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CONCEPTUAL DESIGNS FOR UTILITY LOAD-LEVELING BATTERY WITH Li/FeS CELLS

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A. A. Chilenskas, W. Grieve,
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July 1980

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ABSTRACT

In 1978, a conceptual design of a 100 MW-h load-leveling battery system having Li alloy/FeS cells was developed as a result of a joint effort between ANL and Rockwell International. In this conceptual design, the submodule, which was the basic replaceable unit for the system, had a capacity of 240 kW-h and consisted of ninety-six 2.5 kW-h cells. However, a study by Rockwell indicated that the cost for battery hardware, \$60-80/kW-h (cells and converters not included), was too high. Most of this cost was contributed by the submodule structure and the charge equalization scheme, which was the same as that developed for electric-vehicle batteries.

In 1979, subsequent efforts were concentrated on lowering these hardware costs and resulted in the development of three modified designs, which are presented in this report. The first, developed at ANL, consisted of a 30 kW-h cell/submodule and the electric-vehicle equalization scheme. The hardware cost for this modified design was quite low, about \$25/kW-h; however, this design was eventually rejected owing to the apparent impracticality of such a large cell. The two other modified designs had more conservative cell designs. One of them, developed at ANL, consisted of a 120 kW-h submodule consisting of one hundred 1.2 kW-h cells; the other, developed at Rockwell, consisted of a 1020 kW-h submodule consisting of four hundred and eight 2.5 kW-h cells. For both of these designs, an alternative method of equalization, in which fixed resistance shunts are used on each cell, was proposed; this equalization method adds little equipment cost to the system and only sacrifices about 4% of the coulombic and energy efficiencies. The cost of battery hardware for these two designs was estimated to be acceptable, about \$22-60/kW-h. Some questions remain on the assumed capabilities of the cells and the feasibility of the battery hardware.

I. INTRODUCTION

The primary purpose of an utility load-leveling plant is to increase the utilization of base-load electric generating plants in meeting their electrical

loads, and to reduce the need for oil- or gas-burning peaking units. An additional purpose is to improve the efficiency of the electrical transmission and distribution system in terms of energy and cost. The secondary goal becomes possible through dispersed urban siting for load-leveling battery plants. Physical guidelines for load-leveling battery plants have been generated by the electric utility industry and the U.S. Department of Energy. These are summarized in Table 1. The commercial availability of an adequate and efficient ac/dc converter concurrent with battery commercialization is assumed; converter performance and cost are outside the scope of the present effort.

Table 1. Guidelines for a Load-Leveling Battery Plant

Criteria	Requirement ^a
Capacity, MW-h	100
Minimum Footprint, kW-h/ft ²	8 (exclusive of converter)
Daily Cycling Schedule, h	
Discharge (20 MW)	5
Charge	7 (to 85% charge capacity)
Minimum Energy Efficiency (dc out/dc in), %	75
Maximum Height, ft	20

^aBased upon guidelines formulated by the Electric Power Research Institute.

Throughout this report, the terms "module" and "submodule" are used to describe components of a load-leveling battery. A module, which is an independent unit of the battery, consists of thermally insulated housing or a designated region within a housing, thermal management system, bus-work, certain switchgear, instrumentation, and miscellaneous structures and devices to support submodules and to facilitate their replacement. Submodules are structurally and electrically integrated removable units, comprised of a number of cells and the mechanical structure and electrical conductors required to tie these cells together.

In 1978, a conceptual design of a 100 MW-h load-leveling battery¹ having Li-Al/FeS or Li-Si/FeS cells was developed as a result of a joint effort between ANL and the Energy Systems Group (ESG) at Rockwell International. This design, hereafter referred to as 1978 RD, was very conservative in most respects. It utilized 2.5 kW-h cells of conventional design (vertical electrodes, flooded electrolyte, electric-vehicle cell feedthrough technology). Appendix A

provides more detailed description of the 2.5 kW-h cell. The 1978 RD also included the adoption of the electronic charge-equalization method that had been developed at ANL for electric-vehicle (EV) batteries (discussed later). The 1978 RD concept utilized braided cables (stainless-clad copper conductors) for intercell connectors, and it had four cells mounted side-by-side in parallel-connected ensembles. Each ensemble was mounted on its own shelf in a tall bookcase-type structure, which was the removable unit, or submodule. A submodule consisted of ninety-six cells and a module consisted of thirty-six submodules. The 100 MW-h battery had two groups of six modules arranged on either side of an electric-power processing center, which contained two ac-dc converters,* circuit breakers, and transformers interfacing with the utility distribution or transmission system.

The fact that four cells at 2.5 kW-h were connected in parallel to form 10 kW-h ensembles is believed to have imposed an unrealistic requirement on cell reliability. Other than the cell reliability uncertainty, the 1978 RD concept utilized components and engineering about which there were few major uncertainties. The estimated cost was \$80/kW-h (1978 dollars) for the battery hardware (exclusive of cells).† Of this cost, \$35 was contributed by the bookcase submodule and \$20 by the charge equalization system. In subsequent efforts, modified designs were developed to reduce the cost of the submodule structure and the equalizing system.

The first modified design, designated the LFSC concept, had a large (30 kW-h), free-standing cell, which is described in Appendix B. In the LFSC concept, the submodule structure was entirely eliminated by transferring that structural function to the cell container, which was a large (8-ft high) vertical tank, rectangular in cross-section, containing a stack of several hundred electrode-pairs horizontally oriented. Feedthroughs penetrated one side wall of each cell, with four to eight feedthroughs per cell distributed uniformly along the height of the wall. The cell capacity chosen for this concept was the maximum that would be consistent with a desired battery voltage of about 2000 V and a converter power rating of 10 MW. In the LFSC concept, each of the two converters was connected to a single string of 30 kW-h cells, 1680 cells in a string for a capacity of 50 MW-h per converter. This reduced the number of cells in the 100 MW-h battery system to 3360 cells. This minimal number of cells, in combination with the geometry of the free-standing cells, reduced the cost of the electronic equalizing system to about \$3/kW-h and produced an estimated cost of \$25/kW-h (1979 dollars) for the battery hardware. This design demonstrated that drastic changes in the 1978 RD could produce a drastic reduction in cost. However, the LFSC concept was discarded because it did not represent the anticipated cell technology of the mid-1980's, and even more because of strong doubts concerning the producibility and reliability of such a large cell.

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*The interface of a load-leveling battery with converters was studied by United Technologies Corp.² under a contract with ANL

†Costs estimated by the Rockwell pricing department; an organization that is independent of the design teams assigned to the concepts.

Two other modified designs were then developed with much more conservative cell designs. The first, designated the small-cell stack concept (SCS), was conceived at ANL; and the second, designated the large-cell submodule concept (LCS), was conceived at Rockwell by ESG. The LCS concept utilized the same cell size as that of the 1978 RD, 2.5 kW-h; and the LCS concept utilized 1.2 kW-h cells, which would be about three times as large as present engineering-scale Li-Al/FeS cells. A detailed description of these two designs is given in this report. For both designs, an electronic equalization scheme was devised in which the need to run conductors to each cell (1978 RD) was eliminated; this contributed to a significant reduction in battery-hardware cost over that of the 1978 RD.

The modified designs were based upon the Li-Al/FeS cell, which is the most advanced lithium/iron sulfide cell at present. However, there is nothing in the conceptual designs which would preclude cells with negative electrodes of Li-Si. The operating characteristics assumed for the Li-Al/FeS cell are given in Table 2, and are consistent with the technology anticipated for the mid-1980's.

Table 2. Operating Characteristics of Li-Al/FeS Cell

Temperature, °C	425-500
Voltage Range, V	1.0-1.6
Reversible Thermodynamic Coefficient, W/A (the TΔS heat generation and absorption rate)	0.1
Specific Energy, W-h/kg	60
Heat Capacity, cal/g·°C	0.23
Energy Efficiency, %	90
Discharge Current Density, mA/cm ²	50
Electrode Constraint, psi	30 (normal to electrode plane)

II. GENERAL CHARACTERISTICS OF BATTERIES

A. Cell Reliability and Battery Maintenance

In Fig. 1, the capital cost of energy delivered by the battery is expressed on the basis of an annual capacity attrition rate of 2%. Thus, over a ten-year period, the average energy capacity would be about 90% of the initial capacity; and the battery capacity would be about 80% of the initial capacity at the end of the assumed cell-life of 10 years. There are no provisions in these costs for replacement of failed cells within the 10-year cell

Fig. 1. Costs for Load-Leveling Battery System (fixed charge rates taken from Ref. 3)

life. Figure 1 is discussed further in Section V.A of this report. In this section, we investigate the assumption that all submodules can remain in place for 10 years with no greater capacity attrition than 2% per year. It became clear during the design studies that frequent replacement of submodules could impose significant costs due to maintenance operations and increased capital needs. It is obviously desirable to avoid such costs, as well as to avoid costly design complications that might require frequent submodule replacement.

Most cell failures can be characterized as partial short circuits (high-resistance shorts) rather than open-circuit faults. The nature of the battery service is such that partially short-circuited cells tend to become overdischarged. As a consequence, partially short-circuited cells will have a tendency to undergo a reversal of polarity, at least over a portion of the discharge period. For this reason, it is assumed that all cell faults are short circuits and that, on the average, a single failed cell causes the loss of voltage of two cells.*

*Preliminary experimental evidence has been obtained to support this assumption using multiplate electric-vehicle cells.⁴

A stochastic process in which events (e.g., cell failures) occur at random times, with some constant average rate, m , and with no coincident events, is described by the Poisson distribution, which expresses the probability, P , of observing exactly x events in time interval t as follows:

$$P(x) = e^{-mt} \left[\frac{(mt)^x}{x!} \right] \quad (1)$$

The probability of y events is

$$\begin{aligned} p(y) &= P(0) + P(1) + \dots + P(y) \\ &= \sum_{x=0}^y e^{-mt} \frac{(mt)^x}{x!} \end{aligned} \quad (2)$$

The ac-dc converter technology of the 1980's is expected to favor a battery terminal voltage of at least 1800 V. The battery was assumed to be composed of strings of cells, 1800 cells in series within each string. When 90 cells in a string have failed, 180 cells will have been effectively removed from participation, and 10% of the string capacity will have been lost. The probability of this happening within 10 years can be obtained from Eq. 2 by setting $y = 90$ and $t = 10$. However, m --the number of cells (1800) times the individual cell failure rate during a 10-year service life--is not known. Therefore, we investigated the required cell reliability such that some designated probability of string survival will result with only a 10% loss of capacity, 20% loss, 30% loss, etc.

Figure 2 shows the results of computations employing Eq. 2. For example, if faulted cells were the only mechanism for a loss of string capacity and if an 80% surviving capacity after 10 years were acceptable, then cell mean-time-before-failure (MTBF) of 100 years would be consistent with a 50% probability of survival. A cell MTBF of 110 years would provide a 90% probability of survival at the 80% capacity level; in this case, on the average one string out of 10 would require the replacement of at least one submodule during 10 years.

Another factor must also be taken into consideration: the string capacity also erodes as a result of individual cell capacity fading. If the average cell fading rate is, for example, 0.004% of initial capacity per cycle, then the capacity loss in 10 years would be 10%. Consequently, a total capacity loss (i.e., cell failure plus string capacity erosion) of 20% would be observed. The survival of 90% of the cells (at 50% confidence level) will require a cell MTBF of 200 years, according to Fig. 2. If such a MTBF can actually be achieved by future LiAl/FeS cells the load-leveling battery could attain a reasonable rate of maintenance, corresponding to the servicing of about half

Fig. 2. Cell Reliability Curves

of the strings in ten years (maintenance would mainly be the replacement of a single submodule.)

If EV cells had a MTBF of 200 years (again assuming that each faulted cell effectively removes one other cell), then the probability of a 120-cell electric-vehicle battery surviving 5 years with 90% of its original capacity would be about 60%. In this calculation, we have neglected any fading of capacity of non-faulted cells. A 60% survival rate would probably not be acceptable to the EV industry. The cell reliability required for a load-leveling battery seems to be somewhat less than that required for EV batteries; and, if a satisfactory cell reliability for the EV application is developed, it would probably suffice for load leveling. There are no experimental data concerning the possible size dependence on cell reliability; but it is possible that reliability may diminish with increasing cell size (load-leveling cells will be larger than EV cells).

If the actual MTBF of LiAl/FeS cells is found to be significantly less than 200 years, the costs of a load-leveling battery will be increased by the following factors:

- 1) partial loss of battery availability during the submodule replacement operations;
- 2) labor costs of frequent submodule replacements; and
- 3) capital cost of replacement submodules (or replacement cells if the submodule is repaired).

No serious attempt was made to optimize the battery conceptual designs for levels of cell reliability less than 200 years.

B. Charge Equalization

The LiAl/FeS cells, like other non-aqueous electrolyte cells, lack the inherent protection against overcharge that lead-acid cells possess. In the latter, an attempt to further charge a fully charged cell will cause electrolysis of the water in the electrolyte. This limits the voltage rise across the cell, thereby protecting the cell against deleterious electrochemical reactions, but causing problems with venting and water replacement. No such voltage limiting reaction exists in present-day LiAl/FeS cells^{*}; therefore, an attempt to pass a charging current through a fully charged cell will cause the potential to rise above the 1.6 V nominal voltage for full charge until harmful corrosion reactions result. Therefore, when two or more LiAl/FeS cells are being charged in series, it is necessary to provide some means of discerning an incipient overcharge on any cell. Furthermore, since differences in rates of self-discharge will exist from cell to cell, a series string of cells under charge-discharge cycling will be prone to a monotonic accumulation of cell-to-cell differences in charge. This monotonic drift of one cell relative to others eventually results in the weakest cell becoming completely discharged while other cells are charged. For the present, there is only one known method of dealing with this problem of dispersion of self-discharge rates--charge equalization (*i.e.*, a periodic adjustment of the charge on each cell of the string so that all cells are made to have essentially equal charges). In order to equalize charge, some electrical access to each cell must be available independently of all other cells. Appendix C is devoted to a detailed discussion of equalization problems and techniques.

In the EV battery development program at ANL, W. H. DeLuca et al.⁵ developed a means of equalizing in which conductors are run to each intercell connector in the series string. These conductors are used both to sense incipient overcharge (a voltage measurement on each cell) and, after bulk charge of the string, to provide an appropriate increment of charge to each cell that is not already fully charged. An electronic device to be associated with each cell has been developed to perform the voltage sensing and control of the equalizing current. This device must be located in an ambient-temperature space. The nature of the electronic control of equalizing charge current places a constraint on the IR voltage drop in the equalizing conductors during equalization. This limit on IR voltage drop has not placed a serious penalty on the EV battery because the lengths of conductor are of the order of 10 feet, and only about half of that is in the high-temperature battery space. However, large size of a load-leveling battery tends to be incompatible with this limitation on IR drop, which can be accommodated only by incurring substantial costs in conductors or design complications.

---

^{*}An electrochemical reaction has been proposed that could provide overcharge protection for Li/MS cells by T. Kaun and A. Chilenskas of the Chemical Engineering Division at ANL.

In the 1978 RD concept, the electronic equalization concept of the EV battery was adopted directly. For this design concept, a cell assembly of 10 kW-h (four cells of 2.5 kW-h each) was located at each voltage tier in the series string. Therefore, in the 100 MW-h battery of the 1978 RD, about 10,000 equalization conductors and electronic devices were required. Because of the limit on IR drop, the high-temperature segments of the equalization conductors had to be quite large (#6 AWG), protected against oxidation, and provided with high-temperature electrical insulation. As a result of these requirements, an analysis by the ESG of Rockwell¹ indicated a cost of about \$20/kW-h (storage capacity) for the equalization system. Subsequent conceptual design efforts concentrated on reducing the costs of equalization.

In the LFSC concept, the above-mentioned electronic equalization system was retained, but the numbers of electronic modules and equalizing conductors were reduced by a factor of three because the effective cell size was tripled relative to the 1978 RD concept (30 vs. 10 kW-h). Furthermore, the cell configuration and arrangement in the LFSC made it possible to employ very short runs of equalizing conductors inside the high-temperature zone. As a result, a cost of only about \$3/kW-h was estimated for the equalization system. However, serious doubts remained about the technical and commercial feasibility of the 30 kW-h cell in the LFSC.

A new method of equalization, referred to as passive equalization with fixed shunts, was adopted for the SCS and LCS concepts. In this system, each cell includes an electrical shunt resistor, R_e , between the positive and negative terminals. Equalization consists of periodic complete discharge of all cells. The resistance of R_e must be large enough so that the shunted current is small relative to the cell charge (*i.e.*, the shunted current must require many days to discharge a fully charged cell). On the other hand, R_e must be smaller than the internal "parallel" resistance of the worst functional cell in the string; consequently, R_e is the controlling self-discharge process. But mainly, R_e must be small enough to bleed off the residual charge of a nominally discharged cell (*i.e.*, a cell having a terminal potential of 1 V under nominal discharge current) in the designated time period for equalization. During equalization, each cell is discharged independently of all others, therefore, an abnormal transport of active material cannot occur within the cell. In the equalization discharge process, as a cell approaches complete discharge, the shunt current decays exponentially.

The proper sizes of shunt resistor are about 1 Ω for the SCS concept and about 0.5 Ω for the LCS concept. Furthermore, a 1.8% dispersion of coulombic efficiency (maximum cell-to-cell variation) can be managed by this system, with a nightly equalization period of 6 h plus a weekend equalization period of 48 h. The equalization period is simply an open-circuit interval following battery discharge and preceding charge. This ability to accommodate a 1.8% coulombic-efficiency dispersion in a routine operating schedule is considered very satisfactory.

C. Protection of Cells from Over-charge and Over-discharge

The charging of a string of cells must be terminated when any one cell begins to approach a terminal voltage of 1.6 V; otherwise, irreversible corrosion damage will commence within the fully charged cell. Similarly, during discharge, as soon as any one cell approaches the utilization of all of the accessible sulfur in forming Li_2S at the positive electrode, the discharge current must be terminated so as not to force an abnormal transport of active materials. For the EV-type equalization method, such protection is provided by the electronic system, which monitors the terminal voltage of every cell in the battery. However, installing conductors to every cell is not economical, and the fixed-shunt equalizing system was proposed expressly to avoid such numerous conductors. Therefore, some means of sensing incipient over-charge and over-discharge in any cell had to be devised. The method proposed was to monitor the voltage across series groups of N cells (where $N \gg 1$), along with the current in each string of the battery. The number N must be chosen to provide confidence that any single cell in the N cells will be protected.

The factors that are at least theoretically detectable by the voltage measurements across the N -cell group and the measurements of all string currents are as follows:

1. The series resistance of each group of N cells might be measured by correlating an ac ripple voltage with an ac ripple current, either deliberately imposed or naturally present. As cells approach full discharge, their series resistance increases markedly.
2. Changes in the voltage, V_N , across a group of N cells would reflect (with attenuation by a factor $1/N$) a change in the terminal voltage of any cell in the group of N . A determination of $(V_N)^{-1}(dV_N/dQ)$, where Q denotes charge, should signal a rapid change of a single cell and thus indicate an approach to full charge or discharge.
3. A decrease of current in a given string, relative to the average current of all others in parallel at a given time, would indicate that the string may be approaching the end of charge or end of discharge.
4. The cumulative charge supplied or withdrawn at any time would be monitored and would be correlated with the other observations to decide upon when to terminate charge or discharge.

Factors (1) and (2) in a single cell provide a signal magnitude of about 100% of the nominal steady voltage value, as full charge or full discharge are approached. In the case of cell resistance as full charge is approached, the resistance rises steeply only as 1.6 V is surpassed; therefore, not much time is provided to terminate charge. If the number of series cells in a control block were 10, sudden increases of about 10% or more would be obtained for both

the observed resistance and $(V_N)^{-1}(dV_N/dQ)$. Either of these signals alone would be sufficient, and the simultaneous occurrence of both would constitute clear guidance for terminating charge or discharge. When N equals 50, these signals at end of charge or discharge would be about 2%, which is marginal. However, the coincidence of these two observations in conjunction with an appropriate state-of-charge indication and perhaps a consistent relationship of the string current relative to other strings can probably provide protection with $N = 50$. Computer simulations have indicated that incipient over-charge and over-discharge can be discerned with $N = 50$.

In the SCS and LCS concepts, N has been taken as 50, although $N = 25$ or $N = 10$ might have been safer choices. For $N = 50$, the cost of the instrumentation system for protecting cells is relatively minor. This aspect deserves further analysis.

D. Structural Materials

The materials requirements for the battery structures are that they provide reliable and safe service for 20 years at 450°C in an air atmosphere.* Table 3 summarizes some properties of the major choices of metals. Low carbon steel is considered not usable because of graphitization. The principal choice is between an alloy steel (e.g., 1/2% Cr-1/2% Mo), which has a low cost of raw

Table 3. Structural Material Selection

Steel	Allowable Stress at 454°C (1% creep in 100,000 h), kip/in. ²	Raw Material Cost, \$/lb	Remarks
Low Carbon Steel	6.6 ^a	0.20	Graphitization may occur above 426°C.
1/2%Cr-1/2%Mo	13.4	0.36	Requires heat treatment when welded.
2 1/4% Cr-1% Mo	14.4	0.47	Requires heat treatment when welded.
304 Stainless Steel	14.9	0.96	Easy to form and easy to weld without heat treatment.

^aUse of material above 426°C is not current practice under Section 1 of the ASME Boiler and Pressure Vessel Code and is not contemplated for the Li/FeS battery.

*The use of an inert atmosphere was considered early in the study, but was found to incur higher operating costs than could be justified by the savings in hardware costs.

material but a high fabrication cost when welded, and 304 stainless steel, which has a high cost of material but is easily welded. The LCS concept utilizes 1/2%Cr-1/2% Mo steel for structural parts of the submodule, and features a modular housing constructed primarily of refractory concrete. The concrete specifications are given in Table 4. The SCS concept employs 304 stainless steel in the submodule structure and for those components of the building structure that are exposed to high temperature.

Table 4. Refractory Concrete Properties

Cement ^a Properties	
Typical Composition, wt %	
Al ₂ O ₃	39
TiO ₂	2.5
CaO	38
Fe ₂ O	12
FeO	4
SiO ₂	4.5
Specific Gravity	2
Thermal Conductivity, Btu/h-ft-°F	0.6
Minimum Compressive Strength (concrete after heating), psi	500
^a Calcium aluminate cement with clay (firebrick aggregate).	

E. Electrical Materials

The requirement for a 20-year life in air at temperatures up to 500°C imposes some severe constraints on the selection of conductor materials. Copper, for example, cannot be used without some rather significant measures to protect it against oxidation. The problems of conductor materials selection are as follows:

1. All metallic conductors undergo an increase in electrical resistivity with increasing temperature, and, at operating temperature (450°C), the increment is substantial.
2. Some metals oxidize rapidly at operating temperature and form no reliable protective coating.

3. When the bus conductor material has a significantly different coefficient of thermal expansion than the structure, sufficient flexibility must be designed into the bus to prevent relatively fragile components (such as feedthroughs) from carrying large differential expansion forces.
4. The mechanical strength of conductor materials is reduced at operating temperatures.
5. Most mechanical joining methods have doubtful long-term efficacy under the present operating conditions, and many metallurgical bonds are subject to oxidation. Welded joints may have high resistances because of small fillet areas. Information is needed on solder and braze alloys that do not melt below 600°C, but have low resistivity.
6. A high thermal emissivity may be required in some designs, and this may require a coating or paint.

Stainless steel-clad copper was selected by ANL for the SCS concept, and chrome-copper alloy with chrome plate (or possibly with a high-temperature paint on nonelectrical contact surfaces) was chosen by Rockwell for the LCS concept. The two selections should be interchangeable between the two battery concepts; the different selections simply reflect differing engineering opinions. Other conductor materials were discarded for various reasons. Aluminum exhibits a loss of structural strength at 450°C and would probably be difficult to fabricate with electrical junctions. For low carbon steel, large cross sections that are needed for low-electrical resistance result in sufficient stiffness by which cell terminal insulators could be damaged by thermal expansion forces. Bare copper has too high of an oxidation rate. In nickel plated copper, the diffusion rate of nickel is too high at 450°C; this would compromise surface protection and increase electrical resistance.

Materials for electrical insulation seem limited to either ceramics (e.g., alumina) or mica. A 3000-V isolation is required for all concepts, which is equivalent to a 2-cm air gap at 450°C. The SCS concept employs both types of materials and the LCS concept employs cast alumina pieces. The acceptability of mica may be in doubt because it can absorb molten salt.

F. Thermal Management

The objectives of the thermal management system are to bring the battery to operating temperature (425 to 500°C) at startup and after any cooldown; to maintain the cells in the battery at a uniform temperature; to remove sufficient heat during operation to maintain the cells within 425 to 500°C; and to maintain battery temperature within the designated range during periods of standby, preferably without consuming power for standby periods of 2 days or shorter. The thermal management system consists of thermal insulation on the battery enclosures; electrical and/or other heaters; a cooling system, either an air circulation system for pure convective cooling, or a system of tubes

and a coolant circulating system for radiative-convective cooling; and instrumentation for control and temperature verification. Since the battery operating temperature is much greater than ambient temperature, cooling is a minor engineering task. However, conservation of heat during several days of standby (as on weekends) is a difficult task, requiring the maintenance of temperature uniformity among all the cells of the battery. It is presently assumed that all cells should be within a 25°C temperature span at any given time, and that no cell should exceed 425 to 500°C during operation. These assumptions may be subject to change as new information or a new cell technology emerges, but the concepts considered here were subject to the above assumptions.

Heat generation in LiAl/FeS cells involves two phenomena: (1) reversible electrochemical heating during the exothermic discharge reaction and cooling during the endothermic charge reaction, and (2) irreversible heating due to current passing through the IR drops in current collectors, bus conductors, etc., and through polarization overpotentials.

The ratio of the reversible heat generation during discharge to the energy capacity of the cell can be expressed as:

$$Q_R/Q_0 = 0.1/\bar{V}_D \quad (3)$$

where

Q_R = reversible energy release, W-h

Q_0 = energy capacity of cell, W-h

$\bar{V}_D$ = mean terminal voltage of cell during discharge, V

The factor 0.1 V is a theoretical thermodynamic value, confirmed by experiments.⁶ A value of about 1.2 V is expected for $\bar{V}_D$, which would make $Q_R/Q_0 = 0.08$. For a 1200 W-h cell (as in the SCS concept), the reversible heat per cycle would then be about 100 W-h. More importantly, the adiabatic temperature change attributable to the reversible heat is

$$\Delta T_R = \frac{Q_R/Q_0}{c/s} = \frac{0.1s}{c\bar{V}_D} \quad (4)$$

where

ΔT_R = adiabatic temperature change due to the reversible heat, °C

c = specific heat of the cell, W-h/kg°C

s = specific energy of the cell, W-h/kg

Typical values of c and s for load-leveling cells are as follows:
 $c = 0.3 \text{ W-h/kg}^\circ\text{C}$ and $s = 60 \text{ W-h/kg}$. For these values and a $\bar{V}_D$ of 1.2 V,

$$\Delta T_R \approx 17^\circ\text{C}$$

Therefore, if there were only reversible heating and cooling and the cells were perfectly insulated, the cell temperature would increase about 17°C during discharge and would decrease an equal amount during charge.

The adiabatic temperature change attributable to the irreversible heating is calculated in the following manner. The irreversible losses during discharge and charge are assumed to be distributed as the inverse square of the discharge and charge times (T_D and T_C , respectively). Thus, the irreversible heat release during discharge (Q_D) and charge (Q_C) are related as follows:

$$\frac{Q_D}{Q_C} = \left(\frac{T_C}{T_D} \right)^2 \quad (5)$$

For 5-h discharge and 7-h charge rates,

$$\frac{Q_D}{Q_C} = \frac{49}{25} \approx 2 \quad (6)$$

The energy efficiency of the cell (ϵ) can be expressed as:

$$\epsilon = \frac{Q_0}{Q_0 + Q_D + Q_C} \quad (7)$$

or

$$\epsilon = \frac{1}{1 + 1.5Q_D/Q_0} \quad (8)$$

The temperature rise resulting from irreversible heating during discharge, ΔT_D , is given by

$$\Delta T_D = \frac{Q_D/Q_0}{c/s} \quad (9)$$

$$= \frac{s}{1.50} \left(\frac{1}{\epsilon} - 1 \right) \quad (10)$$

For the same values of c and s given above,

$$\Delta T_D = 133 \frac{1}{\epsilon} - 1 \quad (11)$$

The irreversible heat would then be responsible for adiabatic temperature rises as a function of cycle energy efficiency as shown in Table 5. (ΔT_C denotes the rise during charge and is simply half of ΔT_D .) For a reversible

Table 5. Irreversible Heating during Discharge and Charge

ϵ	$\Delta T_D, ^\circ\text{C}$	$\Delta T_C, ^\circ\text{C}$
0.9	14.8	7.4
0.85	23.5	11.7
0.80	33.2	16.6
0.75	44.3	22.2

temperature change of 17° , and an energy efficiency of 0.80, the total adiabatic temperature change would be approximately zero during charge and a rise of about 50°C during discharge. For an efficiency of 0.9, the temperature of the adiabatic cell would decrease about 10°C during charge and increase about 32°C during discharge.

Two methods of thermal management were considered--forced air convective cooling and radiative heat transfer. At temperatures of 425 to 500°C , radiative heat transfer is highly effective, while forced-air convective cooling tends to suffer from the relatively low density of the air. Temperature control systems employing radiative transfer will have cooled surfaces (e.g., tubes) to which the cells radiate, and convection systems will require the circulation of large volumes of air. By either method, it is important to avoid localized over-cooling. The thermal design of the battery housing (i.e., the thermal insulation) is determined by the preference for a two-day standby without power input. Therefore, the required amount of thermal insulation depends critically on the cell energy efficiency and the configuration of the housing, but is relatively independent of other parameters.

G. Electrical Plant and Interfaces

The load-leveling battery will be connected to the utility distribution network through two power converters of 10-MW capacity each. These converters serve a dual function: during the charge cycle, they convert the commercial 60 Hz alternating current to direct current for battery charging; and, during the discharge cycle, the direct current from the battery is converted to alternating current and delivered to the electric-utility distribution network. The proposed converters are of the self-commutated type, thus providing a

flexible leading and lagging reactive power control. For dc system protection and switching, fusible, non-load interrupting switches are proposed. The fuses will be of the high-speed, current-limiting type. For the interface with the utility distribution system, standard circuit breakers and protective relaying will be used. There is to be a master site controller as part of the system to perform the following functions: initiate, terminate, and control the rates of charge and discharge, either automatically or in response to a utility dispatcher's commands; monitor critical parameters for safety and efficiency; and log data and communicate with dispatcher.

Measurements to be monitored by the site controller consist of the following: battery terminal voltage; voltages (mean and rms ripple) across each 50-cell segment of each string; currents (mean and rms ripple) in each string; ac voltage, current, and power; dc ground current in both ground current detectors; status of all disconnect switches; and status of all module thermal management systems as to heating, cooling, standby and outputs from the several thermocouples in each module air distribution system.

The voltage of the battery is governed by the operational characteristics of the power converter. The recent study on the power converter by United Technologies Corp.² showed that a number of voltage ranges are compatible with the converter. According to this study, for a ratio of high-to-low voltage equal to 1.5 for the battery, the optimum voltage range is 2400 to 3600 V; for a ratio of 1.65, the indicated optimum voltage range is 2180 to 3600 V. The voltage of the cell under consideration is 1 V at the end of discharge (EOD) and 1.6 V at the end of charge (EOC). Therefore, approximately 2200 individual cells or parallel ensembles of cells would provide this optimum voltage range. The same study showed that, with only a minor penalty in converter efficiency, the voltage ranges may vary from the optimum values as long as the upper limit of 3600 V is not exceeded.

III. THE SCS CONCEPT

The SCS concept, developed at ANL, is based upon the use of 1.2 kW-h cells in 120 kW-h submodules. The 100 MW-h system consists of eight modules, two converters, and two transformers and is arranged as shown in Fig. 3. The energy footprint is about 10 kW-h/ft² for the modules and associated space (excluding converters and transformers); the footprint including the ancillary equipment is 7.2 kW-h/ft².

A. Cell and Submodule Designs

The cell in the SCS concept has case dimensions (outer) of 30 x 27 x 4.0 cm. Electrode dimensions are approximately 26-cm square, six electrode pairs per cell. The separator material is assumed to be MgO powder. An electrolyte-starved cell is proposed so that the location of the gas-filled ullage volume can be predetermined. That ullage would be made contiguous with the internal portions of the feedthrough to keep bulk liquid electrolyte away from those parts. The cell case is negative, and the feedthrough conductor

FOOTPRINT: OVERALL 7.2 kWh/sq. ft.

BATTERY ONLY (LESS CONVERTERS AND
TRANSFORMERS) 9.83 kWh/sq. ft. INCLUDING
5 ft. MARGIN AROUND BATTERY BUILDING.

Fig. 3. Schematic of SCS Concept

is the positive terminal. Electric-vehicle cell technology would be utilized for the cell and feedthrough design. During discharge, the average current density and terminal voltage would be, respectively, 50 mA/cm² and about 1.2 V; therefore, the energy rating of the cell would be 1.2 kW-h. A 0.9- Ω fixed shunt (a 14-cm length of 24-gage nichrome wire attached to the cell exterior) would be used for equalization and connect the positive feedthrough conductor with the negative case.

Two stacks of 50 horizontally oriented cells are mounted in a single structural frame, which forms the removable unit or submodule (see Fig. 4). The submodule is a factory-assembled unit. Cells are separated from each other by 0.25-mm sheets of reconstituted mica insulation or ceramic matting and connected in electrical series so that a submodule contains 100 cells in series; at EOD, the voltage across a submodule would be 100 V. Since the energy capacity of each cell is 1.2 kW-h, a submodule is a 120 kW-h unit. The structural frame is made of 304 stainless steel, and the cells are maintained at a 2-cm distance from it by insulating spacer strips. The frame is at ground potential. A row of nine submodules is supported from beneath by a beam, which is part of the fixed structure of the module. The base of the submodule frame is maintained in position by simple guide brackets attached to the supporting beam. The submodule is free-standing and requires no other structural support.

Fig. 4. Submodule Design for SCS Concept

The current path in a submodule begins at the negative electrode of the top-most cell of one of the stacks and proceeds down the string of cells in that stack to the positive terminal of the bottom-most cell, from which it is conducted across to the negative terminal of the bottom cell of the companion

stack in the submodule. The current then flows upward through the second stack and leaves the submodule through the positive terminal of the top cell of that stack. All current-carrying connections to a submodule are attached at the top. The current does not exceed 240 A at EOD; consequently, the submodule-to-submodule conductors can be small. These conductors are brought upward from the top of each submodule, penetrating a layer of thermal insulation which is loosely attached at the top of the submodule. Connections of these inter-submodule conductors are made above the thermal insulation. When it becomes necessary to replace a submodule, the inter-submodule conductors are cut with the aid of a long-handled tool and spliced.

Inter-cell connectors are straps made of stainless steel-clad copper with sufficient flexibility so as not to exert an excessive mechanical load on cell feedthrough. These straps are to be integral with the feedthrough conductor and brazed into a socket-type receptacle or the cell case during assembly of the submodule. These connectors and the other bus conductors of the system are sized for a 3% energy dissipation; this can be reduced with minimal impact on costs, if it should prove necessary.

A submodule weighs about 2090 kg (4600 lb) and stands about 2.5-m high. It is lowered into the module housing by a portable crane, discussed later. At the top of each submodule structure, a pair of plates maintains a constraining force on each stack of cells; this is provided to prevent electrode swelling. A pressure of up to 200 kPa (30 psi) is exerted on the cell stacks by these devices. Each submodule also includes a voltage monitor tap at the interstack conductor at the bottom of the submodule. A small conductor is run up the submodule to penetrate the thermal insulation at the top along with the current-carrying conductors. Thus, each submodule has only three conductors.

B. Battery Electrical Organization

In a single submodule, 100 individual cells are connected in series. As shown in Fig. 5, a module consists of six cell strings connected in parallel, a string being composed of 18 submodules. As shown in Fig. 6, four modules are connected in parallel to a common bus connected to the dc terminals of the power converter. With the string of 18 submodules of 100 cells each, all connected in series, the dc system voltage is 1800 V at EOD and 2880 V at EOC. For overcurrent protection of the dc system, high-speed, current-limiting fuses are used in each string, each module, and the four-module circuit to the converter. Manually operated switches are provided for each of these circuits.

For ground-fault detection, the four-module circuit is grounded through a high resistance with a fuse in parallel with the resistor.* In case of a ground fault, the fuse will provide a low-resistance current path until the ground current increases to the fuse capacity. After the fuse has been interrupted, the magnitude of the ground current will be limited by the grounding

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*This system was recommended by Vivirito and Kornbrust in the United Technologies Corp. report, Ref. 2.

	QUANTITY	CAPACITY
CELLS/SUBMODULE	100	120 kWh
SUBMODULE/STRINGS	18	2160 kWh
STRINGS/MODULE	6	12960 kWh
SUBMODULE/MODULE	108	12960 kWh

Fig. 5. Module Electrical Arrangement of SCS Concept

IN CASE OF GROUND FAULT,
THE FUSE, IN PARALLEL WITH
RESISTOR, BLOWS AND CURRENT
FLOWS THROUGH HIGH OHMIC
VALUE RESISTOR AND IS DETECTED
BY TRANSUCER AND GROUND
INDICATOR

Fig. 6. Electrical Schematic of SCS Battery System

resistor to about one ampere to prevent damage to the battery system, and to provide a positive ground-fault indication and alarm. Identifying the faulty module would then be possible by opening the module switches, one by one, until the ground indication ceases.

C. Battery Module and Housing Structure

The SCS module is defined by the electrical circuit arrangement and thermal management scheme. In contrast to the other three concepts considered, each housing of the SCS concept contains two modules, not one. Eight

modules in four buildings comprise the 100 MW-h plant. The module contains six strings of 1800 cells, for a total of 10,800 cells and an energy capacity of 13 MW-h. The building dimensions are 17 m (56 ft) by 6 m (20 ft) by 5.5 m (18 ft) and contain a total capacity of 25 MW-h. Each module is electrically integrated as shown in Fig. 5 and has a fused disconnect switch and bus conductor to the converter. Each module also has thermal management consisting of a single blower, tubing, and temperature control system. In their present form, the SCS buildings do not provide inter-module thermal isolation of the two enclosed modules, but an insulated partition or curtain could be included with a minimal dimensional change and a negligible cost increment. Such a partition is presently believed to be necessary. An overall view of the module building is drawn in Fig. 7.

For the SCS module, the problems of thermal expansion and heat leakage through structural members were addressed carefully. The major structural components in the high-temperature region of the module are the beams upon which the submodules rest, nine submodules per beam. These beams have a cross section of 38 x 20 x 0.64 cm, and are 7.3-m long. Each of these beams is supported from beneath by three stainless-steel stanchions. The center stanchion rigidly supports and attaches the beam midpoint to the substructure, which is at low temperature and beneath a layer of thermal insulation interposed between the box beams and the substructure. The two stanchions which support the ends of the box beams rest upon a sliding pad ("Lubrite") at the substructure. Therefore, the box beams are permitted to undergo the significant thermal expansion associated with a 450°C temperature change, thermal stresses are avoided, and one point of the beam is in a known and fixed location. The stanchions are the only structural pathways for heat leakage through the thermal insulation. The heat leakage by this route has been calculated as about 2 kW per building which is small relative to the approximate total heat loss of about 56 kW per building and the approximate 40-kW heat generation by the equalizing shunts.

Fig. 7. Drawing of Single Building for SCS Concept

The box beams are grouped in pairs and are oriented along the length of the module; each pair spans the length of the module. There are six such pairs that form six longitudinal rows of supports for the six rows of submodules.

The ambient-temperature substructure which supports the vertical stanchions is, in turn, supported by concrete piers. The steel substructure is factory fabricated and shipped to the site in sections. The earth beneath the module is excavated to a depth of 0.9 m (3 ft), a length of 17 m (56 ft), and a width of 7.2 m (24 ft), and the concrete piers extend to grade level. Insulated air ducts of the thermal management system run longitudinally through the excavated space. Ambient-temperature steel columns for roof support are braced by the concrete piers and integral with the steel substructure. These columns also provide the means for mounting corrugated steel wall sheeting, to which is attached one foot of high-temperature fibrous insulation.

The sectionalized sheet-metal roof and ambient-temperature superstructure serve to suspend rectangular panels of thermal insulation above each submodule, thereby forming a suspended ceiling of insulation. The insulation panels are individually removable from above, after the corresponding roof section has been lifted off. Once this operation is completed, a submodule can be removed. A portion of the module housing and structure is shown in Fig. 8.

D. Thermal Management

Cell-temperature control is accomplished by an array of radiator tubes through which air is forced at the desired temperature. The radiative heat exchange between the cells and the tubes causes any given cell to be heated or cooled, depending on whether that cell is colder or hotter than the radiator tubes within its vicinity. The radiator tubes have a 2.2-cm OD, are formed as hairpin coils, and are mounted vertically with the return-bends of the hairpins at the top and with the plane of the hairpin parallel to the exposed surfaces of the cells. There are two hairpin coils per submodule; thus, every stack of cells is exposed to one hairpin on each side of the box beam that supports the submodule. The hairpin-tube arrangement is shown in Fig. 9. Ceramic stand-off blocks at occasional stations would prevent electrical contact with the cells. Also, the return-bends of the hairpin tubes would be anchored to the superstructure of the building.

Air is supplied to and returned from each hairpin coil via an array of distribution manifolds, which are served, in turn, by a pair of 60-cm-dia ducts (supply and return) that run the length of the module and can be seen at the bottom of Fig. 8. The air is recirculated except for a fraction of the flow which may be exchanged with ambient air in order to provide cooling. The temperature of the air flowing to the supply duct and hence to the hairpins would be controlled between 350 and 450°C, depending on the activity of the battery (i.e., charge, standby, or discharge). The thermal management system for each module has its own blower (2800 cfm at 5-1/2 in. H₂O pressure) and electric heater (50 kW). The blower motor is 5 hp. The electric heater is required for the initial heat up and to sustain the battery temperature during prolonged periods of standby (longer than a weekend). Air temperature is controlled

Fig. 8. Schematic of SCS Module Housing and Structure

through activating the heater or the ambient-air dampers in response to the return-air temperature.

Radiant heat exchange between a cell stack and a hairpin coil can be quite effective in producing a uniform temperature of cells in a stack (in this case, 50 cells constitute a stack). By selecting the appropriate supply air temperature, the designer can achieve a cell temperature variation of only a few degrees within the stack, according to a computer study performed as part of this work. In cooling the stack of cells at steady state, the cooler leg of the hairpin receives more radiation than the warmer leg, of course. As one traverses upward toward the return bend, the temperature of the cooler leg increases, while the temperature of the warmer leg decreases; consequently, there is a rather wide range of conditions for which the net cooling effect is nearly constant. In the analysis of the SCS thermal management system, the heat transfer parameters given in Table 6 were assumed or derived.

Fig. 9. Hairpin Tube Arrangement for SCS Thermal Management

Table 6. Heat Transfer Parameters

Hairpin Configuration, cm	
Tube Outside Diameter	2.2
Tube Wall	0.03
Tube spacing (center to center)	17
Emissivity (all surfaces)	0.6
Air Flow	
Velocity, cm/s	1900
Pressure Drop(in hairpin), in. H ₂ O	4.8

Assuming a steady-state heat generation rate of 1 kW per stack (which would correspond to a time midway through a 5-h discharge for 90% efficient cells) and an air supply temperature of 375°C, the cell surface temperatures would vary between 472 and 478°C in the 50-cell stack. This equilibrium calculation was carried out to demonstrate the adequacy of the hairpin coil concept. The removal of only 1 kW of heat per stack would cause the temperature to drift upward about 12°C during discharge; therefore, the stored heat could sustain the battery temperature against the inevitable heat losses of

the module and the cooling of the cells during charge. If the cell efficiency were less than the assumed 90%, the heat generation rate would be greater. In that case, the control system would detect a higher return air temperature than specified, and a lower temperature supply air would be provided. Thermocouples in several branches of the return-air duct system would provide information on the degree of uniformity of temperature.

During periods of standby, air could be circulated at full volumetric rate in the system of hairpin tubes to maintain temperature uniformity among the various cells. The thickness of thermal insulation on the walls, ceiling, and substructure of the building has been selected to limit the rate of cooling of the battery to 3°C per day. This corresponds to a heat flux through the insulation of 0.037 kW/m² (38 Btu/h-ft²) and requires a 30 cm (12 in.) thickness of high-temperature fibrous insulation having a thermal conductivity of 10⁻³ W/cm°C (0.05 Btu/ft-h-°F) at 450°C (such as Owens Corning TIW Fiberglas).

The blower for each module is located in a small shed at one end of the building.

E. Submodule Replacement Procedure

The first step in removing a submodule is to open the module disconnect switch and the appropriate string disconnect switch. A portable crane is used to remove the required section of roof, exposing the thermal insulation along with the associated two bus conductors and one voltage lead. These conductors would be grappled and severed by means of tooling and remote handling devices. These devices have not yet been designed, but they appear within the state of the art and are not expected to have significant cost. For the second step, the insulation panel above the submodule is lifted by the crane, and a metal shroud or caisson is lowered over the submodule. This shroud is open at both ends, and fits the submodule with a clearance of about 1 cm. The lower lip of the shroud is fixed in location on the box beam (which supports the submodule) by lugs on the beams for that purpose. The shroud is clamped down from above to keep it in place when the submodule is lifted out by the crane. The shroud then serves as a barrier to the escape of hot air from the building and as a guide for the insertion of the replacement submodule. For the third step, the replacement submodule is lowered into the shroud and seated on the box beam in the same location as its predecessor. In the fourth step, three conductors are attached and suspended above the replacement submodule, the shroud lifted out from around the submodule, and the insulation panel put in place above the submodule after the penetrations of the three conductors have been made. At this point, the module would have regained thermal integrity. The conductors are then spliced by special tooling to restore electrical integrity. In the final step, the roof section is replaced; and, after a thermal equilibration time of perhaps one day, the module is put back into operation.

The submodule replacement operation is conducted with the module and replacement submodule in a fully discharged condition. The replacement submodule is preheated in an insulated cask, from which it is lowered into the module. This is done to minimize the thermal shock on the replacement.

IV. THE LCS CONCEPT

A schematic of the components for the LCS concept of Rockwell's ESG is given in Fig. 10; Figure 11 shows a perspective drawing of the entire battery system. The LCS concept utilizes larger cells (2.5 kW-h) and larger submodules

FIGURE 10. LCS FACILITY PLAN

Fig. 10. Schematic Representation of LCS Concept

(1020 kW-h) than the SCS. The LCS concept was designed to provide for the shipping and handling of a minimum number of components. Toward that goal, the submodule size was selected as the maximum truckable weight (about 40,000 lb). Special consideration was given to submodule handling and replacement techniques and apparatus. A single concrete structure houses the entire 100 MW-h battery system, which includes two converters and transformers. Submodules are moved horizontally on special rollers in and out of compartments at the periphery of the building. The energy footprint is 8 kW-h/ft² for the battery building and associated area for submodule loading; the footprint including ancillary equipment is 6 kW-h/ft².

A. Cell, Stack, and Submodule Designs

The LCS concept is based on 2.5 kW-h (free-standing, single feedthrough) cells of two types: type A has the cell case at negative polarity, as in conventional Li/FeS cells, and type B has a positive polarity case. The LCS cells will consist of 34 electrode pairs having dimensions of 16-cm square and

Fig. 11. Drawing of SCS Concept

being oriented vertically* in a free-standing configuration; this cell design is similar to that tested at ESG Rockwell several years ago. The mean current density is 50 mA/cm^2 , and the specific energy is 67 W-h/kg . The cells will have thick walls (about 5 mm) to withstand the internal pressures without significant deflections and, as a result, will provide a good conduction path to the electrodes having the same polarity. The additional stress produced by the stack weight of 460 kg (1000 lb) is small ($<150 \text{ psi}$) because of these heavy walls. Both types of cells utilize a hermetically sealed feedthrough in the top of the case, above the electrolyte level. The feedthrough is envisioned to be larger in diameter (5 cm) and shorter in length than the feedthroughs now used for EV cells and will mate directly with the case of another cell. This design is necessary because the stiffness of a conventional conductor capable of carrying the cell current at EOD of 500 A could produce severe bending loads on the feedthrough. The cell design also minimizes both power losses and the resultant localized heating of the conductors.

As shown in Fig. 12, twelve of the above LCS cells, separated by alumina spacers, constitute a cell stack, which is interconnected alternately at the top and bottom to adjacent stacks. This arrangement eliminates the need for external cell interconnectors and also eliminates the need for vertical bus runs by routing the current down one stack and up the adjacent stack. Figure 12 also illustrates the type of flexible interstack connections envisioned to eliminate tolerance problems and prevent side loads from being transmitted from stack to stack. The cell interconnections in each stack are made at the

*This is the electrode orientation currently used for Li-Al/FeS electric-vehicle cells.

Fig. 12. LCS Cell Stack

factory by furnace brazing all 12 cells in the stack; braze preforms are used in the joints. A 67% aluminum and 33% copper eutectic alloy, which melts at 540°C and has good electrical conductivity, could be used for this purpose. The remelt temperature of this alloy is expected to be no higher than 600°C , which permits repair of the stack.

The LCS submodule consists of two rows of cell stacks, 17 stacks in a row, and is the field replaceable unit. Figure 13 illustrates the LCS submodule, which has a capacity of 1.02 MW-h. The 408 cells in the submodule

Fig. 13. LCS Submodule

are connected in series, with 5 submodules comprising a cell string. The submodule interconnections are made through MULTI-LAM connectors so that the submodules can be remotely disconnected, removed, and replaced in the plant without the need for cutting and rebrazing of connectors during the replacement operation. The electrical arrangement for the submodule is depicted in Fig. 14. The total ohmic losses for the cell interconnects and bus conductors will be about 1% of the energy delivered each cycle. The low voltage losses in the bus network are helpful in being able to detect and prevent cell overcharge or over-discharge, since this maximizes the change in string current caused by cells reaching the end of their charge or discharge cycle.

Fig. 14. Electrical Interconnections in LCS Submodule

B. Electrical Arrangement

Five submodules in series form a string of 2040 cells, having a voltage of 2040 V at EOD and 3260 V at EOC. As shown in Fig. 15, ten strings are connected in parallel to each of the two converters in the 100 MW-h battery system. Each string is provided with a pair of fuses and disconnect switches for safety purposes. A pair of current-limiting fuses and isolation switches are provided on the output of each converter; thus, no redundant switches are included in the battery design.

Battery electrical distribution losses are estimated to be less than 1 MW-h (1%) for the LCS concept due to the maintenance of short coupling distances throughout the design (partially shown in Fig. 14). All electrical power disconnects will utilize the MULTI-LAM type contact strips, with a mechanical interlock keyed to the bay door so that the submodules are disconnected from the plant circuits automatically by lifting the door.

Temperatures and voltages will be monitored (922 leads total) and thermal controls activated by either a small, special-purpose microprocessor/minicomputer or a site-master controller. Voltage measurements of groups of 48 cells will require only nine instrumentation leads from each submodule, for which a high-temperature connector would be developed.

As shown in Fig. 14, two sets of electrical buses convey the dc power to the converters that are located on one end of the plant.

C. Battery Building

A single concrete building is proposed to house the 100 submodules, which are located in module compartments with five submodules to a compartment. Each compartment houses a full cell string. Figure 16 shows a schematic of the concrete building. The air ducts and plenums of the thermal management system are built into the middle and upper regions of the building.

The battery building is to be constructed of poured footings and pre-cast concrete slabs. All footings and internal walls are to be refractory concrete. A reinforcing bar can be used only in low-temperature regions. Some form of expansion joint will be required in the concrete structure, but the details of this have not yet been examined. The exterior walls and roof will be maintained at low temperatures by means of an interior layer of high-temperature fibrous insulation, 30-cm (12 in.) thick, which limits the rate of heat loss as well as protects the upper structure. In place of thermal insulation, the heat loss through the floor is diminished by a substrate of crushed rock, four-feet deep. A greater depth may be required, subject to further analysis.

D. Thermal Management

Steel panels with a high-temperature coating are used for the thermal control ducts. Two plenums are formed across the top and back of each set of five modules, which are served by the four thermal-control blower units mounted as indicated in Fig. 16.

Fig. 15. Electrical Arrangement of LCS Battery System

Fig. 16. Sectional View of LCS Module

To maintain the cell temperature within 25°C of each other at all times, an air recirculation system with convective cooling of the cells (radiative cooling system used with the SCS concept) was proposed. During discharge cycles only, the system mixes 5% of ambient bleed air with the recirculating air to increase the amount of energy removed from the cells. The energy removed from the cells is transferred to the outside walls, permeates the insulation, and then is released into the environment. For this type of cooling system to be successful, the thermal losses through the exterior walls of the plant must be almost as great as the amount of energy rejected from the cells. Consequently, only a small amount of bleed air is needed to maintain a relatively constant temperature throughout the plant.

The above cooling mode will increase the temperatures of the cells about $2\text{--}3^{\circ}\text{C}$ a day during cycling (normally, the five day week); during the inactive period (the weekend), the temperature will decrease 10 to 15°C due to the thermal losses from the plant. Therefore, for the entire seven-day week no net temperature change will occur.

The cooling air circulates through two main distribution ducts in the center of the plant and is introduced into the bays through the bottom of the submodule. Orifices between each stack of cells (51 per submodule) are used

to maintain equal air flow between each of the cell stacks. These orifices are responsible for approximately one-half of the pressure losses in the recirculation system; and, hence, they regulate the flow effectively. This pressure loss produces a high (about 30 m/s) velocity jet that entrains three times the orifice flow rate of air from the bay as it flows by the cells. This effect gives good convective heat transfer and minimizes the differences in air temperature from the bottom to the top of the stacks. Each bay is equipped with inlet and outlet dampers to isolate the bay if repairs are needed.

The cooling air is circulated using centrifugal fans of approximately 25 hp that service five bays each. Startup heating (and heating during inactive periods) is supplied by electrical heaters located at the fan outlets in a bypass section of the ducting and are, therefore, normally out of the air flow path. These heaters are capable of supplying 75 kW each to balance the thermal losses during periods of inactivity.

Each fan has an ambient-air bleed damper that is normally used only during the discharge cycle of the plant, but can be used continuously if the temperatures within the plant become higher than desired. This provides a safety factor in the cooling system in the event of a short circuit.

As the cells age, the heat rejection rates from each cell will diverge in a more or less random manner. A high emissivity coating is used on the cells to enhance the interchange of energy between stacks; this effect will aid in maintaining a uniform temperature of the cells throughout the plant.

E. Transporter and Submodule Loader Design

An essential element of the LCS design is the transporter unit, which is basically a van trailer suitable for on- and off-road operation with a (stubby) tractor unit and/or yard engine. The trailer is part of the battery facility and is necessary for transfer of a submodule assembly in the hot condition. As presently conceived, the transporter accommodates only one submodule.

Transfer of submodules in the hot condition minimizes battery down-time (maximizes availability). To minimize cost, only one transporter is assigned to each battery facility; and, at this time, no maintenance requirements are projected that require more than one transporter per facility. Additional study and analysis of maintenance requirements are necessary, but beyond the scope of the present conceptual design studies.

A view of the transporter is shown in Fig. 17. The functions implemented by the transporter include van leveling operations, submodule vertical support, submodule alignment operation, submodule controlled heat-up and cool-down, module access panel operation, submodule lift operation, and submodule insertion and removal. The transporter eliminates redundancy for each function. In the transporter, an A-frame type structural support for the submodule is supported on several lead-screw operated dovetail slides. These are used for lateral and angular alignment of the submodule with a slot available for it in the module

Fig. 17. Submodule Transporter

compartment. The structure includes sway-control devices and a thermal-control apparatus. The submodule is preheated in the transporter by an electrical heater blower associated with the transporter and transferred from the transporter vehicle to the module on a set of roller devices, which are retracted from beneath the submodule after transfer.

In order to maintain low cost and minimum footprint, a standard Hi-Boy Trailer unit was selected as the transporter because its short overall length allows the use of minimal ramp area. For transportation purposes, this particular trailer unit may require waivers and/or selected routing since it exceeds maximum truckable height limits (13 ft-6 in.) for the U.S.A. A Lo-Boy Trailer, which is lower but longer than the Hi-Boy, might be preferred, after further study.

The module is wider than the van (8-ft maximum); consequently, an insulated panel is included on the rear of the transporter that can be slid over to either side to cover the remaining aperture during replacement operations.

V. CONCLUDING REMARKS

A. Cost Estimates

Cost estimates of the SCS and LCS concepts were made by the cost estimating department at Rockwell. The cost methodology used was in accordance with a method developed by A. D. Little, Inc.,⁷ as amended by subsequent letters. Materials costs were based on current catalog prices and suppliers' quotations. A production rate of 25 batteries per year was assumed, at 100 MW-h capacity (nominal) per battery. Land acquisition and site specific land preparation costs were excluded. Battery design and development costs were also excluded from the estimates.

The estimates of labor and equipment requirements for manufacturing these batteries are considered to be subject to a very large uncertainty. It was not possible to prepare a manufacturing plan, and the precision of the labor estimate has been placed at no better than plus or minus 50%.

Table 7 shows the estimates of manufacturing parameters used in estimating the costs for the SCS and LSC concepts; these parameters are used for calculating the factory lease costs, equipment depreciation costs, and payroll costs.

Table 7. Manufacturing Parameters Estimated for Battery Pricing

Manufacturing Plant	SCS Concept	LCS Concept
Area (20-ft height), ft ²	215,000	195,000
Equipment Cost, \$	5,300,000	1,850,000
Personnel, ^a number of		
day shift	90 ^b	66
night shift	80 ^b	39

^aIncludes warehouse, production, maintenance, and supervisory personnel.

^bThe ANL authors believe that these estimates overstate the labor required, and that appropriate manufacturing engineering could reduce the production labor drastically.

Table 8 presents a hypothetical income statement for an enterprise which produces 25 batteries annually. Materials costs include an allowance of 10% for losses. Overhead costs are simply 150% of labor, where labor is priced at \$10 per hour. The profit after taxes is 15% of the assets employed. The assets are comprised of the cost of the equipment (see Table 7) plus the

Table 8. Hypothetical Annual Income Statement for a
Manufacturer of 100 MW-h Batteries (25
batteries per year)

	Cost, \$	
	SCS Concept	LCS Concept
Material & Subcontract	32,964,000	30,934,000
Labor	26,966,000 (±13,483,000)	13,807,000 (±6,903,500)
Depreciation	530,000	285,000
Overhead	40,449,000 (±20,224,500)	20,710,500 (±10,355,250)
Manufacturing & Installation Costs	101,984,000 (±33,707,500)	66,711,500 (±17,258,750)
Income Taxes	5,384,280 (±1,516,838)	3,429,520 (±776,644)
Income After Taxes	5,384,280 (±1,516,838)	3,429,520 (±776,644)
Gross Sales	112,752,560 (±36,741,175)	73,570,540 (±18,812,038)

working capital, which is 30% of the annual manufacturing cost. In Table 8, the 50% uncertainty in each labor estimate affects the total manufacturing cost, the required income after taxes, the income tax, and the gross sales. Although both concepts are rated at a few percent above 100 MW-h, when allowance is made for the ohmic losses during discharge, the net output would be very close to 100 MW-h; thus, that capacity was used to calculate the selling price in dollars per kilowatt hour. These values were calculated to be \$45.10 ± 14.70/kW-h for the SCS concept and \$29.43 ± 7.52/kW-h for the LCS concept. The uncertainty in the required labor yields a large uncertainty in the selling price. The price varies by a factor of two for the SCS concept, and by a factor of 1.7 for the LCS concept.

B. Unresolved Problems in SCS and LCS Concepts

The major technical problems remaining to be solved in the two concepts are addressed here. These problems are viewed as measures of the technical risks represented by each concept, and also as possible additional tasks to be undertaken if either concept is pursued further.

1. Cell Reliability

Achievement of a MTBF of about 200 years is viewed as a potentially difficult problem and will require a large program of cell testing and development. Both concepts are subject to this problem. The degree to which each of the cell concepts differs from EV cells must be assessed with respect to MTBF. In both concepts, the hermetic feedthrough is a significant departure from EV technology. In the SCS concept, an electrolyte-starved cell may or may not be beyond the EV cell technology of the mid-1980's, but operability in the horizontal orientation will undoubtedly not be tested in the EV program. In the LCS concept, the compact feedthrough will require a major design and test program for its development.

2. Charge Equalization and Cell Protection

It appears, through the analysis presented in this report, that charge equalization by the fixed-shunt resistor technique should be adequate for both the SCS and LCS concepts. However, this idea requires further study and experimental verification. The use of voltage measurements across 50 cells for discerning the approach to full charge or full discharge of any cell in the group especially requires further analysis and experimentation. If the system had been based on 25 cells in a group, or even 10, the overall cost would not have been significantly affected, but this design decision does require further investigation. The cost of voltage sensors has been assumed as about \$25 per point in the quantities involved, based on published prices of isolation amplifiers. This is equivalent to \$.42/kW-h in the SCS concept, and about half that in the LCS concept. This cost has been questioned as perhaps being low by a factor of about 4, but it will still be a minor cost component if 50 cells can be spanned in one measurement.

3. Submodule Design

In the SCS concept, there appear to be few significant risks in the submodule structure or features. The bottom cell in the stack would be subjected to the weight of 49 cells above it, constituting a pressure of about 118 kPa (1.18 atm or 17 psi) normal to the electrodes. This is about half the pressure that would be applied to the cells by the structure for constraining electrode swelling. The stack would be vulnerable to an electrolyte leak, but almost any arrangement of cells in a vertical array would be subject to that risk.

In the LCS concept, major risks in the submodule design arise from the use of soldered joints between cells. The solder is an uncommon alloy,

and its properties are not thoroughly known. The soldering flux, if any, has not been defined, so the problems associated with it are not known. The premise that the submodule will maintain its integrity while operating close to the melting point of the solder is contrary to standard engineering practice, and requires demonstration.

4. Building Design

In the SCS concept, additional design efforts are required for the roof panel. Aside from the roof, the structural components appear to contain no significant problems.

The LCS concept features a high-temperature concrete building for which some significant questions arise. As of the present, thermal expansion and thermal stresses have not been examined. Heat leakage through the uninsulated floor of the building would appear to be a problem for thermal management; furthermore, it might affect the soil stability beneath the building. The need to limit the downward heat flux did influence the choice of a gravel bed beneath the building floor, but this deserves a more thorough analysis. The differential thermal expansion of the submodules relative to the concrete floor might also cause a problem of the submodules tending to "walk" within the space provided for them, and this might require some device to fix their locations.

5. Submodule Replacement

The SCS concept leaves a number of questions untouched regarding submodule replacement. The tools and devices for cutting and splicing the conductors have not been considered in any detail. The insulated cask to preheat a replacement submodule and to lower it into place in the module has not been designed. In general, the procedures for replacing a submodule have been only tentatively considered.

Submodule replacement in the LCS concept has received a relatively great amount of attention, and the procedures are defined fairly well. However, the MULTI-LAM connectors that would be used for bus conductors and instrument leads are untested under the conditions to which they would be subjected. The proposed roller devices beneath a submodule leave questions about their functioning on concrete at 450°C. The problem of aligning the 40,000-lb submodule within the intended space in its module also needs further attention.

6. Summary and Conclusions

A summary of the estimated hardware cost (i.e., exclusive of cells and converters) and technical risk of the four conceptual designs of load-leveling batteries is given in Table 9.

The battery costs can be assessed in terms of the fixed charges they represent, with the aid of Fig. 1 and with the assumption of cell costs. The cost per kilowatt-hour for a load-leveling cell has been estimated by

Table 9. Estimated Battery-Hardware Selling Price

Concept (cell capacity)	Selling Price, ^a \$/kW-h (1979\$)	Technical Risk ^c	
		Cell	Hardware
1978 RD (2.5 kW-h)	60 to 88 ^b	Substantial risk due to 4 cells in parallel	Low Risk
SCS (1.2 kW-h)	30 to 60	Moderate risk beyond EV cell	Risk in sub-module replacement procedures
LCS (2.5 kW-h)	22 to 37	Moderate risk beyond EV cell	Risk in concrete/steel interfaces and in submodule structural integrity in handling
LFSC (30 kW-h)	22 to 25	Very high risk	Low Risk

^aDoes not include cost of cells or converters.

^bEstimates originally made in 1978 dollars, and increased 10% for inflation.

^cThe term "risk" is used to convey the degree to which an item is not defined, is not represented by existing hardware, or contains problems for which a definite solution is not presently visible. This factor involves a personal judgement by the ANL authors.

A. A. Chilenskas *et al.*⁸ to be between \$24 and \$41/kW-h. Table 10 shows the fixed costs of the four concepts for several cell costs. These fixed costs vary from 50 to 90 mills/kW-h for the SCS concept and from 40 to 70 mills/kW-h for the LCS concept. Whether such fixed costs will be acceptable to utilities will depend on the nature of the daily load variations and the costs of alternatives. It is important to note that the total fixed costs are somewhat more sensitive to the cost of the cells than to the cost of the battery hardware. Therefore, any future efforts to refine the cost estimates should address the interaction between the battery concept and the cell cost.

The ESG at Rockwell prepared an environmental impact statement for load-leveling batteries. This work, summarized in Appendix D, indicated that the production of 45,000 MW-h of Li/FeS load-leveling batteries by 2000 would require 22.5×10^6 kg of lithium, which is a relatively small quantity. The operation of this quantity of load-leveling batteries would have no significant effect on the pollution level in the environment.

Table 10. Fixed Costs of the Four Conceptual Designs

Concept ^a	Hardware Cost, \$/kW-h	Fixed Cost at Indicated Cell Cost, mills/kW-h		
		\$24/kW-h	\$32/kW-h	\$40/kW-h
1978 RD	60-88	75 to 99	83 to 107	92 to 115
SCS	30-60	50 to 75	58 to 83	66 to 92
LCS	22-37	43 to 56	51 to 64	59 to 72
LFSC	22-25	43 to 46	51 to 54	59 to 62

^aAssumptions made: 10-yr cell life, 20-yr hardware life, 250 cycle per year, and 2% capacity attrition per year.

^bFixed charge rates as given in the Electric Power Research Institute report EPRI-PS-866-SR (June 1978).

APPENDIX A

DEVELOPMENT OF SPECIFICATIONS FOR A LOAD-LEVELING CELL

The first assumption made was that the positive-electrode reactant for a load-leveling cell will be FeS rather than FeS₂. This choice was made because our present understanding of the electrode stability and corrosion processes in a cell suggests that an FeS cell will have a greater likelihood of a long life than an FeS₂ cell. To determine the best design for a load-leveling cell, we fixed several features of the cell design by cautious extrapolation from the available experience with laboratory and electric-vehicle prototype cells. The following two assumptions on cell lifetime were implicit in this extrapolation:

1. We assume that cell life is inversely related to current density; and, therefore, a low current density is desired.
2. We assume that cell life and reliability are inversely related to the number of electrode pairs within a single case, and possibly to the size of those electrodes. Therefore, we were reluctant to hypothesize a cell size any larger than economic factors demand.

The above assumptions are somewhat arbitrary, since there are no data available on the performance of high energy-capacity cells, nor on the relationship (if any) between cell size and cell lifetime. Cell lifetimes of at least 10 years in service (250 cycles/yr) are required for plant economy.

1. Cell-Energy Capacity

After considerable deliberation, we selected a nominal cell size of 2.5 kW-h for the load-leveling application. This size was arrived at after considering the effects of cell size on the associated costs of battery hardware. An analysis of battery-hardware costs by Rockwell has shown that, for cells with vertically oriented electrodes,* if the cell size is less than 2.5 kW-h, the costs of making the very numerous intercell connections become prohibitive. The selection of the 2.5 kW-h size represents about a factor of five increase beyond present electric-vehicle developmental cells, and such cells appear to be technically achievable by the mid-1980's. Rockwell International's Energy Systems Group built one 2.5 kW-h Li-Si/FeS cell which failed early in testing. The causes of failure of that one cell are believed to be understood, and appear avoidable in the future. Perhaps future research and development may support the design of a load-leveling plant that utilizes larger cells, but at present the selection of the 2.5 kW-h size appears to be reasonable.

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*This is the electrode orientation currently used for Li-Al/FeS electric-vehicle cells.

2. Cell Constraint

In a load-leveling cell, damage from the swelling of electrodes must be avoided through proper design of the electrodes and cell case. The design of the battery module or submodule structure would be encumbered (perhaps significantly) if the cells had to be externally constrained against the destructive effects of electrode swelling, and it is assumed that no such constraint will be necessary. To date, most of the test data on cell performance have been obtained with the cell-case sides clamped so as to prevent gross swelling of the electrodes during cycling. Estimates of the forces applied by electrode swelling, based on several instances of observed plastic deformations in the constraining members, indicate from 1 to 5 atm.

In cells with LiAl negative electrodes, post-test destructive examinations have indicated that the utilized portion of the negative electrodes tend to a porosity of about 40% (a density of about 60% of theoretical). If the initial density of this electrode is higher, the utilized portion will swell until 60% density is attained. If the initial density is 60% or less, it is expected (although not yet proven) that the negative electrode will not tend to swell. We assume for the present that swelling of the negative electrode can be avoided by providing 40% porosity. The positive electrode will also require a large porosity, as will be discussed. Allowance is being made for a thicker case wall than would be provided for externally constrained cells. We believe that this combination of design restrictions will eliminate the need for external structural constraints on the cells.

3. Cell Case Configuration

The size of the electrodes in the Rockwell 2.5 kW-h cell is nominally 9 by 9 in. An electrode of this size is believed to be appropriate for economical load-leveling cells. Therefore, a case configuration was adopted that would accommodate nominal 9-in. square electrodes and a projected capacity of 2.5 kW-h. The case configuration is illustrated in Fig. A-1. The details of the terminals, and their locations on the cell case, have not yet been decided. The precise location of the terminals will be influenced by the submodule design. At present, we anticipate locating the positive terminal on the top of the cell, near the front face and to one side of the cell vertical mid-plane. The negative terminal location, according to present plans, would be on the bottom of the cell, near the front face and displaced to the other side of the cell mid-plane, with respect to the positive terminal. This arrangement facilitates interconnections of cells in a submodule.

The volume associated with the dimensions in Fig. A-1 is 11.1 liters. The energy density that would result from 2.5 kW-h capacity in that envelope would be 225 W-h/L. The present energy-density goal for the load-leveling cell is conservative with respect to that of electric-vehicle cells being developed (for example, the Mark IA battery developed by Eagle-Picher had a cell energy density of 320 W-h/L). This will permit a lower average current density, which is expected to favor cell longevity.

Fig. A-1. Case Dimensions (outer) for 2.5 kW-h Cell

4. Anticipated Cell Properties

a. Separator Materials

The cost goal for load-leveling cells is less than \$30/kW-h. Present costs of cloth or felt made of boron nitride (BN) are such as to make BN separators (commonly used in electric-vehicle cells) alone more expensive than the goal for total cell cost. Prices of BN felt or cloth separators may decrease markedly in the future, as industry invests in large-scale plants in response to a growing market. An alternative separator material is MgO powder. The material cost of MgO powder is very low. The costs of placing it in the cell, either in the form of pressed plates or directly as powder, are not presently known for a commercial cell-manufacturing operation. It is assumed here that either BN felt or MgO powder separators will become low enough in cost to permit one or the other to be used in economical load-leveling cells.

b. Electrolyte Material

Research at ANL during the past year has indicated that, when the LiCl-KCl electrolyte with an LiCl content above that of the eutectic is used, a high utilization of the positive active material is achieved.⁹ It is assumed henceforth that the load-leveling cell will employ an electrolyte that is rich in LiCl.

c. Electrode Plaques

The LiAl alloy in the negative electrode will contain 48 to 50 at.% lithium. Lower concentrations of lithium would be wasteful of space, and

somewhat higher concentrations would risk the formation of liquid lithium. The theoretical capacity of the lithium in the negative electrode will be at least 20% greater than the theoretical capacity of the sulfur in the positive electrode. The reason for this is to avoid a phase change in the LiAl alloy (to the α phase) at about 10 at. % lithium. This might occur as the cell approaches full discharge were it not for a 20% reserve lithium capacity with respect to the sulfur capacity. As mentioned earlier, the porosity of the negative electrode will be set at 40% (60% of theoretical density). The porosity of the FeS in the fully charged positive electrode should be about 65% (35% of theoretical density) to accommodate Li_2S in the discharged state with a density of about 80% of theoretical. This is adopted to minimize the tendency of electrodes to swell.

d. Thickness of Separators

As mentioned earlier, cell life was assumed to be related inversely to current density—the higher the current density, the lower the cell life. We also believe that cell life may be related directly to the thickness of the separator, at least for thin separators. These two relationships, if true, would appear to cause a design conflict because a low current density is achievable only by using a large number of electrode pairs including separators. The effect of separator thickness (in conjunction with electrode number) upon current density and cell resistance is explored in Appendix A.1. It is shown there that current densities in the range of 40 to 60 mA/cm^2 will allow optimal separator thicknesses, 2.5 to 3.0 mm; the corresponding number of electrode pairs for these conditions are between 14 and 20.

5. Projected Cell Characteristics

The design of the electrical and thermal aspects of a load-leveling plant requires that certain cell performance characteristics be projected. This projection was made by scaling some of the test results from a multiplate cell intended for electric vehicle service* to that of a load-leveling cell. This projection is recognized as being only approximate, and it is anticipated that, as more test data become available and as analytical models are improved, the projections will also become more reliable. Figures A-2, -3, and -4 show the projected terminal voltage, current, and heat generation, respectively, for a 2.5 kW-h cell during a 5-h discharge at a constant power of 500 W and a 7-h bulk charge at constant current. A detailed description on how these figures were generated is given in Appendix A.2.

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*This is the Mark 1A cell described in Ref. 10.

CALCULATED VOLTAGE HISTORY AT 500 WATTS

Fig. A-2. Calculated Voltage of Load-Leveling Cell

CURRENT DURING 500 WATT DISCHARGE

Fig. A-3. Calculated Current of Load-Leveling Cell

Fig. A-4. Calculated Heat Generation of Load-Leveling Cell

APPENDIX A.1

SEPARATOR THICKNESS FOR 2.5 kW-h LOAD-LEVELING CELL

For these calculations, a constant-power discharge was assumed, although this is not essential. The cell energy capacity can be expressed as:

$$E = NAviT \quad (1)$$

where E = cell energy capacity, W-h

N = number of electrode pairs

A = area of one electrode pair, cm^2

V = mean voltage at the terminals during discharge, V

i = mean current density during discharge, A/cm^2

T = duration of discharge, h.

The thickness available for a single electrode-pair is given by

$$t_t = \frac{W}{N} \quad (2)$$

where W is the internal dimension of the cell case normal to the electrodes, and t_t is the total thickness of one electrode pair (cm). The electrode pair is composed of active material, current collector(s), and separator-retainers. Consequently,

$$t_t = t_a + t_c + t_s \quad (3)$$

where t_a = thickness of active material (both positive and negative)

t_c = thickness of current collector(s)

t_s = thickness of separator and particle retainers.

We will derive expressions for t_a and t_c and then solve for t_s .

The required thickness of active material is derived as follows. The theoretical loading (mass of active material), FeS, per square centimeter of electrode surface for the positive electrode is

$$M_p' = \frac{2F}{M_p} \quad (4)$$

where F is Faraday's constant and M_p is the molecular weight of FeS. Since the molecular weight of FeS is 87.9, the value of M_p' is 0.61 A-h/g. An approximate relationship for positive-electrode utilization in an electrolyte saturated with LiCl was derived by H. Shimotake.* This expression is

$$U_p = 1 - 4i \quad (5)$$

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*Chemical Engineering Division, ANL.

Then the actual positive loading is

$$M_p = \frac{iT}{0.61 (1 - 4i)} \quad (6)$$

and the thickness of the positive active material is

$$t_{ap} = \frac{iT}{(0.61) (1 - 4i) \rho_p (1 - \alpha_p)} \quad (7)$$

where ρ_p is the theoretical density, and α_p is the porosity of the positive electrode.

For 50 at. % lithium in the LiAl alloy of the negative electrode, lithium (at 6.94 g) would have associated with it one mole of aluminum (at 26.98 g); consequently, the theoretical loading per coulomb would be 3.5×10^{-4} g/C (the sum of the weights for Li and Al divided by F). The theoretical negative loading would be

$$M'_n = 3.5 \times 10^{-4} (iT) \times 3600 = 1.27 iT \quad (8)$$

The actual required loading to assure a 20% excess of lithium in the LiAl alloy is obtained by dividing M'_n by the utilization factor of the positive material and 1.2. Thus,

$$M_n = \frac{1.27 iT}{(1.2) (1 - 4i)} = \frac{iT}{0.95 (1 - 4i)} \quad (9)$$

and

$$t_{an} = \frac{iT}{(0.95) (1 - 4i) \rho_n (1 - \alpha_n)} \quad (10)$$

The thickness of total active material, t_a , is the sum of t_{ap} and t_{an} . Thus

$$t_a = \frac{iT}{(1 - 4i)} \left[\frac{1}{0.61 \rho_p (1 - \alpha_p)} + \frac{1}{0.95 \rho_n (1 - \alpha_n)} \right] \quad (11)$$

The densities are 4.74 g/cm^3 for FeS and 1.74 g/cm^3 for 50 at.% LiAl; furthermore, as mentioned previously, the porosities should be 0.65 for the positive electrode and 0.40 for the negative electrode. Substituting these values into Eq. (11), we obtain

$$t_a = \frac{2.0 iT}{(1 - 4i)}$$

For a 5-h discharge time,

$$t_a = \frac{10 \cdot i}{(1 - 4i)} \quad (12)$$

The positive electrode will have an iron current collector, and the aluminum matrix of the negative electrode will serve as the negative current collector. For our calculations of the thickness of the positive current collector, we assumed that the potential difference between the bottom and top of the collector does not exceed 0.01 V. The thickness is determined as follows. If a uniform current density is present at the surface of a current collector and this current is being drawn off at one end only, then the potential difference between ends of the collector can be shown to be:

$$\Delta V = \frac{ri}{2 t_c} H^2 \quad (13)$$

where H is the height, r is the resistivity, and t_c the thickness of the current collector. If $\Delta V = 0.01$ V, $H = 22$ cm, and $r = 40 \times 10^{-6}$ Ω -cm, then the collector thickness is

$$t_c = 0.97 \cdot i \approx i \quad (14)$$

Combining Eqs. 2, 3, 12, and 15, we obtain

$$t_s = \frac{W}{N} - \frac{10 i}{1 - 4i} - i \quad (15)$$

The mean voltage at the terminals is

$$V = V_{oc} - i R_T \quad (16)$$

where V_{oc} is the open circuit voltage and R_T is the resistance associated with 1 cm² of electrode. Furthermore, R_T can be expressed as

$$R_T = R_O + t_s R_S \quad (17)$$

where R_O is the specific resistance of all except the separator, and R_S is the resistivity of the separator. Substituting Eqs. 16 and 17 into 1, we get

$$E = NAiT \left[V_{oc} - i (R_O + t_s R_S) \right] \quad (18)$$

Equations 15 and 18 are solved together (numerically) to determine t_s and i as a function of N for assigned values of E , W , A , T , V_{oc} , R_O , and R_S . Those values are listed in Table A-1. The separator thickness as a function of current density was calculated for these parameters and for cell energy capacities of 2.00, 2.25, 2.50, and 2.75 kW-h; plots of these data are shown in

Table A-1. Assigned Values for Determining Optimum Separator Thickness

Variables	
Available Space, ^a cm	16.5
Electrode Area, ^b cm ²	480
Discharge Time, h	5
Open-Circuit Voltage, V	1.33
Separator Resistivity, ^c Ω -cm	2.6
Cell Specific Resistance, ^d Ω -cm ²	1.5

^aThe external case dimension normal to electrode surface is 17.1 cm. A wall thickness of 0.32 cm is assumed; this thickness is greater than usual practice so that the case can provide additional restraint.

^bThis is for a square (21.9 cm) electrode.

^cAn electrolyte resistivity of 0.65 Ω -cm and a geometrical factor of four to account for the porosity and tortuosity of the separator are assumed.

^dExperience suggests a value as low as 1.0 Ω -cm² is attainable.

Fig. A-5. It is seen that, as the number of electrode pairs is increased and the current density diminishes, the available space for separators and particle retainers increases to a maximum and then decreases. The increase in thickness at high current densities as the current density is diminished is attributed to increasing utilization of active material and increasing terminal voltage. The eventual decline in available space as the number of electrodes is increased is attributed simply to the subdivision of a virtually constant dimension into an increasing number of separators. Figure A-5 shows that the 2.5 kW-h cell can accommodate a separator and particle retainer thickness of between 2.5 and 3.0 mm per electrode pair, at a current density of 50 ± 10 mA/cm², with the number of electrode pairs in the range from 13 to 20.

Fig. A-5. Available Space for Separator in Load-Leveling Cell

APPENDIX A.2

PROJECTED PERFORMANCE CHARACTERISTICS OF A 2.5 kW-h
LOAD-LEVELING CELL

For purposes of the conceptual design of the electrical and thermal management systems, it is necessary to project the approximate current, voltage, and heat generation of the load-leveling cell during discharge and charge. At the present stage of conceptual design, no great accuracy is required. The known parameters are a cell energy capacity of 2.5 kW-h, a discharge time of 5 h, a charge time of 7 h, discharge at constant power, and charge at constant current.

A phenomenological model was created for calculating the required histories, based on laboratory test data from electric-vehicle cells (no performance data are available for a long-lifetime 2.5 kW-h cell). The model starts with a voltage vs. current curve such as shown in Fig. A-6. The measurements shown in this figure were made in a test of a Mark IA electric-vehicle cell, where the cell was charged and then immediately discharged after the 1.6 V charge cut-off was reached. Similarly, as soon as the 0.9 V discharge cut-off was reached, charging commenced. The data of Fig. A-6 are for a single charge-discharge cycle after a few such cycles had been completed. The voltage curves for this cell would be changed if there had been a waiting period between charge and discharge (as in load-leveling service). The shape of the curves very early in charge or discharge would be especially susceptible to such a modification of the cycle. Therefore, we truncated the charge curve at a voltage somewhat above the theoretical open-circuit voltage (OCV) of 1.33 V, and the discharge curve at a voltage somewhat below the OCV. This can be seen as a short horizontal line at the far left end of each curve in Fig. A-6.

Fig. A-6. Cell Voltage vs. Capacity for EV Cell

The next step in the model was to reduce the curves of Fig. A-6 to the basis of ampere-hours of discharge or charge per unit electrode area at a constant current density. This generalized pair of curves was then manipulated as follows to obtain the projected characteristics shown in Fig. A-7. The

Fig. A-7. Cell Voltage vs. Current Density for Load-Leveling Cell

curves from Fig. A-6, after having been altered to account for electrode area, were multiplied by a scale factor to account for the ratio of accessible active material in the hypothetical cell to that in the test cell. This factor includes both the effect of changed utilization and changed loading of active material. The magnitude used for this factor was 1.67, indicating that the load-leveling cell will have a higher utilization and/or a heavier loading than the vehicle cell. A change in the cell resistance and polarization characteristic for the load-leveling cell was taken into account by scaling the distance between each test curve and the OCV line in Fig. A-6 by a factor to represent the effect of cell design improvements that would reduce the resistance and polarization. The factor used in the present case was 0.8. This is recognized to be a crude treatment of a complex system. The various curves of constant current density were generated by assuming that, at any given state of charge, the difference between the cell terminal voltage and the OCV would be proportional to the current density. This yielded the projected voltage curves at various discharge-charge currents shown in Fig. A-7.

The discharge power was calculated (2.5 kW-h output in five hours requires 500 W). Previously, the electrode area was determined to be 10^4 cm^2 (480 cm^2 per electrode pair, times about 20 electrode pairs). A computation was then made, utilizing the projected characteristics of Fig. A-7, with a constant

power discharge of about 50 mW/cm². This yielded the computed current-density history shown in Fig. A-8, and the voltage and current histories shown in Figs. A-2 and A-3. Those curves show a few strange bumps which were produced by the truncation of the original test data at the low capacity condition and from random measurement and curve-reading errors.

Fig. A-8. Current Density vs. Discharge Time for Load-Leveling Cells

In addition to voltage and current during charge and discharge, it is necessary to project the heat generated for the load-leveling cell. Heat generation is the result of both irreversible electrical dissipative processes and reversible electrochemical reactions, which occur simultaneously and which are additive in their effect. The reversible reactions liberate heat during discharge and absorb heat during charge, whereas the irreversible processes always liberate heat. The rate of heat generation by irreversible processes (e.g., I^2R losses in conductors and $I\eta$ losses, where η is polarization over potential) is simply $I \times (V - OCV)$, where V is the terminal voltage, and where the sign of the product is taken as positive, whether during charge or discharge. The reversible electrochemical process generates heat at a theoretical rate of 0.112 I watts during discharge and absorbs at the same rate during charge. Therefore, the expression used for heat generation rate was

$$Q = |I\Delta V| \pm 0.112I$$

where ΔV is $V - OCV$, and the positive sign refers to discharge and the negative to charge. The theoretical heat generation for the reversible processes is

considered tentative pending experimental verification. (The above relations were provided by M. M. Farahat* and M. Roche.*) By substituting the data of Figs. A-2 and -3 into this equation, we obtained the heating history during charge and discharge for a 2.5 kW-h cell shown in Fig. A-4.

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APPENDIX B

THE LARGE FREE-STANDING CELL (LFSC)

The LFSC design was an attempt to simplify the battery hardware to an extreme. Chronologically, the LFSC concept preceded the development of the SCS and LCS concepts and the passive-shunt equalization scheme (described in Appendix C). The primary advantage of the LFSC concept was to reduce the number of equalization units to an absolute minimum by employing the largest cell possible (without contradicting system limitations such as voltage requirements, converter capacity, etc.). Also, it was assumed that the failure-rate of the cells would be low enough that it would be permissible to allow time for a module to cool to ambient temperature before replacing a failed cell.

The system and cell requirements which lead to the determination of the largest cell size are as follows:

1. energy storage facility capacity, 100 MW-h for 5-h discharge,
2. nominal size of available ac/dc converters, 10 MW,
3. range of dc voltage permitted for efficient converter operation, 2700 to 1600 V,
4. range of voltage of an individual cell, beginning to end of discharge, 1.6 to 1.0 V.

These requirements lead to the selection of 1680 cells in a series string, one string per converter, two converters per facility. It follows that each cell should have an energy capacity of about 30 kW-h. The dimensions of the cell are limited by the allowable temperature rise of the cell midpoint during discharge and the cost of internal bus conductors and current collectors, in conjunction with permissible voltage drops in those components. These factors have been analyzed, and nominal configuration limitations have been identified for a discharge current density of 50 mA/cm².

If heat is removed from only two opposing faces of the cell normal to the planes of the electrodes, then the maximum permissible value for this dimension is about 26 cm. In order to achieve a large amount of stored energy per unit area of floor, the height of the cell should be as great as practical. If the electrodes are oriented horizontally, a stack height of about two meters could be achieved. The cell would contain 212 electrode pairs grouped to form four "elementary cells," each of 53 electrode pairs. Each elementary cell has its own terminals, located on two of the side walls of the complete cell. Thus, each 30 kW-h cell would have four positive feedthroughs on one side and four negative terminals on the opposite side (the cell case is electrically negative). The positive feedthrough conductors of one 30 kW-h cell are welded (at the battery site) to the negative terminals of the adjacent cell. This concept of free-standing cells assumes the feasibility of horizontally oriented electrodes and feedthroughs submerged in molten salt electrolyte.

For a permissible voltage drop of about 20 mV in the internal conductors, the maximum value for the length and width, considering cell economics, is on the order of 40 cm. These dimensions suggest a limit of about 8 kW-h for an elementary cell. However, a larger cell can be attained by inserting into a single container several 8 kW-h assemblages of electrodes and their associated conductors (*i.e.*, several elementary cells), with each assemblage having its own external terminals. In this arrangement, the several elementary cells within the same container are connected in parallel (to avoid large potential differences within the cell). In this fashion, large cell sizes can be attained; and the 30 kW-h capacity found to be desirable for this concept can be achieved by combining four elementary cells in a single can.

Figure B-1 summarizes the major features of the LFSC cell. The rod rising from the rear face of the cell is an extension of the negative terminal. This extension or mast penetrates the thermal insulation and is the terminal for the equalizer conductors. This arrangement permits the equalizer conductors to be at ambient temperature. Since the cross section of this mast can be large, it can be made of steel. Figure B-2 illustrates the electrode dimensions.

Fig. B-1. Design of LFSC

Fig. B-2. Electrode Dimensions of LFSC

The 1680 cells comprising a 50 MW-h string are grouped in 10 separately housed modules of 168 cells each. Figure B-3 shows the arrangement of cells in a module; Figure B-4 shows a view of six such cells within a module. The size of the module is determined mainly by transportation limits and the requirement for access to all cells. The transportation limit refers to the maximum dimensions allowable for truck transport of prefabricated structures from factory to battery site. The access limit results from the requirement

Fig. B-3. Module of LFSC Concept

Fig. B-4. Six Cells within a LFSC Module

that, to replace any cell, it will be necessary to cut and re-weld the electrical connections with adjacent cells; this operation is expected to require access from the side as well as the top of a module. This limits the maximum transverse dimension of the module. Our present estimate is that 2.1 m (7 ft) interior width of the module is satisfactory in both respects, as is 2.4 m (8 ft) interior height. The length of the module can be selected somewhat more freely. The longer the module, the more field labor will be required in assembling prefabricated structures and the greater the loss of electrical capacity when a module has to be cooled for repair. Obviously, shorter modules will entail more modules, excess inter-module bus work, and more heat loss through end walls. The LFSC concept employs a module length of 12 m (40 ft), a height of 2.4 m (8 ft), and a width of 2.7 m (9 ft), which would be transportable by truck. This structure would have 30 cm (1 ft) of thermal insulation installed internally on its sides, ends, and bottom. A separate removable roof would be placed on top. The structure would be placed on concrete footings, which would be protected against exposure to high temperatures by a structural design which incorporates a load-bearing thermal barrier between the high-temperature space and the footing. Figure B-5 shows a vertical section of the structure that would support the cells.

By using 30 cm of high-temperature glass wool insulation, the heat loss of the module would be limited to about 20 kW, which is about 40% of the average net heat generated in the module on a daily charge-discharge cycle. The remaining 60% of the generated heat could be disposed of by a cooling system in which the coolant (air at about 400°C) is circulated through cooling coils arrayed between cells. Radiative heat transfer is the principal mode of heat transfer from cells to coils. The coils and the circulating air within them also serve to redistribute heat among the various cells of the module. There is no contact between the tubing and the cell.

Fig. B-5. Structure to Support Cells in LFSC Concept

All cells within a module are series connected. Ten modules are also series connected to form a 50 MW-h bank, which is served by one ac-dc converter. Each cell must be connected to a charge-equalization electronic module, which is located outside of the module since it cannot tolerate temperatures of 450 to 500°C. The voltage drop in the equalizing conductors is an important consideration, and a significant advantage of the postulated module design is that it permits these conductors to operate at ambient temperature where their resistance is relatively low. Equalizer conductors would be #6 AWG. The charge equalization system has been designed for an equalizing current of 30 A. The coulombic efficiency difference between the best and worst cells among the 168 cells in a module would be about 0.4% (on an 11-h laboratory charge-discharge cycle) after about 10 years of load-leveling service. This is equivalent to a coulombic efficiency range of about 4% in the smaller electric-vehicle cells now being developed.

Figure B-6 shows a schematic of a 100 MW-h battery employing the LFSC concept. The energy footprint, including all ancillary equipment and converters, is 6.9 kW-h/ft². Table B-1 shows the estimated hardware costs (to the utility) of the LFSC concept in 1978 dollars. These battery hardware costs were estimated by the ANL staff,* using the 1978 RD costs as reference. It is difficult to see how the battery costs could be reduced much below the LFSC cost of \$23/kW-h. However, in this concept, a great many functions and problems are transferred to the cell; and it is doubtful that a satisfactory cell can be developed for the LFSC concept without a major program beyond the development program for electric-vehicle cells.

Fig. B-6. Schematic of LFSC Concept

*The other three concepts discussed in this report were priced by Rockwell International. The pricing of the LFSC concept is not considered as accurate as that of the other three.

Table B-1. Cost Estimate for LFSC Concept

Component	Cost, ^a \$/kW-h
Module Structure	5
Equalizing System	3
Thermal Management	2
Cell Installation	3
Other Field Labor	3
Auxiliary Power & Misc.	1
Site Controller & Instr.	2
Thermal Insulation	1
Circuit Protection	2
Handling Equip. & Misc.	<u>1</u>
Total	23

^aCosts given in 1978 dollars.

APPENDIX C

CHARGE EQUALIZATION AND CELL PROTECTION

1. Charge Equalization Compensates for Variations in Self-Discharge Rates Only

Although cell-to-cell variations may occur in the form of variations in accessible active material and polarization overpotentials as well as self-discharge rates, only the latter requires the occasional equalization of charge. The other variations (active material and polarization) necessitate the reduction in capacity of the battery to that of the weakest cell, and are not correctable by the equalization of charge.

Consider cells in a series string in which all cells are identical except one. The dissimilar cell has less active material available, so that its capacity is some fraction (F) of the other cells in the string. A zero self-discharge rate is assumed for all of the cells. A discharge period is begun with all cells fully charged. After discharging to FQ (where Q is the capacity of the normal cells), the weakest cell would be completely discharged. If it is desired to avoid overdischarging that cell, the discharge process would have to be terminated. In the charge period that follows, the charging to FQ restores all cells to the fully charged condition. In practice, the fully charged condition might have to be approached slowly in order to avoid overcharging, but all cells would reach the fully charged state simultaneously. There would be no need for a charge equalization process.

Next consider a similar string of cells with zero self-discharge rate, but with the dissimilar cell having a higher polarization overpotential than the others. All of the cells have the same quantity of accessible active material. The greater polarization of the one cell has the effect of lowering the terminal voltage of the string, and perhaps reducing the useful output of the battery. However, no differences will arise in the amount of charge required by each cell. Again, there would be no need for charge equalization.

Now consider the cells in the series string to be identical in every respect except that of self-discharge rate. In this case, all of the cells except one would have the same self-discharge current, I_s , and the dissimilar cell would have a self-discharge current of $I_s + \Delta I_s$. Over a cycle time of T (hours) during which a charge Q is removed and a charge $Q + TI_s$ is replaced in the battery, the dissimilar cell would lose an increment of charge equal to $\Delta I_s T$ relative to the other cells. After n cycles, the dissimilar cell would be deficient in capacity by $n\Delta I_s T$. Eventually the cell would become completely discharged. If a charge equalization process is applied before the weak cell is completely discharged and is repeated periodically, the difference in self-discharge rate is corrected for, and the cycling may be continued indefinitely.

Of all the possible differences in properties from one cell to another, only the difference in self-discharge rate is amenable to correction by charge equalization. Furthermore, only periodic charge equalization is capable of correcting for differences in self-discharge rate, at least with current knowledge and technology.

2. The Influence of the Charge-Discharge Cycle on Coulombic and Energy Efficiency

Consider a cell with a self-discharge current of I_s operating on a cycle in which Q_1 of charge is delivered every T_1 (includes the charging and waiting times). The same cell operating on a cycle comprised of Q_2 and T_2 would exhibit a different coulombic efficiency. The relationship between η_{c1} and η_{c2} (the coulombic efficiencies in the two cases) is shown below:

$$\eta_{c1} = \frac{1}{1 + \frac{T_1 I_s}{Q_1}} \quad (1)$$

$$\eta_{c2} = \frac{1}{1 + \frac{T_2 I_s}{Q_2}} \quad (2)$$

The calculation can be generalized by observing that I_s/Q_1 and I_s/Q_2 are equal to t_1^{-1} and t_2^{-1} , respectively, representing time constants for complete self-discharge from a hypothetical state of charge Q_1 (or Q_2). Then Eqs. 1 and 2 become

$$\eta_{c1} = \frac{1}{1 + T_1/t_1} \quad (3)$$

$$\eta_{c2} = \frac{1}{1 + T_2/t_2} \quad (4)$$

and

$$\frac{\eta_{c1}}{\eta_{c2}} = \frac{1 + T_2/t_2}{1 + T_1/t_1} = \left(\frac{t_1}{t_2}\right) \left(\frac{t_2 + T_2}{t_1 + T_1}\right) \quad (5)$$

For a cell that is tested in the laboratory on an 11-h cycle (T_1) with 100 A-h capacity per cycle (Q_1) and coulombic efficiency of 0.90 (η_c), $I_s = 1.0101$ A and $t_1 = 99.00$ h. Now consider the same cell operated for five load-leveling cycles ($T_2 = 168$ h). If the self-discharge current and the capacity are the same as above, then the new coulombic efficiency is obtained from Eq. 5 as follows:

$$\frac{\eta_{c2}}{\eta_{c1}} = \frac{t_2}{t_1} \left(\frac{t_1 + T_1}{t_2 + T_2} \right)$$

$$Q_2 = 5 Q_1$$

$$t_2 = 5 t_1 = 495 \text{ h}$$

$$\frac{\eta_{c2}}{\eta_{c1}} = (5) \frac{99 + 11}{495 + 168} = 0.83$$

$$\eta_{c2} = 0.747$$

Calculations of η_{c2} versus η_{c1} are plotted in Fig. C-1.

LABORATORY CYCLE: 11 HOURS, 1 CHARGE-DISCHARGE

LOAD-LEVELING CYCLE: 168 HOURS, 5 CHARGE-DISCHARGE

Fig. C-1. Coulombic Efficiency of Five Load-Leveling Cycles versus One Laboratory Cycle

For a cell, $\Delta V = \bar{V}_c - \bar{V}_d$ where $\bar{V}_c$ and $\bar{V}_d$ are the average terminal voltage during charge and discharge, respectively. For a given cycle in which Q is delivered to the load and Q/η_c is returned to the cell, the energy efficiency, η_E , is

$$\eta_E = \frac{Q \bar{V}_d}{Q \bar{V}_c / \eta_c} = \eta_c \frac{\bar{V}_d}{\bar{V}_c} \quad (6)$$

or

$$\eta_E = \eta_c \left(1 - \frac{\Delta V}{\bar{V}_c} \right) \quad (7)$$

For present-generation FeS cells, which are normally charged and discharged at 7- and 5-h rates, respectively, $\Delta V = 0.2$ V and $\bar{V}_c = 1.4$ V. Hence,

$$\eta_E = \eta_c \left(1 - \frac{1}{7} \right) = 0.86 \eta_c \quad (8)$$

Therefore, a high energy efficiency can only be achieved with a high coulombic efficiency.

3. The Required Frequency of Equalization

During an average cycle, the increment of charge-difference between the strongest and weakest cells in a string increases by the average time per cycle multiplied by the difference between the self-discharge current of the weakest (I_{sw}) and strongest cell (I_{ss}). This is the increment by which that series string loses capacity per cycle (assuming that over-charge and over-discharge are avoided for all cells in the string). Then the capacity at the n th cycle can be expressed as:

$$Q(n) = Q_0 - nt(I_{sw} - I_{ss}) \quad (9)$$

where Q_0 is the nominal charge capacity per cycle. If the strongest cell in the string has virtually zero self-discharge current, then

$$Q(n) = Q_0 - nt I_{sw} \quad (10)$$

Since $t_w = Q_0/I_{sw}$, then

$$\frac{Q(n)}{Q_0} = 1 - \frac{nt I_{sw}}{Q_0} = 1 - \frac{nt}{t_w} \quad (11)$$

However,

$$\eta_{cw} = \frac{1}{1 + t/t_w}$$

or

$$\frac{t}{t_w} = \frac{1}{\eta_{cw}} - 1$$

and, therefore,

$$\frac{Q(n)}{Q_0} = 1 - n \left(\frac{1 - \eta_{cw}}{\eta_{cw}} \right) \quad (12)$$

Table C-1 shows the values of $Q(n)/Q_0$ as a function of cycle number for $\eta_{cw} = 0.95$ and $\eta_{cw} = 0.99$. This table shows that, if the criterion for equalizing the various cells in a string was set at 10% capacity loss due to cell mismatch, then equalization would have to be every one or two cycles when $\eta_{cw} = 0.95$, and every ten cycles when $\eta_{cw} = 0.99$.

Table C-1. Capacity Reduction as a Function of Cycle Number

Number of Cycles (n)	$Q(n)/Q_0$	
	$\eta_{cw} = 0.95$	$\eta_{cw} = 0.99$
1	0.948	0.99
2	0.895	0.98
4	0.79	0.96
8	0.58	0.92
10	0.48	0.90

The required coulombic efficiency for the weakest cell in a string to achieve equalization once each week ($n=5$), with $Q(n)/Q_0 = 0.90$, is obtained as follows:

$$0.90 = 1 - 5 \left(\frac{1 - \eta_{cw}}{\eta_{cw}} \right)$$

$$\frac{1 - \eta_{cw}}{\eta_{cw}} = 0.02$$

$$\eta_{cw} = 0.98$$

According to Fig. C-1, a cell having a 98% coulombic efficiency on the weekly load-leveling cycle of 168 h would have a coulombic efficiency of 99.3% on the 11-h laboratory cycle.

The conclusion from these calculations is that a very high coulombic efficiency will be required from even the worst cell in the string, if equalization is to be performed as infrequently as once per week.

4. Two Alternative Methods of Equalization

a. Electronic Electric-Vehicle Equalization

An electronic system for equalizing charge in an electric vehicle (EV) battery has been developed by DeLuca et al.⁵ In this system, each cell in the series string has one equalizing conductor connected to each of its terminals; and these conductors are extended to the ambient-temperature region external to the battery's thermal insulation. Each cell's equalizing conductor is connected to an electronic circuit (one circuit for each cell) which monitors the cell voltage and shunts the charging current around a cell when the terminal voltage of that cell reaches a preset level, such as 1.6 V (full charge). The electronic circuit does this shunting of a fully charged cell without draining charge from the cell. In this manner, all cells in a string can be brought to full charge despite differing charge quantities for the various cells.

The electronic unit associated with each cell is basically a power transistor capable of conducting the charging current (albeit a diminished charging current when equalization is performed). The transistor is activated by a comparator circuit which compares the cell voltage with a reference. Such a system has been built and demonstrated on a small (6-V) electric-vehicle battery. The same concept was adopted for the 1978RD as well as the LFSC load-leveling batteries.

In the case of the 1978RD concept, the effective size of the units in a series string was 10 kW-h (four 2.5 kW-h cells in parallel). For this 100 MW-h battery design, there would be over 10,000 equalizing conductors and 10,000 electronic units. The cost of the equalizing system would be very high,

about \$20/kW-h including the electronic units, power supplies, and equalizer conductors. The latter were particularly costly and introduced troublesome design complications. The major problem arose from the limitation on the voltage drop that can be permitted in the equalizing conductors. The total available voltage per circuit is about 1.6 V (the terminal voltage of a cell at full charge); and the voltage drop through the transistor of the electronic unit will be several tenths of a volt, perhaps 0.6 V. This leaves about 1 V for IR drop in the conductors. Since the lengths of the conductors are considerably greater in the load-leveling battery than in the smaller EV battery, the conductors must have larger cross sections. In the 1978RD concept, high-temperature conductors of AWG No. 6 were required.

The use of smaller units for equalization such as single cells would require more numerous equalizing conductors, etc., albeit of somewhat reduced size. The required equalizing current is believed to vary not proportionately with effective cell size, but more likely as the square root of cell size. Therefore, the use of smaller cells does not greatly reduce the required quantity of equalizer conductor material and, more importantly, increases the number of connections, fittings, and electrical insulation.

The LFSC concept was investigated in an effort to reduce the costs of the equalizing system by the use of fewer but larger cells. The LFSC concept, although questionable with respect to cell reliability, did reduce equalizer costs to about \$3/kW-h. Only part of this drastic reduction in cost is attributable to the fewer number of cells in the LFSC concept; a secondary but important factor was a geometrical configuration which allowed a large reduction in the lengths of conductors within the high-temperature region. The improved configuration is peculiar to the LFSC concept and is not a generally usable approach toward reducing the equalizer costs.

b. Passive Equalization with Fixed Shunts

An alternative method of equalization was devised for the SCS (1.2 kW-h cell) and LCS (2.5 kW-h cell) concepts. In this equalizing system, a great amount of hardware is eliminated at the cost of a modest reduction in capacity and coulombic efficiency for all of the cells. Instead of equalizing at the fully charged point in the cycle, as in the electronic system, the proposed method would equalize at the point of nominal full discharge, equalization consisting of independently discharging each cell from a nominal one volt to essentially zero volts.

Each cell would have a shunt resistor connected across its terminals. It would be desirable to switch these shunts off at all times except when it is necessary to equalize. However, that would introduce an unacceptable level of complexity and cost. Therefore, for this system, the shunts are fixed to each cell and impose a small drain on the system. Some equalization would be provided at the completion of each discharge period, while the battery is on

open-circuit standby before the beginning of charge. Furthermore, every weekend, a period of nearly 48 h would be available for equalization. Occasionally, there might have to be periods of several days during which individual strings would be isolated and equalized.

The size of the shunt resistor was selected to meet the following criteria:

- (1) The shunt resistance, R_e , should be significantly less than the internal leakage resistance of the weakest cell in the series string.
- (2) R_e should be small enough that the strongest cell's residual capacity at the completion of a normal discharge could be drained off by the shunt in several days of standing at open circuit.
- (3) R_e should be large enough that only a loss of several percent coulombic efficiency would occur during a 24-h cycle.

Criterion (1) appears easily satisfied for any R_e that would satisfy (2) and (3). If a loss of coulombic efficiency of 4% is acceptable (and that would appear to be about the maximum justifiable), a lower bound on R_e would be, according to criterion (3),

$$R_e = \frac{24\bar{E}}{0.04Q} = 600\bar{E}/Q \quad (13)$$

where R_e = the shunt resistance, Ω

$\bar{E}$ = the cycle-average terminal voltage, V

Q = the nominal capacity of the cell, A-h

Criterion (2) is somewhat more difficult to quantify within present knowledge of a cell's behavior as complete discharge is approached. First, we assumed that the strongest cell has a residual capacity of 0.1Q at the end of discharge of the weakest cell in the string. If the cell were simply a capacitor of capacitance, C, its voltage history would be, starting from 1.0 V at $t = 0$,

$$V(t) = \exp - \frac{t}{R_e C} \quad (14)$$

where R is in ohms and C is in farads. For this analogy, the time T (seconds) required to reach a terminal voltage of V(T) is

$$T = R_e C \ln\left(\frac{1}{V(T)}\right) \quad (15)$$

If $V(T)$ is arbitrarily set at 0.368 V, representing an essentially fully discharged battery, then,

$$T = R_e C \ln\left(\frac{1}{0.368}\right) = R_e C \quad (16)$$

Assuming that C is sufficient to contain a charge $0.1Q$ at a voltage of 1.0 V, we obtained the following expression for C in coulombs:

$$C = \frac{(0.1) Q (3600)}{V} = 360Q \quad (17)$$

Substituting this into Eq. 16 yields

$$R_e = \frac{T}{360 Q} \quad (18)$$

The equalization time in days (D) is

$$R_e = 240 \frac{D}{Q} \quad (19)$$

Substituting Eq. 13 into 19 yields

$$600 \bar{E}/Q = 240 D/Q \quad (20)$$

or

$$D = 2.5 \bar{E} \quad (21)$$

Since $\bar{E}$ will be about 1.3 V, the equalization time will necessarily be about 3.5 days (subject to the assumptions of capacitor-like behavior and a 4% sacrifice in coulombic efficiency). Therefore, to equalize the cells, a string would only have to be taken out of service for either a Friday or a Monday in addition to the normal weekend shutdown. It also follows from Eq. 19 that

$$R_e = \frac{840}{Q} \quad (22)$$

In the SCS concept, $Q = 960$ A-h; hence, $R_e = 0.88\Omega$.

In the LCS concept, $Q = 2000$ A-h; hence, $R_e = 0.42\Omega$.

The charge losses due to the equalizing shunts also represent electrical energy losses, but serve to heat the battery space. During standby, this heat source is useful in maintaining the temperature of the battery, and it permits the thermal insulation of the housings to be substantially reduced.

If shunt resistors are used in equalization, the daily cycle should be arranged so that charging commences as long after the end of discharge as possible. In that way, partial equalization would be accomplished on each cycle. The quantity of charge (q) that can be drained from a nominally discharged cell in a 6-h period would be, in coulombs,

$$C = \frac{q (3600)}{V} = 3600q$$

From Eq. 16, we see that

$$C = \frac{(6) (3600)}{R_e}$$

and, from Eq. 22, that

$$C = \frac{6 (3600)}{840} Q$$

Solving for q/Q , we obtain $1/140$. Hence, cell-to-cell differences of about 0.7% of the nominal charge of a cell can be equilibrated on a daily basis.

One can ask how great a cell-to-cell difference in coulombic efficiency can be equalized in this daily 6-h period. Using Eq. (12) with $n = 1$ and $Q(n)/Q_0 = \frac{139}{140}$ for the weakest cell (where the strongest cell has $\eta_c = 1$), we obtain

$$\frac{139}{140} = \frac{2\eta_{cw} - 1}{\eta_{cw}}$$

Thus, η_{cw} equals 0.993. As long as the cell-to-cell differences are no greater than 0.7% in coulombic efficiency, the shunts will be able to equalize the cells during a normal daily cycle. Similarly, with a daily 6-h equalization plus a weekend period of 48 h (say, from 9 p.m. Friday to 9 p.m. Sunday), a cell-to-cell difference in coulombic efficiency of up to 1.8% can be tolerated without requiring special periods of equalization. That is, if the weakest cell in a string has a coulombic efficiency as low as 0.982 on the load-leveling cycle (excluding the effect of the shunt) and the the strongest cell has a coulombic efficiency of virtually unity, then the shunts will be capable of maintaining equalization during a normal weekly operating cycle.

Shunts in the range of 0.4 to 0.9 Ω could be made of short lengths of nichrome wire, probably mounted on a ceramic form. Power dissipation of 2 to 5 W would be required and is not expected to be difficult to achieve.

APPENDIX D

ENVIRONMENTAL AND SAFETY ANALYSIS*

This section presents a summary of a 1978 study performed at the Energy Systems Group at Rockwell on the environmental impact of widespread usage of lithium alloy/iron sulfide batteries for stationary energy storage and the safety hazards expected in the construction and operation of these batteries.¹¹ Reference is also made to additional articles and reports issued since the ESG report was completed where these are believed to be pertinent to this subject.

1. Magnitude of Battery Usage

Any effort to determine the environmental impact of the production and operation of lithium alloy/iron sulfide batteries requires, as a first step, an estimation of the production rate and total installed capacity of those batteries over the coming decades. Since the estimate will be affected by the cost of the battery, the cost of fuel for alternative sources of energy (particularly for gas turbine generators), the growth rate of electric power consumption in the U.S., and the market share to be captured by any one battery, wide variations are naturally expected.

A report, commissioned by the Energy Research and Development Administration in 1975, postulated five scenarios for electric energy production for a period up to the end of this century.¹² The one originally selected for the ESG study is shown in Table D-1. The mix of energy sources for 1985 and 2000,

Table D-1.

A Projected National Electrical Energy
Production Scenario

Energy Source	Energy Consumed, 10 ⁶ MW-h		
	1976	1985	2000
Coal	920	976	860
Oil	318	285	184
Gas	246	268	0
Nuclear	173	1284	2553
Hydro	305	336	362
Other	4	68	376
Total	1966	3217	4335

*Prepared by the Energy Systems Group at Rockwell International.

as compared to 1976, assumes a sharply decreasing use of oil and gas, a slowly declining use of coal, and large increases in nuclear and other (solar, wind, and geothermal) energy sources. Equally important, an aggressive energy conservation program was envisioned.

On the above basis, assuming that the power output of the batteries was 3% of the total power output for five hours each day and 260 days per year, the installed battery capacity could range from 15,000 MW-h in 1985 to 75,000 MW-h in the year 2000. A more recent reference establishes the market for load-leveling batteries as a function of battery cost over this time period.¹³ For 1985, the market was found to range from nil to 8,500 MW-h; for 2000, it would range from 5,000 to 225,000 MW-h. This study assumed a fuel-cost escalation of 2.4%/year and a 4% yearly growth in peaking power needs.

At this time, the probability of achieving the 1985 capacity with lithium alloy/iron sulfide batteries appears remote. The first tests of a 5 to 10 MW-h prototype battery at the BEST facility will probably not be underway before that date. Thus, actual production and operation of these batteries will be governed by development progress and the lead time required to establish manufacturing facilities for commercial production. In this context, there is little significance to any estimates for large installed capacities for this battery prior to 1990 or, more likely, 2000. At that time, the question of the division of the market among various advanced batteries may be the more significant factor.

In view of the uncertainties discussed above, there is reason to accept the installed capacity value of 45,000 MW-h and a production rate of 2,500 MW-h/yr projected for 2000 in the ESG report¹¹ as representing a reasonable upper bound. This total capacity will, therefore, be used in estimating the impact of this capacity and production rate on lithium resources, air quality, petroleum consumption, and land use.

2. Effect on Lithium Resources

Although some disagreement exists among authorities, conservative estimates¹⁴ of the North American lithium resources amount to approximately 940×10^6 kg. More optimistic estimates¹⁵ place the U.S. resources alone at $3,500 \times 10^6$ kg. Based on a consumption of 0.5 kg of lithium per kilowatt-hour capacity (in the form of lithium chloride and lithium metal) by lithium alloy/iron sulfide load-leveling batteries, 45,000 MW-h of these batteries would require a total of 22.5×10^6 kg lithium by 2000. A production rate 2,500 MW-h in that year would require a production rate for lithium of 1.25×10^6 kg.

To the above numbers must be added consumption of lithium by conventional uses and, probably, by electric vehicles using similar lithium alloy/iron sulfide batteries. Lithium is the basis of 70 different chemical compounds made today. Among these, lithium carbonate is the most widely used. It is involved

in the production of vitreous enameled steel, photochromic lenses, automobile headlights, television picture tubes, drugs, and aluminum. Lithium hydroxide is second to carbonate in tonnage use. It is used principally in the manufacture of lubricating grease for automobiles, trucks, planes, and ships. Based on the expansion rate of the lithium industry during this past decade, the required production capacity to accommodate the conventional uses of lithium was estimated to range from 53 to 124×10^6 kg by 2000. A more modest estimate of 10×10^6 kg was made by ANL¹⁶ as the yearly production required for these uses. In the ANL report, it was projected that 1.1×10^6 vehicles equipped with 40 kW-h lithium alloy/iron sulfide batteries will be produced in 2000; an incremental production of 22×10^6 kg of lithium would be required for this purpose.

Based on the above numbers, a total annual production of 33 to 147×10^6 kg would be required for lithium in all forms by 2000. Consumption of lithium by load-leveling batteries would be trivial in this context, even with respect to conventional uses.

Using the assumption of an annual production rate of 5×10^6 kg in 1985 as made by ANL and linearizing this production rate up to 2000, we obtained a total consumption for all purposes of 285 to $1,140 \times 10^6$ kg. These numbers correspond to 30 to 120% of the conservative estimate and 8 to 32% of the more optimistic estimate given at the beginning of this section. Again, the consumption of 22.5×10^6 kg of lithium by load-leveling batteries by 2000 is a small fraction of the total. The studies made by ANL concluded that consumption of lithium for all purposes considered above would consume about 15% of U.S. resources. (It should be noted that none of these calculations allow for the possible consumption of lithium for fusion-generated power by the end of the century.)

3. Effects on Air Quality

Any reduction in the amount of CO_2 , CO, NO_x , SO_2 , and particulates added annually to the environment by the use of 45,000 MW-h of load-leveling batteries by 2000 can be expected to be minor. Table D-2 shows the quantities of contaminants released by all sources in the nation and the percent reductions in each contaminant expected from the substitution of 45,000 MW-h battery-plant capacity for a like capacity of oil-fired power plants. It is apparent from the above table that a tenfold increase in the capacity of battery plants would be required for this development to have significance on a national scale. Calculations made for the California South Coast Air Basin suggest, however, that even limited use of battery plants could have greater significance with respect to the air quality in concentrated urban areas.¹¹

For the purposes of the National Environmental Policy Act, it is adequate to note that the operation of the battery plants has no deleterious effect on air quality. Manufacture and/or reclamation of the batteries, however, represents another source of concern. It is difficult to address this matter

TABLE D-2.

**Potential Impact of Li/MS Batteries on National Air Quality
By Year 2000**

Emissions	National Levels	Percent Reduction in Total U.S. Levels with 4,500 MW-h Battery Plants
CO ₂ , 10 ¹¹ kg	59.2	0.05
CO, 10 ⁷ kg	2,486.8	neg.
NO _x , 10 ⁹ kg	9.4	0.06
Particulates, 10 ⁸ kg	113.8	0.01
Hydrocarbons, 10 ⁸ kg	34.8	0.02
SO ₂ , 10 ⁹ kg	11.7	0.12

without a specific manufacturing/reclamation plant layout and detailed procedures for all processing steps. At this stage of battery development, these details are lacking. Information of interest in this connection is given later.

4. Effects on Oil Consumption

Estimated total recoverable oil reserves in the U.S. amount to the equivalent of approximately 586×10^9 MW-h of thermal energy.¹⁷ Forty percent of these reserves are recoverable by currently used commercial methods, the remainder being tied up in oil shale. National oil consumption for 1985 and 2000 is projected at the equivalent of 7.4×10^9 MW-h and 8.1×10^9 MW-h, respectively. National conventional oil reserves could be depleted in as little as three to four decades. Oil recovery from shale is not expected to supply more than 3% of our national oil needs by 1985 and 29% by the year 2000. Therefore, the potential impact of Li/FeS battery power-peaking systems on the national oil reserves and production is important to assess.

A report prepared for DOE¹³ estimates that 1 MW of installed battery capacity saves approximately 1,600 barrels of oil per year. Thus, the installation of 45,000 MW-h of battery capacity by 2000 would eliminate 14×10^6 barrels of imported fuel, if the batteries were discharged at the 5-h rate. Assuming a present cost of \$22/barrel for imported oil and the escalation factor of 2.4%/yr used in the referenced report, the cost of oil would be \$35 a barrel by 2000. Current events suggest that this price may be exceeded in a

year or two. Even this conservative cost for a barrel of oil and the limited battery penetration projected here yields a saving of a half billion dollars a year in imported oil.

5. Effects on Land Use

Due to the compact design of the battery system, footprints on the order of 5 kW-h/ft² can be easily attained. Estimated land requirements associated with the introduction of 45,000 MW-h of batteries by 2000 will be approximately 9×10^6 ft². On a national basis, no significant environmental effect from this land use is expected, since it is likely that the power-peaking batteries could be accommodated on land already held by the utilities.

6. Safety Hazards

Manufacturing, operation, and reclamation of lithium alloy/iron sulfide batteries will require separate analysis, as the hazards expected from those operations differ widely.

a. Battery Manufacture

The manufacture of many components of these batteries will employ operations common to many industries and will present no unusual or severe safety hazards. Some materials used in them do, however, require special handling procedures. The nature of these special procedures will depend on the state of charge in which the battery is assembled. At present it is likely that the active materials will be either partially or fully charged. In the partially charged state, the active material in the positive electrode will consist of iron, lithium sulfide, and iron sulfide (FeS) powders. The active material in the negative electrode will consist of lithium-aluminum alloy and/or, at some future time, lithium-silicon alloy. In the fully charged state, lithium sulfide will not be used in the positive electrode and relatively greater (or more lithium-rich) quantities of lithium alloy will be used in the negative electrode.

Of the materials listed above, lithium sulfide and the lithium alloys present unusual problems from a safety standpoint. Both react with moisture and must be processed, stored, and handled with suitable precautions. Laboratory experience to date has shown that these materials can be safely handled in a "dry" room (<200 ppm of moisture) with normal precautions to avoid ingestion, skin contact, and dust inhalation. Inadvertent contact with water will, however, release H₂S from Li₂S and generate hydrogen violently from the lithium alloys. The highly poisonous nature of H₂S (800 to 1,000 ppm is fatal in 20 minutes) and the explosive properties of hydrogen require that full precautions be taken in the processing, handling, and storage of large quantities of these materials to avoid direct contact with water under all foreseeable conditions.

Even under dry-room conditions, slow evolution of H_2S and H_2 could occur and continuous low-level monitors should be provided for both gases in storage and working areas. It follows also that local fire authorities should be fully informed of the nature of these materials in the event that their services are required.

The electrolyte contains both $LiCl$ and KCl . Lithium salts are known to affect the nervous system, and lithium carbonate is sometimes prescribed as an antidepressant. As the long-term effects of continuous exposure of workers to lithium-containing dusts is, however, unknown, protection is advisable. A value of LD_{50} for lithium carbonate of 650 mg/kg^{18} suggests that the hazard of accidental ingestion of lethal amounts of $LiCl$ is very remote. Potassium chloride is innocuous in any reasonable amount and is used as a salt substitute.

No hazards are known to exist in the handling of BN felt or MgO powder, the most likely cell separator materials. It is likely, however, that beryllium oxide (BeO) will be used in small quantities for the feedthrough. Dusts of this material are toxic. Proper procedures for the fabrication of BeO parts without hazard to workers have been developed.

The metal forming and assembly procedures as well as the handling of hot cells are matters normally coming under OSHA regulations, which must be complied with in all manufacturing plants. A similar statement can be made for all electrical equipment to be installed in the manufacturing plant.

b. Battery Installation and Operation

Since the cells must be hermetically sealed, handling and installation should not involve accidental human contact with the active materials discussed above. Protection from electrical shock would involve no procedure not already common in electric utility plants. Replacement of hot battery modules will necessarily require protection of the workers, but will not differ from similar situations encountered in foundries and metal-treating establishments. The logistics of this operation will require specialized equipment designed to protect the worker under these circumstances.

The only unusual hazards in battery operation foreseeable at this time would be in circumstances where the protective cell case was breached. The more likely failure in this case would involve leakage of electrolyte from a faulty weld in the case. In this event, access of air to the interior of the case would be extremely limited, and heat or fume generation by reaction of air or moisture with the contents would be correspondingly slow. Under all conditions but total charge, electrolyte leaking from the cell would be saturated with Li_2S . As this salt is sparingly soluble in the electrolyte ($<2 \text{ g/L}$ at 450°C) at the cell operating temperature, the quantity of H_2S generated even from a number of leaking cells would release only a trivial amount of this gas into the battery system. This small amount may, however, be detectable by odor (about 10 ppb) well before any conceivable hazard to personnel existed. The more probable case would involve complaints about plant odor.

Another safety hazard might result from the forcible rupture of a cell case, instantly exposing the active materials to the atmosphere. No known circumstance exists which could cause this to occur in the operation of load-leveling batteries. Tests performed with electric-vehicle cells¹⁹ offer assurance of safety even under this extreme circumstance. Two cells, at 460°C, were crushed by a falling weight, rupturing the cases and exposing the cell contents to air. No evidence was detected of an explosion, electric arcing, electrolyte dispersion, fire or fumes. Samples taken for hydrogen and hydrogen sulfide at the test site immediately after the test showed no evidence of these gases, although an odor taken to be H₂S or SO₂ was noticed.

One failure mode for load-leveling batteries could involve a massive short circuit with consequent heating of the cells both by entropic generation of heat and by internal resistance heating. Again, the unexpected short-circuiting of a 20-kW-h battery module at ANL offers assurance on this point. This battery module was completely discharged in a matter of minutes, with cell temperatures exceeding 1000°C. No fire, explosion, or release of fumes accompanied this accident.

The most direct corrective action to any unforeseen circumstance involving potential safety hazards involves cooling of the cells below the freezing point of the electrolyte. This should be accomplished readily by the heat management system. After this action, the active materials would be completely encapsulated within the frozen salt, reducing all possible reaction rates to insignificant levels.

c. Battery Reclamation

It is predictable that reclamation of failed cells will be economically desirable. Some will be factory rejects, others will be those taken from service. Although most will be in the fully discharged state, some may be at least partially charged. Although no procedures have been devised as yet for reclaiming metals and lithium salts from these cells, they will probably be cut up or reduced to fragments in some fashion, after which, at some point, water will be used to extract the lithium salts. While, in principle, completely discharged cells will contain little lithium metal in alloy form, some amount of this element will always be present. The process used will have to be engineered to accommodate the reaction of lithium and lithium sulfide with water to form hydrogen and hydrogen sulfide gases and to protect the workers and the surrounding area from hydrogen sulfide. This operation will present the most serious concern from safety and environmental standpoints.

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