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TEST RESULTS FOR 36-V Li/FeS BATTERY

by

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ABSTRACT

This report describes a collaborative effort between Argonne National Laboratory (ANL) and the Westinghouse Naval Systems Division from 1986 to 1989. This effort resulted in the design, fabrication, and testing of two 36-V lithium-alloy/iron monosulfide (Li/FeS) batteries. The test results provided validation of a conceptual design for a full-scale electric van battery, as well as design and performance data for 12-V Li/FeS modules and fractional-scale battery components.

I. INTRODUCTION

This report summarizes work performed in a collaborative effort between ANL and the Westinghouse Naval Systems Division from 1986 to 1989. It covers the design, fabrication, and test of two 36-V Li/FeS batteries, both of which used the full-scale Li/FeS cell developed by Westinghouse. The first battery (MK-I) was built as a laboratory model and was tested at ANL's battery test facility. The second battery (MK-II) was designed to be tested in an electric van at the Tennessee Valley Authority's (TVA's) test facility in Chattanooga, Tennessee. However, shakedown testing prior to the vehicle test revealed several design flaws in the thermal management system of the battery, and the in-vehicle test plan was abandoned. The thermal management system was subsequently reworked to permit the battery to be tested in the laboratory. The results presented here are from the laboratory tests performed at ANL and include battery tests using computer-controlled electrical simulations of vehicle driving profiles.

II. BATTERY DESIGN

A. Van Battery Conceptual Design

A conceptual design for a Li-alloy/FeS van battery was completed at ANL under DOE sponsorship in 1987. The principal design features are illustrated in the artist's sketch shown as Fig. 1. The main features are the following:

- (1) The battery consists of eighteen 12-V modules, each of which contains nine series-connected cells. These modules are connected in series to provide the full battery voltage (216 V).
- (2) An air-cooled, electrically heated heat exchanger is used as a tray to anchor the 12-V modules within the battery case.
- (3) A five-sided vacuum/multifoil insulated battery case is used to minimize heat loss.

Fig. 1. Conceptual Design for Li/FeS Van Battery

- (4) An insulating plug consisting of sheet metal and conventional insulation and forming the sixth side is used to seal the 12-V modules within an inert atmosphere in the battery case.

The dimensions, weight, and projected performance of Li/FeS batteries were calculated for four electric vans (General Motors G-van, Chrysler TE van, Ford ETX-II, and the Eaton DSEP) and are given in Table 1.¹ The performance requirements for these vans were developed by the DOE Task Force on Electric Vehicle Battery Goals.²

B. The 36-V Li/FeS Battery Design

The two batteries tested in this program were fractional-scale van batteries (36-V each). The first 36-V battery (MK-I) was assembled by Westinghouse using the full-scale Li/FeS cell developed in an Electric Power Research Institute (EPRI) sponsored program,³ an air-cooled heat exchanger based on an ANL conceptual design,⁴ and a vacuum/fiberglass board insulated battery case fabricated by the Linde Division of Union Carbide.⁵ A photograph of the MK-I battery prior to its insertion into the insulated case is shown in Fig. 2.

The second 36-V battery (MK-II) was designed by ANL and assembled from components supplied by various industrial suppliers, e.g., the 12-V modules and the heat exchanger were from Westinghouse. For the MK-II battery, a new concept employing compressed multifoil insulation for an insulated case was developed in a joint program between ANL and Meyer Tool and Manufacturing, Inc.⁶ A photograph of the MK-II battery just prior to its insertion into the insulated case is shown in Fig. 3. The insulated case developed for the MK-II battery is shown in Fig. 4.

A report summarizing the design work conducted at ANL and Westinghouse has been prepared.⁷ This report gives a detailed description of the 36-V van battery design.

Table 1. Design and Projected Performance for Li-Alloy/FeS Van Battery

	TE Van	G-Van	ETX-II	DSEP
Battery Design				
Number of cell plates	7.0	7.0	9.0	7
Number of cells	162	208	147	144
Cell weight, kg	2.7	3.1	3.5	3.3
Battery weight, kg	548	799	642	594
Energy Output				
Ah output/cell	232	278	305	312
Wh output/cell	281	336	369	377
Battery output, kWh (Wh/kg)	46 (83)	70 (87)	54 (84)	54 (91)
Vehicle Design				
Vehicle test weight, kg	2067	3372	2232	2113
Vehicle efficiency, kWh/tonne mile	0.17	0.16	0.19	0.19
Range, mi (km)	127 (204)	130 (209)	124 (199)	132 (212)
Acceleration (End-of-Discharge)				
Battery power, kW	43.4	55.7	51.3	49.6
Power coefficient, kW/tonne	21.0	16.5	23.0	23.5
0-30 mph, s	8.0	10.0	7.0	6.9
0-50 mph, s	22.0	28.0	20.0	19.6

Fig. 2. Photograph of MK-I Battery without Insulated Case

Fig. 3. Photograph of MK-II Battery without Insulated Case

Fig. 4. Photograph of Insulated Battery Case for MK-II Battery

C. Design of 12-V Modules

The 12-V modules consisted of nine cells connected in series and clamped between restraining plates (see Fig. 5). The cells are separated from each other by the use of an insulating paint, a sheet of mica, or both. The design requirements for the module and the work performed to meet these requirements have been previously reported.⁷ The cells were a multiplate, prismatic design of about 300-Ah capacity. They employed Li-Al-Si alloy for the negative electrode, FeS powder for the positive electrode, a lithium-containing molten salt mixture for the electrolyte, and a pressed mixture of a salt and MgO powder for the separator.

Fig. 5. Photograph of 12-V Li/FeS Module (nine cells)

D. Battery Specifications

The MK-II battery was designed to be sufficiently lightweight and compact to allow its integration into the power train of an electric van for in-vehicle road testing. The size, weight, and volume of the MK-II battery are given in Table 2.

As shown in the table, the cell/battery weight ratio achieved in the MK-II battery was 0.53, compared to our goal of 0.8 for a full-scale battery.* The disparity is due, in part, to the fractional scale of the MK-II battery; however, additional weight reduction studies are needed and should focus on the

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* This weight ratio is often expressed as a "battery burden," which in this case is 1.25, i.e., the battery weight is 1.25 times cell weight.

Table 2. Specifications for MK-II Battery

Weight, kg (wt %)	
Cells (27)	75.6 (53.4)
Module Hardware	11.2 (7.9)
Heat Exchanger	7.7 (5.4)
Case	32.2 (22.7)
Insulating Plug	10.4 (7.4)
Cover	2.2 (1.6)
Misc. (wiring, bus, insulation)	2.1 (1.6)
Total	141.6
Size and Volume	
Cell Size, ^a cm	18.25 x 1460 x 3.97
Cell Volume, L	1.06
Battery Size, cm	47.6 x 27.9 x 85.1
Battery Volume, L	113.2

^aWithout feedthrough.

insulated case and the insulated plug. Some additional, but smaller, weight savings are possible by optimizing the weight for the heat exchanger and module hardware. The overall goal of 0.8 cell weight fraction is realistic, but will require several iterations of design and test to achieve. Sufficient small-scale work has been performed to validate the basic design concepts; weight optimization should now be performed at full scale.

E. Vacuum-Insulated Case

Vacuum insulation has been developed by the Linde Division of Union Carbide, as noted previously. It is, however, not available in commercial quantities and is expensive to produce for the small quantities needed for developmental batteries. Therefore, we decided to explore the use of an alternative material, compressed multifoil (alternating layers of aluminum foil and glass-fiber paper),⁶ that showed promise of reducing the cost of the batteries required for our test and of being cheaper in large-volume production.

Two 36-V battery cases were built using a technique developed by F. Meyer Tool and Manufacturing that compresses the multifoil during manufacture by winding it under tension onto a stainless steel shell. An outer shell encloses the multifoil and is welded vacuum tight to the inner shell. The second case that was fabricated by this process demonstrated satisfactory thermal performance and was used for the MK-II battery.

The insulated case met our expectations in terms of manufacturability, cost, and thermal resistance. During the test period, however, gas pressure buildup in the vacuum annulus required occasional pumping to maintain the required low pressure. In scaling up this concept, attention will need to be paid to reducing the quantities of absorbed gases on the insulation during manufacture, obtaining leak-tight welds using thin-walled construction materials, and using getters that can be replaced or regenerated in situ.

F. Insulated Case Cover/Penetrations

The design for the battery-case end cover (see Fig. 1) was the least advanced and contributed disproportionately to the weight of the 36-V batteries. Program limitations dictated the use of readily available high-temperature materials (insulation, wire, plugs, etc.) with consequent penalties in weight and heat loss. Additional attention needs to be given to the basic design of the plug and to the use of low-weight insulated wire and high-temperature multipin connectors for the various electrical leads.

G. Heater

The heater design for the 36-V batteries used electrical resistance heaters mounted on the top surface of the heat exchanger, the inner wall adjacent to the front cover, and the wall at the back of the battery case. Three sides (top, left, and right) of the battery case were left unheated to simplify fabrication and operation of the heating system.

Thermal tests of the MK-I battery showed that it met our design goal of keeping the cells to within a $\pm 5^\circ\text{C}$ variation within the case; however, the MK-II battery showed a larger cell temperature gradient of $\pm 10^\circ\text{C}$. To meet the desired goal of $\pm 5^\circ\text{C}$, we recommend that future batteries be heated internally at all surfaces exposed to the modules, e.g., all six sides of a prismatic case. In addition, the insulation used to electrically isolate the cells should be kept as thin as possible to minimize the thermal resistance from the center to the end of the 12-V modules. The MK-II modules were insulated by a sheet of mica in addition to the insulating paint used in the MK-I. The additional insulation was at least partially responsible for the larger cell temperature gradient experienced in the MK-II tests.

H. Cooling System

The main component of the cooling system is the heat exchanger that provides an air-cooled surface in contact with the bottom of the cells. In general, the design of the heat exchanger proved satisfactory; however, under some test conditions, an increased temperature gradient was observed due to a nonuniform coolant flow. Simple design modifications are available to correct this deficiency.

The possibility of simplifying temperature control exists through the use of the low-melting electrolytes ($\sim 310^\circ\text{C}$) currently under test at ANL. It may be possible to dispense with cooling during discharge entirely by letting the cell temperature rise to absorb the heat generated. In a Li/FeS battery using an electrolyte with a melting point of 310°C , it would be possible to maintain the battery temperature between 400 and 450°C for typical van driving patterns. The battery could then be cooled overnight to bring the temperature down to the required starting temperature in preparation for the next day's operation. Because the required heat removal rate is low, a simple, lightweight air-cooling system could be readily designed.

I. Charger

The charger used for these battery tests was one developed previously by ANL and used successfully in many tests.⁸ This device provides precise voltage monitoring and current shunting capability for each cell in the battery, resulting in excellent charge control. The charger does, however, complicate the battery design because it requires a wire for every cell that needs to be passed through the insulated front cover and connected to the charger.

Researchers at ANL have developed a simpler charging system, based upon an electrochemical charge equalization mechanism internal to the cell. This system eliminates the need for an external

charge equalizer. Through this mechanism, voltage at the top of charge is stabilized by the diffusion of lithium from the negative to the positive electrode equal to the amount transported by the charging current in the opposite direction.^{9,10} This mechanism has been demonstrated in laboratory-sized cells (25-Ah capacity) at ANL at low-current levels (3 mA/cm²), albeit at levels sufficient to provide charge equalization.

III. THERMAL MANAGEMENT DESIGN

Lithium/iron sulfide batteries operate at temperatures ranging from about 400 to 500 °C. The high temperature is necessary to keep the molten salt electrolyte above its freezing temperature. The high operating temperature is regarded as a liability by battery technologists; however, some advantages that tend to offset the disadvantages result from high-temperature operation. The most important advantages and disadvantages are summarized in Table 3.

Table 3. Advantages and Disadvantages for High-Temperature Operation

Advantages	Disadvantages
1. Constant energy output regardless of ambient air temperature.	1. The insulated case adds undesirable weight, bulk, and cost. ^a
2. Small, lightweight cooling system due to the large cooling temperature gradient.	2. Energy ^b is required to maintain battery operating temperature.
3. High temperature favors rapid electrochemical reactions, resulting in high power capability.	3. Batteries unattended for longer than one week will freeze. Reactivation, by heating, will require 12-24 h.
4. The insulated case provides a sealed, weather-proof container for the cells.	4. Corrosion of construction materials is accelerated by high temperatures.

^aWe estimate that the insulated case will add about 10% to the battery cost.

^bAs an example, an electric van operating 5 days/week at 50 miles/day will require an additional 5% electrical energy for heating.

The thermal management requirements are as follows:

- (1) Maintain battery heat loss at an acceptable low value. Our goal for an electric van battery is 300 W.
- (2) Maintain all cells above the electrolyte melting point and keep them within 10 °C of each other to minimize differences in self-discharge rates.
- (3) Provide automatic control of the heating/cooling system to maintain operating temperature in the proper range during charge, discharge, or standby operation.

Aspects of the thermal management of this battery have been described in earlier publications.^{4,11,12} In Sections III and IV, we describe some recent calculations and test results.

A. Cell and Battery Resistance

The most important battery parameter needed to properly evaluate heating effects during charge and discharge is the battery resistance.

Table 4 lists cell and battery resistance measurements at three states of charge (SOC). The cell resistance was obtained from Westinghouse measurements of a single cell, and the battery resistance was obtained by high-voltage pulse measurement of the assembled MK-II battery. The measured values at 100% SOC agree to within about 7%. Calculated values for battery resistance are also included in this table. The values in Table 4 were used in the subsequent calculations dealing with cell heat generation and temperature rise.

Table 4. Cell and Battery Resistance at Three States of Charge

State of Charge, %	Cell Resistance, ^a Ω	Battery Resistance, Ω	
		Calculated ^b	Measured ^c
100	0.0010	0.0270	0.0250
50	0.0011	0.0297	---
20	0.00125	0.0337	---

^aMeasured resistance of a single cell (Westinghouse data).

^bSum of 27 cells.

^cHigh-voltage pulse measurement of MK-II 36-V battery. The resistance of the positive and negative buses was measured to be 0.0025 Ω and is included in the measured value of 0.0250 Ω .

B. Heat Generation

The self-heating of Li/FeS cells can be calculated from

$$W = i^2 R \pm ki \quad (1)$$

where W = heating rate, W

R = cell resistance, Ω

i = current, A

$k = 0.08$ W/A

In this equation, ki reflects entropic heating or cooling (heating occurs during discharge and cooling occurs during charge for FeS cells; the reverse is true for FeS₂ cells).

The self-heating of a Westinghouse Li/FeS cell can be approximated by:

$$W = k_1 i^{1.75} \quad \text{where } k_1 = 0.00572 \text{ W/A} \quad (2)$$

Thus, a cell discharged at 75 A would generate 11 W, while a cell delivering 300 A would generate 124 W. Quadrupling the current in going from the current demand during cruising (75 A) to the current needed during acceleration (300 A) results in more that a 10-fold increase in cell heat generation. Heat generation of a Westinghouse cell as a function of discharge current and SOC is plotted in Fig. 6.

Fig. 6. Cell Heat Generation as Function of State-of-Charge (SOC) and Discharge Current

C. Temperature Rise Rate

The temperature rise rate of the cells within a well-insulated battery case can be closely approximated by considering the heat absorbed adiabatically, i.e., without loss to the surroundings. The adiabatic temperature rise of a Westinghouse cell is given by

$$W = mCt' \quad (3)$$

where m = cell weight (2.8 kg)

C = heat capacity, Wh/g•°C

t' = temperature rise, °C/h

An approximation for the adiabatic rate of temperature rise can be obtained from the expression:

$$t' = \frac{W}{mC} = 0.007 i^{1.75} \quad (4)$$

A plot of the rate of cell temperature rise as a function of battery discharge current and SOC is given in Fig. 7.

Fig. 7. Rate of Cell Temperature Rise as Function of State-of-Charge and Discharge Current

It is important to consider the temperature rise rate of the copper bus used to carry current out of the battery enclosure, because bus bar melting must be avoided, and bus temperatures significantly higher than cell temperatures can result in "hot spots" in the vicinity of thermocouples and lead to erroneous temperature readings.

The adiabatic temperature rise rate of the copper bus used to carry battery current is given by

$$t' = \frac{W}{mC} = \frac{i^2 R l / A}{\rho l A C} \quad (5)$$

where R = resistivity at 500°C ($5.08 \times 10^{-6} \Omega\text{-cm}$)

C = heat capacity ($1.19 \times 10^{-4} \text{ Wh/g}^\circ\text{C}$)

ρ = density (8.8 g/cm^3)

l = length, cm

A = area, cm^2

This equation reduces to

$$t' = 0.0078 i^2 / d^4 \quad (6)$$

where d = diameter of bus, cm

The calculated results of adiabatic temperature rise for three copper bus diameters are compared with the rate of temperature rise for the cells in Fig. 8. The t' values for all three buses are higher than those for the cells.

Fig. 8. Temperature Rise for Different Diameter Copper Buses and Li/FeS Cells as Function of Discharge Current

For the initial tests with the MK-II battery, where 1/4-in. diameter copper rod was used as the bus, the rate of temperature rise was significantly higher than that for the cells. This effect caused the overheating of the space above the battery where thermocouples were located. This overheating resulted in erroneous temperature readings, which resulted in premature termination of discharge. A trade-off analysis for copper bus size was then conducted. The results are summarized in Table 5.

Comparing t' values in Table 5 with the rate calculated for the cells shows that an increase in copper rod diameter to 3/8 or 1/2 in. is desirable. The main penalty associated with increasing the copper rod diameter is the weight gain of the system. Increasing the rod diameter from 1/4 to 1/2 in. increases the system weight by 2.75% (cell weight basis) but reduces the power loss (at 300 A) from 4.8 to 1.2% and reduces the adiabatic temperature rise rate of the copper bus to less than twice that of the cells and about equal to that of the intercell connectors. After this analysis, the MK-II battery was modified by replacing the 1/4 in. with a 1/2-in. dia bus.

IV. THERMAL MANAGEMENT TEST RESULTS

A. Heat Loss of the Battery

The results of tests conducted at ANL to determine the steady-state heat loss of the battery at operating temperature are summarized in Table 6. Our design target for a 36-V battery case (without

Table 5. Trade-off Analysis for Copper Bus of Different Diameters

	Copper Bus			Intercell Connectors
	1/4 in.	3/8 in.	1/2 in.	
Conductor Description				
Length, ft	8	8	8	6
Weight, kg	0.69	1.55	2.76	0.37
Resistance (500 °C), Ω	0.0039	0.0017	0.0010	0.0005
% of Cell Weight	0.9	2.0	3.6	2.0
Performance ^a				
Power Loss, ^b %	4.8	2.1	1.2	0.70
Temperature Rise, °C/h	4338	857	270	263

^aAt 300 A and 500 °C. Under these conditions, the adiabatic cell temperature rise is 150 °C/h.

^bExpressed as the percent of instantaneous power delivered by the battery.

Table 6. Heat Loss Measured for the MK-II Battery

Test No.	Test Description	Heat Loss, W
1	MK-II case, 6 in. insulated cover with heated aluminum block simulating 27 cells (no penetrations)	168
2	Assembled MK-II battery. MK-II case, 27 Westinghouse cells, all electrical and gas penetrations through the insulated cover	239 ^a

^aThe battery heater outputs were: front heater, 96 W; bottom heater, 138 W; and back heater, 5 W.

penetrations) of 100 W was not met (168 W was obtained); however, the results are sufficiently encouraging to continue an active interest in developing the compressed multifoil insulation. Our design goal of 300 W for a full-scale van battery is realistic and achievable. The goal can be attained by incremental improvements to the existing design, with particular emphasis given to reducing the number of penetrations through the insulated cover.

B. Temperature Variation within the Battery

An ideal battery temperature control system would maintain all the cells at the exact same temperature. Although this cannot be achieved in practice, it is necessary to minimize temperature variation among the cells for the following reasons:

- (1) The self-discharge rate of a cell is sensitive to temperature. The hottest cells will lose capacity more rapidly than the colder cells, resulting in a battery capacity imbalance.

- (2) The hottest cells will limit the thermal storage capacity of the battery by reaching the maximum allowed temperature first.
- (3) The coldest cells will exhibit the highest resistance because electrolyte conductivity is sensitive to temperature.

The design target we have set for the battery is a cell temperature variation of $\pm 5^{\circ}\text{C}$ from the average, i.e., a 10°C spread. We were not able to maintain this 10°C variation in all our tests and have seen a capacity imbalance that results in lower battery output directly attributable to temperature variation.

To minimize the temperature variation within the battery, we maintained a constant heat input to the front cover of about 100 W during battery discharge while the bottom and back heaters were regulated to maintain a constant temperature. The cells located in the middle of the 12-V module (MK-II test) ran $12\text{--}18^{\circ}\text{C}$ hotter than the end cells. A typical temperature spread of the cells at the start of a test was about 15°C , with approximately the same 15°C spread being maintained during and at the end of discharge. Design modifications that can be made to reduce the temperature variation of the cells are as follows:

- (1) Create a more uniform temperature environment for the cells by heating all six battery enclosure sides. (The present design heats only three sides.)
- (2) Increase the thermal conductivity within the modules by reducing the thermal resistance of the insulation used to electronically isolate cells.
- (3) Reduce the heat flux at the case wall by increasing the insulation thickness or its thermal resistance.

C. Heating and Cooling Rates

Several measured values for heatup and cooling rates for the MK-II battery are compared with calculated values in Table 7. The agreement between the experimental and calculated values is fair. The result obtained at a 70 A discharge suggests that the heat generation rate of the cells had been underestimated. However, the calculated values provide an adequate first approximation for purposes of conceptual and preliminary design of full-scale batteries.

V. BATTERY PERFORMANCE

A. Energy

The battery energy storage requirements for the four electric vans of interest to DOE and EPRI are listed in Table 8. As can be deduced from the the table, an energy output of about 110 Wh/kg on a cell weight basis would provide a range of about 125 mi (204 km) for each of these vehicles. These values can be compared with the energy output test results for the MK-I and MK-II battery, which are summarized in Table 9.

The MK-I battery achieved the highest energy output, 112 Wh/kg on a cell weight basis when tested on a SAE J227a/C cycle. This test validated the Westinghouse cell design in terms of meeting the energy goals for an electric van battery. The MK-II battery, however, was less successful in meeting

Table 7. Calculated and Measured Heatup and Cooling Rates

Typical Test ^a	Test Conditions	Rate, °C/h	
		Calculated	Measured
Cooling Rate	Open Circuit	-6	-7
Heatup Rate	70 A Discharge	+9	+13

^aConstant power input of 100 W to the front heater. Heat capacity of 0.29 W/(kg. °C), heated mass of 84 kg, and battery resistance of 0.41 Ω.

Table 8. Battery Energy Storage Requirements for Different Vans

	TE-Van	G-Van	ETX-II	DSEP
Battery Weight, kg	548	799	642	594
Battery Output, kWh	46	70	54	54
Battery Specific Energy, Wh/kg	83	87	84	91
Cell Specific Energy, ^a Wh/kg	104	109	105	114
Vehicle Range, mi (km)	127 (204)	130 (209)	124 (199)	132 (212)

^aThe battery burden is assumed to be 25%, i.e., the battery weight is 1.25 x cell weight.

Table 9. Energy Output Measured for 36-V Batteries

Battery	Type of Test	Energy Output	
		kW	Wh/kg ^a
MK-I	Constant Current (40 A)	8.3	110
	SAE J227a/C	8.5	112
MK-II	Constant Current		
	40 A	7.4	98
	75 A	7.0	93
	Constant Power		
	10 W/kg	7.6	100
	20 W/kg	7.0	93
	30 W/kg	6.1	81
	Driving Profile		
	SFUDS (350 A) ^b	4.7	62
	SFUDS (200 A) ^c	5.9	78
	SAE J227 a/C	6.0	80

^aEnergy output is calculated on a cell weight basis.

^bSimplified FUDS driving cycle with 350 A limit.

^cSimplified FUDS driving cycle with 200 A limit.

energy goals. The reason for the decrease in performance by the MK-II is the greater difficulty experienced in equalizing cell temperatures. As already noted, nonuniformity of temperature increases the difficulty in achieving equal cell capacities because of the temperature effect upon self-discharge rate and cell resistance. In addition, it is believed that the cells may have been degraded by air in leakage through the positive feedthrough during the storage of the battery. The MK-II battery was stored in the laboratory and exposed to an air atmosphere for more than one year during battery redesign, repair, and reassembly.

B. Power

The power requirements for each of the vans are given in Table 10. As is shown in the table, the power required from the battery on a cell weight basis varies from 88 to 105 W/kg. This power level must be delivered without exceeding the current level and voltage limits dictated by the vehicle power train. The limitations imposed upon the battery design by power train considerations are discussed in Ref. 13.

Table 10. Battery Power Requirements for Different Vans

	TE-Van	G-Van	ETX-II	DSEP
Power, kW	44	56	51	50
Battery Weight, kg	548	799	642	594
Battery Specific Power, W/kg	80	70	79	84
Cell Specific Power,* W/kg	100	88	99	105
Acceleration (0-50 mph), s	22	28	20	20

*A battery burden of 25% is assumed.

The results of single cell, module, and battery power tests are given in Table 11. The single cell tests were conducted at Westinghouse; the 12-V modules were tested at ANL prior to the start of the 36-V battery tests. The single-cell and 12-V module tests showed that the Westinghouse cells have sufficient power for the intended van application. The MK-II battery, however, had lower power. As previously discussed, the poor MK-II performance is due to the temperature variation of the cells during the test rather than an intrinsic lack of power for the battery. Only minor refinements in battery design and temperature control are required to meet the power requirements for the intended application.

C. Battery Life

The calendar- and cycle-life requirements for the electric-vehicle application have been established by the DOE Task Force report.² The requirements are a calendar life of five years and cycle life of 1250 cycles when operating at an average depth-of-discharge (DOD) of 38% or an equivalent of 600 cycles at 80% DOD.

The cycle-life performance of the cells and batteries tested thus far have fallen short of the above requirements. Westinghouse cells, when tested individually, have achieved 300 to 400 cycles¹⁴; moreover, two 12-V modules (tested earlier) and the two 36-V batteries comprised of those cells showed

Table 11. Measured Values for Cell and Battery Power

Type of Test	Current, A	Depth-of-Discharge, %	Specific Power, ^a W/kg
Single Cell ^b	300	80	98
	400	80	115
	500	80	120
12-V Module	300	10	107
	300	50	97
36-V Battery (MK-II) ^c	490	10	125
	380	50	90
	310	80	68

^aCell weight basis.^bWestinghouse data.^cPeak power derived from SFUDS tests at ANL.

lifetimes of only about 120 cycles, with the earliest cell failures occurring at less than 100 cycles. The cause of cell failure was determined by post-test examination of three cells from the MK-I battery.¹⁵ The failure was due to the presence of iron-rich metallic deposits in the separator leading from the positive to the negative electrode. The failure mechanism was similar to that observed in cells tested individually. The shorter lifetime of cells tested in a battery has recently been postulated as being due to the deformation experienced by the cells within a module, particularly those located at or near the center of modules. The walls of the deformed cells bulge inward, which reduces separator thickness and increases the pressure within the electrodes. The added pressure may result in the egress of fine particles of iron and active material from the positive electrode into the separator, adding to the iron particles deposited as a result of the electrochemical formation of iron halides during charge. To check this postulate, we continued testing the MK-II battery until 12 of the 27 cells in the three 12-V modules had failed. The cells were examined following the test and the deformation of the cells noted.

The correlation between cell deformation, cell location in the module, and the cell cycle life is indicated in Table 12. As indicated in the table, the badly deformed cells all failed prior to 141 cycles. The best cells, those that were still operating normally at cycle 141, were those located at the ends of the module and suffered the least deformation. These results show that the initiator of early failure in the battery tests has to do with the design of the cell restraints within the module and not the charging regime, as previously believed. Several simple conceptual design modifications to the cell restraint within the module have been developed to correct this deficiency. We can expect future 12-V modules and batteries comprised of those modules to achieve a cycle life approaching that exhibited by cells tested individually.

D. Charge Equalization

Energy output during battery discharge is limited by the output of the weakest (lowest capacity) cell or group of cells used to monitor and terminate battery discharge. The capacity of a cell depends not only upon the charge input, but also upon the dissipation of the charge by the various cell self-discharge mechanisms. The 36-V battery tests, as already noted, have shown that temperature uniformity is an important factor in maintaining equal self-discharge rates among the cells.

Table 12. Effect of Cell Deformation on Cycle Life

Module 1		Module 2		Module 3	
Cell No. ^a	Cycle Life	Cell No. ^a	Cycle Life	Cell No. ^a	Cycle Life
1	141	10	141	19	141
2	141	11	128 ^b	20	141
3	141	12	128 ^b	21	128
4	141	13	116 ^b	22	124 ^b
5	116	14	116 ^b	23	141
6	79 ^b	15	141	24	140 ^b
7	141	16	124	25	128
8	128	17	141	26	141
9	141	18	141	27	141

^aThe cells are numbered consecutively. For example, in module 1, cell 1 is at one end; cell 5 is at the center, and cell 9 is at the other end.

^bMost badly deformed cells (both sides collapsed inward). Cell 6 was deformed the most with a cell thickness reduction of about 20%. The others marked showed a 10-15% reduction.

Newly fabricated Westinghouse cells of the same design as those in MK-I and MK-II have exhibited self-discharge rates of 100-200 mA. These rates increase slowly with the number of cycles to about 500 mA, increasing rapidly thereafter and indicating the formation of a short circuit. Capacity equalization of the MK-I and MK-II batteries, when cycled on a daily basis, required about a 3-h equalization period with a 3-A current. As the batteries aged with cycling, the time required to equalize increased to about 5 h, with an occasional 10-h period required near the end of battery life.

If the cell self-discharge rates are equal, it is possible to charge the battery to full capacity with little or no equalization. A test was conducted with a 12-V module early in its life, in which 13 cycles were completed without an equalization step while the battery was discharged to 70% DOD on a J227a/C cycle.

E. Reliability

The ability to continue to operate the Li/FeS battery with failed (short-circuited) cells is an important characteristic in terms of battery reliability. Earlier tests with 12-V modules indicated that the battery could continue cycling with one failed cell.³ The MK-II battery test included operating the battery with up to 12 short-circuited cells. The purpose of cycling the battery with short-circuited cells was to determine the voltage characteristics of failed cells, to examine the impact of these cells on the thermal control of the battery, and to provide specimens for post-test examination. The failed cells exhibited a voltage of about -1.6 V for the first few cycles. With continued cycling, the voltage was reduced to -0.6 V and tended to stabilize at that value.

Heat generation proved to be less of a problem than expected. We were able to operate the battery with up to 12 failed cells (constant-current discharge tests) without difficulty. We concluded from these

tests that heat generation of failed cells was only slightly higher than the heat generated from normal cells; thus, the battery cycled as usual except for a loss of about 2 V per cell.

F. Safety

The safety record of this battery continues to be outstanding. As expected, the 36-V battery tests were conducted without safety problems.

A safety report dealing with lithium-alloy/iron sulfide batteries is under preparation at ANL.¹⁶ The preliminary results from this study are summarized as follows:

- (1) Combustible or explosive gases are not generated by the battery during normal or abnormal charge or discharge operations. An explosion hazard does not exist.
- (2) The high (400-500 °C) operating temperature presents little or no hazard. Under normal operating conditions, the battery surfaces and cabling exposed to possible contact by personnel are insulated, and this step reduces the temperatures to modest levels (5-25 °C) above room temperature. Under accident conditions, where the insulating materials are damaged or broken away to expose the cells, contact with surfaces up to 500 °C is possible, but not likely, because of the remote location of the battery relative to the vehicle operator.
- (3) External or interior short circuiting of the battery results in overheating and damage to the cells but does not pressurize or otherwise jeopardize containment of the cells within the battery case. Experimental evidence showed that heat generated during a rapid short circuit was absorbed by the cells without hazard.
- (4) The generation of toxic fumes, such as Li_2O , LiOH , or SO_2 , might be postulated to occur in a severe crash in which the Li/FeS battery case and cell containers are ruptured and the contents exposed to air or water; however, this has been shown not to occur by several drop-tower experiments. The reason for the favorable result is that the lithium and sulfur compounds are protected by the noncombustible molten-salt electrolyte that coats each particle of the active materials.
- (5) For batteries configured into high voltages, the normal precautions against electrical shock must be incorporated into the battery design and operating procedure.
- (6) Maintenance and repair will most likely be handled with the battery and cells cooled to room temperature, although it is possible to design the battery to perform repairs with the battery still hot. Cooling the cells to room temperature solidifies the electrolyte and renders the battery electrically nonconducting, thus minimizing* electric shock hazard during repair work.

VI. CONCLUSION

The tests were performed using three full-scale 12-V/300-Ah modules housed within a vacuum-insulated battery case and other components scaled to fit a battery with a nominal 36-V/8-kWh output.

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*Cells at room temperature (with solidified electrolyte) have exhibited voltages, but the current draw from a battery at room temperature would be very low. The hazard to personnel has not yet been evaluated.

Thermal management studies with the vacuum-insulated case showed that the required heat loss values were closely approached. The heating and cooling system, after being modified to improve temperature measurements, performed according to design expectations.

Electrical performance tests of the battery showed that the cells achieved a specific energy of >110 Wh/kg in driving profile testing (J227a/C) and a specific power of >95 W/kg at 50% DOD and 300 A. These values met our goals for a van battery. Cycle-life expectations, however, were not met. Separate tests of two 12-V modules and two 36-V batteries were performed. The average lifetime obtained was about 120 cycles, compared to 350 cycles for a separate group of similar cells tested individually. Post-test examination of the MK-II battery provided evidence that early failure was due to cell deformation.

Reliability tests showed that the battery could be cycled with one or more failed cells. A battery with failed cells cycled normally except for a loss of about 2 V per failed cell. The I^2R heating associated with a failed cell was found to be only slightly higher than that of a normal cell.

The safety record for the battery continues to be outstanding, as expected from previous test experience and our analysis of the chemistry and electrochemistry of the Li/FeS system.

Overall, the tests provided verification of a conceptual van battery design for a full-scale battery. Only minor modifications were required to successfully operate the fractional-scale batteries and to validate the basic design.

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