hr/kg
1.75	27
4.25	33
6.0	34

Fig. 3. Voltage vs. Capacity at Three Constant Power Discharges for a Lead-Acid Battery

2. In-Vehicle Tests (E. R. Hayes and S. Box*)

To obtain base-line data for in-vehicle battery testing, we road-tested a Renault electric vehicle (motor output, 5.25 kW) powered by twelve 6 V lead-acid batteries. The test track was located at ANL and testing was done at constant and variable speeds. For the constant-speed tests, the total vehicle weight was 925 kg (including driver). For the tests at variable speeds, the J227a (Schedule B) driving test,¹ which is illustrated in Fig. 4, was used; the track for the acceleration and coast-time tests had a constant grade. The total vehicle weight for the J227a tests was 1010 kg (including driver and passenger).

The results of the in-vehicle tests of lead-acid batteries are given in Table 4, the performance data are averaged values for tests run in opposite directions.

* Student from the University of Oklahoma.

TEST PARAMETER	S A E SCHEDULE			
	A	B	C	D
MAX. SPEED, V, MPH	10	20	30	45
ACCEL TIME, t_a , SEC.	4	19	18	28
CRUISE TIME, t_{cr}	0	19	20	50
COAST TIME, t_{co}	2	4	8	10
BRAKE TIME, t_b	3	5	9	9
IDLE TIME, t_i	30	25	25	25

Fig. 4. Driving Cycle Schedules (SAE J227a)

Table 4. Performance Data for a Renault Automobile
Powered by Lead-Acid Batteries

Maximum range on level road		
Constant 24 km/hr		145 km
Constant 40 km/hr		88 km
Speed variable ^a		74 km
Maximum acceleration on level road		
0-20 km/hr		2.1 sec
0-40 km/hr		7.0 sec
0-56 km/hr		21.8 sec
Maximum speed on various grades		
25.5%		20 km/hr
11.2%		36 km/hr
2.2%		52 km/hr
Power to overcome rolling resistance and aerodynamic drag		
20 km/hr		1.51 kW
40 km/hr		3.89 kW
Vehicle energy economy ^b		
Constant 40 km/hr		0.27 kW-hr/km
Variable speed ^a		0.33 kW-hr/km

^aSAE J227a Schedule B.

^bAC power to charger.

3. Comparison of Laboratory and In-Vehicle Battery Tests (E. R. Hayes)

We compared the performance of the lead-acid battery tested in the laboratory with that of one of the batteries in the Renault. Test conditions in each case were based upon the SAE J227a(B) driving cycle; test conditions in the laboratory were chosen to simulate the battery load measured in the road test. The tests terminated when the battery was unable to supply the power required. The results are given in Table 5 and indicate about a 6% greater distance driven in the laboratory simulation test compared to the road test. Many parameters can influence the results of a comparison such as this; however, these preliminary results suggest that laboratory simulation may be a useful tool in evaluating battery design.

Laboratory tests of multiplate Li-Al/FeS cells and a 6 V Li-Al/FeS battery are planned for the next year. The results will be compared with the test results obtained with an in-vehicle test of a 6 V Li-Al/FeS battery planned for early in 1979. Laboratory and in-vehicle testing of a 40 kW-hr Li-Al/FeS battery is scheduled to begin in the spring of 1979.

Table 5. Battery Tests under Laboratory-Simulated and In-Vehicle Driving Cycles

	Laboratory Simulation	In-Vehicle Test
J227a(B) Cycles	174	162
Charge-Discharge Cycles	4	2
Distance Driven, ^a km	56.8	53.5
Battery Energy Output, ^b kW-hr	10.32	c
Energy Consumption, kW-hr/km	0.18	c

^a Averaged value for a single charge-discharge cycle.

^b Based on 12 lead-acid batteries.

^c At the time of these tests, instrumentation for making this measurement was not available.

B. Instrumentation for In-Vehicle Battery Testing
(W. H. DeLuca, E. R. Hayes, F. Hornstra)

An instrumentation package is being designed for measurements of battery parameters related to vehicle operation. Preliminary equipment specifications have been outlined, and various manufacturers and users of in-vehicle test equipment have been contacted to obtain both technical and operational information. Particularly useful have been site visits to the Jet Propulsion Laboratories, NASA/Lewis, and the AMOCO Research Center. Existing instrumentation technology and components are being used in the ANL design whenever possible.

A general outline of the computer-controlled data-acquisition and data-analysis system for the vehicle is given in Fig. 5. During vehicle operation, the on-board data-acquisition system measures and records various performance parameters of the battery and vehicle. This is accomplished by converting the detected analog transducer signals to digital values, which are then stored on cassette magnetic tape. The interface electronics electrically isolates transducer detection points, minimizes noise interference, and conditions the amplitude of the signals for maximum resolution. Digital data recording was selected over an analog scheme due to the volume of data and stability of the overall system that is required to obtain accurate measurements. The system control unit is a microprocessor which executes functions that are pre-programmed in its read-only-memory (ROM). The microprocessor adds flexibility to the operation of the overall system. For example, the sequence and rate

Fig. 5. Block Diagram of Data-Acquisition and Processing System for In-Vehicle Battery Tests

at which the various transducer signals of the microprocessor are sampled can be altered to obtain more data on those parameters found to be more critical in performance evaluation. In addition, the microprocessor allows the generation of local digital displays to aid in calibration and system testing.

The cassette on which the performance data is stored is transferred to an off-board support system, which has the capability to graphically display the recorded test data. Further development of the operating program (ROM) used

in the system control unit on the on-board acquisition system can be performed by the system operator. Test data can be inspected by transferring the information from the cassette tape to a floppy disk and then displaying this data graphically on a cathode-ray tube (CRT) terminal. On the CRT terminal, the detected performance data is displayed as a function of battery operating time; from this data the overall credibility of the indicated performance data can be assessed by the operator. The off-board support system also includes the necessary software and hardware for the operator to further develop the microprocessor program (editor, assembler, PROM programmer, etc.). Further program development is necessary when additional performance parameters are to be monitored or vehicle driving conditions are to be modified.

Final evaluation of battery performance is achieved on the data analysis system. The data on the floppy disk from the support system is transferred to the central processing computer, which is a PDP 11/34 computer.* In this system, the data is processed and graphically displayed in units which permit analysis of battery operation and evaluation of performance. Both a CRT and a printed display are provided to show battery power output at various states of discharge and power demand distribution.

A purchase order was issued to Omnibyte Corp.† to obtain the on-board data acquisition and off-board support systems. These systems (excluding the interface electronics) were delivered in September 1978 and include the hardware and software necessary to initiate in-vehicle testing. The interface electronics (which includes transducers) is unique to the electric vehicle that will be tested; therefore, it must be designed and fabricated at ANL. Development of the interface electronics is presently under way.

* Located in Chemical Engineering Division at ANL.

† Located in Oak Brook, Illinois.

III. DESIGN OF BATTERY SYSTEMS

Over the past year, an electric-vehicle battery case and a charger/equalizer have been designed. In addition, studies have been initiated on the optimal shape for a 50-kW-hr battery.

A. Battery Case

(A. A. Chilenskas, J. A. E. Graae,* M. K. Farahat)

Because the Li/MS_x cell must operate at high temperatures, an electric-vehicle battery must have a case with a low heat loss. This case must be light weight, compact, resistant to vibrations, safe, and economic, and must allow for an efficient interface between the battery and vehicle. The following is a discussion of the work at ANL and at various subcontractors on design and development of electric-vehicle battery cases.

1. Battery/Vehicle Design Integration

In 1977, Budd Co. examined the integration of a 45-60 kW-hr battery (equivalent to Mark II) into vans and automobiles.²

The study of batteries for automobiles showed that a modified Chevette could accommodate three battery cylinders containing a total of 45 kW-hr of energy storage without modifications to the automobile frame or body. For a shorter-range automobile that used only the storage space available in the transmission tunnel, 22 kW-hr of energy could be stored in a single battery cylinder (24.8-cm dia and 234-cm long). For an automobile designed specifically for electric propulsion, a single cylinder (35.6-cm dia. and 234-cm long) could store 45 kW-hr of energy. A design was proposed in which the exterior battery case is an integral part of the frame of the automobile, thus minimizing the automobile's overall weight.

Conventional vans were examined for retrofitting with either cylindrical or rectangular 50-60 kW-hr batteries. The results of this examination showed that the following two battery shapes could be installed in a vehicle without modifications to the vehicle frame: a 50 kW-hr rectangular battery consisting of two modules that are 31.4 x 25.0 x 458 cm, and a 60 kW-hr cylindrical battery consisting of two modules that are 35.5 cm in diameter and 158 cm in length. A van with cylindrical batteries is depicted in Fig. 6.

An analysis³⁻⁴ has been completed at ANL to assess rectangular and cylindrical 50 kW-hr batteries. For this analysis, it was assumed that the present prismatic cell shape can be changed to a circular one without significantly affecting cell performance or cost. As can be seen in Table 6, in comparison with the rectangular battery, the cylindrical battery has a lower weight (excluding cells) and volume, heat loss, and manufacturing cost. An analysis is in progress of these two designs with respect to battery/vehicle

*Private consultant to ANL.

Fig. 6. A Converted Van Powered by a 60 kW-hr Li/MS_x Battery

Table 6. Preliminary Assessment of the Shape for a 50 kW-hr Battery

	Design Shapes	
	Rectangular	Cylindrical
Battery Weight (excluding cells), kg	144	96
Battery Volume, L	312	242
Heat Loss, W	262	133
Jacket Manufacturing Cost, \$	554 ^a (11.08) ^c	316 ^b (6.32) ^c

^a Priced at \$3.85/kg in high-volume production.

^b Priced at \$3.30/kg in high-volume production.

^c Numbers in parenthesis are manufacturing costs in dollars per kilowatt hour.

integration, crash worthiness, and resistance to road vibrations. Although the results are still preliminary, the cylindrical design appears to be more favorable.

2. The Mark IA Battery Case

Under a contract with ANL, Eagle-Picher has designed the Mark IA battery case (including temperature controls). Figure 7 is a sketch of Eagle-Picher's design of a battery case for a 20 kW-hr battery module (Mark IA will consist of two such modules). The rectangular case is composed of two corrugated metal walls; between these two walls is vacuum foil (Multifoil^{*}) for thermal insulation. Other battery case designs were considered (e.g., honeycomb walls, truss and membrane structural support, and thick-wall single-sheet containers), but were eventually discarded in favor of the present design.

A contract for the fabrication of an insulated battery case, based on the Eagle-Picher design, was placed with Thermo Electron Corp. To assure a satisfactory design prior to building the case, Budd Co. was contracted to

Fig. 7. The Mark IA Battery Case

^{*}A registered trademark of Thermo Electron Co., Waltham, MA.

assess all known and anticipated stresses on the battery hardware, including thermal and mechanical stresses due to vibrations. For this purpose, Budd employed the dynamic stress analysis computer program (ANSYS). The results of the stress analysis gave the expected resonant frequencies of the system as well as areas of maximum modal stress. Exact values for component stresses were not calculated because damping factors of the various battery components could not be determined. Based on the stress analysis, it was concluded that structural deflections at operating conditions should be small and well within the design limit.

B. Charger/Equalizer
(W. H. DeLuca, F. Hornstra)

A charger/equalizer system suitable for mass-produced electric-vehicle batteries must be economical, lightweight, reliable, and simple to use. In addition, this charger must have the capability to operate from standard power sources on a daily basis. A contract was issued to TRW Systems in December 1977 to perform a design and cost study for a charger for the Li/MS_x electric-vehicle battery. TRW's final report,⁵ completed in May 1978, includes charger performance specifications, a critical review of previous ANL equalizer work, and a design/cost analysis of a promising charger design.

The economical mass-producible charging system outlined by TRW consists of two components: (1) a main charger which is preset to charge at three current levels for specified periods of time and (2) single-chip integrated circuits which monitor cell voltage and equalize cell current. The current applied during charging for this system is illustrated in Fig. 8. During charging, the initial current, i_1 , is maintained until one of the cells reaches a predetermined voltage. Whether or not this event has occurred is detected by a single-chip cell circuit. The main charger is then switched to output current level i_2 . J. Cox⁶ established a relationship between the

Fig. 8. Step Charging Program Followed by
Controlled Constant-Voltage Charging

state of charge and cell current and voltage. Utilizing this relationship, TRW showed that a Li-Al/FeS battery with i_1 set at the 10-hr rate would switch to level i_2 when the "leading cell" (i.e., the cell closest to the predetermined voltage limit) is about 96% fully charged. Thus the bulk of the charge is done during level i_1 . The main charger remains at level i_2 until the leading cell is detected to be at the predetermined voltage, at which time the main charger current is switched to level i_3 . At this point, the single-chip circuits shunt a preset current equal to level i_3 for each cell detected to be at or above the voltage limit. To eliminate the requirement for separate cell-voltage sense leads, the current shunting circuits are periodically disengaged for a short period of time to allow determination of whether a cell is above or below the voltage limit.

The system cost as outlined by TRW (see Ref. 5) is given in Table 7. Based on the production of 100,000 charging systems per year, a charger cost of approximately \$500 (1978 dollars) is anticipated. The cost of the single-chip monitor/shunt integrated circuit is given at \$2.50 in mass production, but this cost does not include the initial engineering costs.

Based on the concepts outlined by TRW Systems, ANL has designed and fabricated a test charging system. The charger/equalizer system can be adjusted to operate at a bulk current of 6 to 30 A, an equalization range 0.2 to 6.0 A,

Table 7. Estimated Cost of a Li/MS_x
Electric-Vehicle Battery Charger

Subsystem	Cost, ^a \$	
	High Estimate	Low Estimate
Cell monitoring modules ^b	300	300
Current-regulated SCR ^c charger		
Magnetics (70 pounds)	140	105
SCR's and control	25	20
Unit controls and relays	50	35
Flag polling logic and display, Master timing chain	25	15
Mechanical structure	100	75
Savings ^d	-100	-100
Total	540	450

^aBased on 100,000 units/yr and given in 1978 dollars.

^bThis consists of 120 modules at \$2.50 each.

^cSilicon-controller-rectifier.

^dDue to shared vehicle drive train magnetics.

and a cell voltage limit of 1.200 to 2.400 V. Thus the ANL charger/equalizer can be used on a variety of battery systems. The test unit can be preset to provide the charging of battery systems containing from one to six cells. A photograph of the ANL charger/equalizer is shown in Fig. 9. A block diagram of the ANL charging system is given in Fig. 10. As shown in the figure, the charger unit consists of three basic parts: the bulk charger, system controller, and shunt modules.

The bulk charger provides a regulated constant current the amplitude of which is directly proportional to a reference input signal from the system controller. The bulk charger provides essentially constant-voltage, current-limited power. The cell shunt module monitors cell voltage and shunts charge current around cells. The system controller determines the operating mode of the shunt modules. The system controller has a predefined operating format, and utilizes the cell monitor signals from the shunt modules to alter the

Fig. 9. A Six-Cell Charger/Equalizer Test Unit.
ANL Neg. No. 308-78-550.

Fig. 10. ANL Electric Vehicle Battery Charger/Equalizer System

level of the bulk charger's output current. The five-mode sequence operation generated by the controller, illustrated in Fig. 10, is described below:

- A. Power On/Start Up Mode. Activation of the charger/equalizer automatically starts the controller. The bulk current is increased at a controlled rate until the manually set level, I_{BK} , is reached or a cell reaches its voltage limit; when either condition is reached, an automatic advance to the next mode occurs.

- B. Bulk Charge Mode. The charge current is held constant at the level determined in Mode A. When a cell reaches its voltage limit, an automatic advance to the next mode is made.
- C. Taper Charge Mode. The controller reduces the battery charge current by a predefined increment each time that a cell reaches its voltage limit. This gives a taper-charge effect to the battery current and also minimizes the time to equalize the charge in this cell. Operation with a decreasing current continues until the manually set equalization current level, I_{EQ} , is reached or exceeded; at which point an automatic advance to the next mode is made.
- D. Equalization Mode. The bulk current is held at the level determined in Mode C, and the cell shunt modules are activated. Periodically, the controller pulses the shunt modules to accurately determine the cell voltage. Any cells that have reached their voltage limit will have the equalization current shunted around it. This operation continues until the controller determines that all of the cells have reached their voltage limit; at this time an automatic advance to the next mode is made.
- E. Standby Mode. The charge current is reduced to zero; the controller has status displays which show the total time required to charge the battery along with the incremental time consumed in the bulk, taper, and equalization modes. The display also includes an accumulative count of the periods where the shunt modules were not bypassing the equalization current; this information provides an immediate value of the energy efficiency of the equalization mode.

Design and fabrication of the ANL test charger/equalizer was completed in August 1977. A special discharge imbalance circuit has been fabricated which allows the battery cells to be discharged to a pre-determined level of current deviation to evaluate equalization. The test unit has performed accurately and reliably over a variety of operating conditions and has also provided information on cell characteristics at the end of charge. Data obtained from initial testing on lead-acid batteries is presently being reviewed. Future tests are planned using a multiplate Li-Al/FeS cell.

IV. SAFETY AND VIBRATIONAL TESTS

The Li/MS_x cell must be proven to be able to withstand road vibrations and safe in an automobile crash. Thus, tests were conducted to determine the safety and resistance to vibrations of the Li/MS_x cell.

A. Cell Vibrations Tests

Vibration tests were performed on two Li-Al/FeS_2 bicells fabricated by Eagle-Picher (designated EP-034, -035). The basic design for this type of cell is shown in Fig. 11. In these two cells the positive current collector was made of molybdenum; and, therefore, the positive electrode contained welded joints of molybdenum, which are very brittle and break easily.

Fig. 11. Design Features of a Li-Al/FeS_2 Cell Used for Vibration Tests

Vibration testing was completed at Eagle-Picher's Environmental Laboratory. Equipment used includes a Ling Model 275A Exciter, Ling Model PP60/80 power supply, and an instrumentation console for control and monitoring of the vibration levels. The cells were under constant surveillance with a charge/discharge cycler and voltage and current recorder during vibration testing. The cell vibration fixture is shown in Fig. 12. The cell was placed

Fig. 12. Cell Vibration Fixture

in a test fixture and bolted down to a mounting plate. Under the mounting plate are three layers of transite for heat insulation between the oven and the shaker head.

The power leads for the cell were four gauge, asbestos-insulated wire, and the voltage monitoring leads were sixteen gauge high-temperature insulation wires. A brazed joint was utilized at the cell terminals to minimize contact resistance.

The cells were vibrated at a level of 0.6 cm displacement amplitude (5-16 Hz) and 1.5 g (16-50 Hz), with a sweep time of 7.5 min. Each cell underwent 1.37×10^6 vibrational cycles, which is equivalent to the vibrations expected in 12 years of vehicle operation. Each cell was vibrated during a 4-hr discharge (17 A current); neither cell was vibrated during the approximately 8-hr charge (9 A). The results of the tests are shown in Table 8. These test results are considered preliminary. The capacity of Cell EP-036 after 10^6 vibrational cycles was similar to the capacity under static conditions. Cell EP-036 showed a capacity decline of about 28% between cycle 18 and cycle 148.

Table 8. Performance of Li/MS_x Cells
Subjected to Vibrational Tests

Cell No.	Electrical Cycle No.	Vibration	Cell Capacity, ^a A-hr
EP-035	1-34	No	68
	35-36	Yes	67
	37-89	No	56
	90-92	Yes	58
	93-100	No	65
EP-036	1-15	No	87
	16-18	Yes	62
	19-148	No	47

^a Measured capacity during cell discharge for last cycle in the series.

Further vibration testing in fiscal year 1979 is planned of prototype Mark IA cells and of the Mark IA battery jacket. Vibrational testing of many more cells is required to arrive at a statistically valid conclusion regarding the effect of road vibrations upon cell capacity.

B. Safety Tests

An assessment of the safety aspects of the lithium/metal sulfide battery has been conducted by Budd Co.² Destructive tests on cells at operating temperatures were carried out (the cells were crushed and the contents exposed to air). No signs of fire or other chemical reactions were observed. Tests also indicated that the cells are sufficiently resilient to absorb their own kinetic energy from a crash into a barrier at 50 km/hr (30 mph), with only a small amount of salt escaping from the cell housing. Safety tests using Mark IA multiplate cells are planned for FY 1979.

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