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**A PRELIMINARY ESTIMATE OF THE MANUFACTURING
COST FOR LITHIUM/METAL SULFIDE CELLS FOR
STATIONARY AND MOBILE APPLICATIONS**

by

**A. A. Chilenskas, J. C. Schaefer,
W. L. Towle, and D. L. Barney**

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ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS

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Chemical Engineering Division

January 1980

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**Private Consultant to ANL

TABLE OF CONTENTS

	<u>Page</u>
ABSTRACT	1 1/A6
I. INTRODUCTION.	1 1/A6
II. CONSTRUCTION OF Li-Al/FeS _x CELLS	2 1/A7
III. COST ANALYSIS	4 1/A9
A. Materials Costs	4 1/A9
B. Costs for Plant, Production Equipment and Labor	9 1/A14
C. Cell Manufacturing Cost	10 1/B1
IV. A COMPARISON BETWEEN ANL AND ARTHUR D. LITTLE MANUFACTURING COST METHODOLOGY	14 1/B6
V. LITHIUM RESOURCES AND REQUIREMENTS	15 1/B7
A. Reserves/Resources Lithium	15 1/B7
B. Lithium Requirements	16 1/B8
VI. CONCLUDING REMARKS	17 1/B9

LIST OF FIGURES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	Lithium-Aluminum/Iron Sulfide Cell	3
2.	Cost Estimates for SES and EV Cells.	12

LIST OF TABLES

<u>No.</u>	<u>Title</u>	<u>Page</u>
1.	The Minimum Weights of Reactant Materials for a Li-Al/FeS Cell	4
2.	Weights of Components in Li/FeS _x Cells	5
3.	Electrolyte Requirements for Li/FeS _x Cells	6
4.	Current Collector Weight for Li/FeS _x Cells	6
5.	A Range of Material Costs for Li/FeS _x Cells	7
6.	Most Expensive Materials in a Li/FeS _x Cell	8
7.	Equipment and Labor Costs for SES Cell	9
8.	Scaling Factors for SES and EV Cells	10
9.	Cost Calculation for EV Cell Produced in a 1.15 x 10 ⁶ kW-hr/yr Plant.	11
10.	Cell Manufacturing Cost Summary.	13
11.	The SES Cell Manufacturing Costs According to Two Costing Methodologies	15
12.	Identified World Lithium Resources	16
13.	Projected Lithium Requirements for the U.S.A.	17

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ABSTRACT

A preliminary estimate has been made of the manufacturing cost for lithium/iron sulfide cells for stationary energy-storage and electric-vehicle applications. This preliminary cost analysis indicated that the manufacturing cost (in 1979 dollars) is \$24 to 41/kW-hr for stationary energy-storage cells and \$31 to 55/kW-hr for electric-vehicle cells. The materials cost was found to contribute between 52 and 65% of this manufacturing cost. The most expensive materials and components were lithium (metal and compounds), \$4.61 to \$14.26/kW-hr; BN felt, \$4.00 to 8.50/kW-hr; feed-through components, \$2.40/kW-hr; positive current collectors, \$1.48 to 2.20/kW-hr; and aluminum, \$1.43 to 1.66/kW-hr.

The projected lithium requirements was determined for use in lithium/iron sulfide batteries and conventional uses to the year 2006. The results showed that the lithium requirements were about 275,000 short tons by 2006, which is equivalent to about 51% of presently known U.S. resources. Of this amount, about 33% would be used in battery production and 67% consumed in conventional uses. It is expected that the lithium used in battery production would be recycled.

I. INTRODUCTION

In a previous report (ANL-76-12),¹ we estimated the manufacturing cost* based upon an estimate of the cost for cell materials, plant construction, operating equipment, and labor of a Li/FeS cell for a stationary energy-storage (SES) battery for load-leveling applications. The present study updates this estimate and also provides an estimate of the manufacturing cost for electric-vehicle (EV) Li/FeS_x cells. These costs were projected for a second-generation manufacturing plant with a high production volume (1.15×10^6 kW-hr/yr).

Since the cost study of 1976, we have gained experience in the fabrication and operation of EV cells and, therefore, can be more certain of our estimate of the cell composition. Furthermore, experience with cell fabrication indicates that this system is amenable to mass production. However, because the Li/FeS_x battery is still in the research and development stage, there remains uncertainty in our estimates of the costs for materials and plant equipment. Consequently, the results reported here are preliminary

* All costs in this report are given in 1979 dollars unless otherwise indicated.

and will require refinement at the pilot-manufacturing and full manufacturing stages of Li/FeS_x battery development. Nonetheless, the present estimates, besides giving some indication of the ultimate manufacturing cost for the cell, point out cell components or materials that will be expensive so that future R&D can be concerned with lowering the cost or finding means of eliminating high cost materials or components.

II. CONSTRUCTION OF Li-Al/FeS_x CELLS

The battery cells under development² at Argonne National Laboratory (ANL) have negative electrodes of lithium-aluminum alloy, positive electrodes of metal sulfide, and an electrolyte of molten LiCl-KCl eutectic. Because the melting point of the electrolyte is 352°C, the battery must be operated at temperatures above 400°C. The cells have a prismatic configuration with vertically oriented electrodes (see Fig. 1). The negative and positive electrodes are separated by a porous material, such as boron nitride (BN) felt, which provides electrical insulation between the electrodes and permits the migration of lithium ions through the electrolyte. Two types of iron sulfides--FeS and FeS₂-- are being used as the active material in most positive electrodes. The overall reactions for cells having FeS or FeS₂ in the positive electrode are as follows:

The theoretical specific energies are about 460 W-hr/kg for reaction (1) and 650 W-hr/kg for reaction (2). Voltage vs. capacity curves show a single voltage plateau at 1.33 V (open circuit) for reaction (1) and two plateaus of equal capacity at 1.76 and 1.33 V (open circuit), respectively, for reaction (2).

The lithium/iron sulfide cell can be assembled in a charged or uncharged state. To assemble a Li-Al/FeS or FeS₂ cell in the charged state, the negative electrodes are normally pressed from Li-Al powder (usually 46-50 at. % lithium), which may or may not be mixed with some of the LiCl-KCl electrolyte powder. The positive electrodes are formed similarly by pressing FeS or FeS₂ powder with or without added electrolyte powder. In the case of the uncharged cell, the positive electrode plaque is pressed from a mixture of Li₂S and iron powder in the appropriate proportions; the negative electrode in this case is an aluminum structure which is converted to the Li-Al alloy electrochemically when the cell is charged.

The first developmental (40 kW-hr) Li-Al/FeS battery for EV applications has recently been fabricated by Eagle-Picher Industries under a contract from ANL. The cells built for this battery have a multiplate design (three FeS-15 wt % Cu₂S positive electrodes and four Li-Al negative electrodes), dimensions of approximately 18.7 x 19.7 x 4.1 cm, weight of about 3.8 kg, theoretical capacities of 400 A-hr, and average discharge voltages of approximately 1.2 V at the 4-hr rate.

Fig. 1. Lithium-Aluminum/Iron Sulfide Cell

Very few SES cells have been tested. For the cost study of 1976, the cell design chosen consisted of Li-Al negative electrodes and FeS-23 wt % Cu_2S positive electrodes and had dimensions of 31.1 x 31.5 x 2.5 cm and a weight of about 6.2 kg. The theoretical cell capacity and average cell voltage were 1000 A-hr and 1.15 V, respectively. A further description of this design can be found in ANL-76-12, pp. 7-8.

III. COST ANALYSIS

The cost contributions made to the manufacturing cost by the cell materials, plant and production equipment, and labor are discussed below.

A. Material Costs

The materials costs for the FeS and FeS₂ cells were estimated by determining the weight of the material or materials required for each cell component and then the expected cost for that material in mass production. The minimum weight of reactant materials for a Li-Al/FeS cell assembled in the uncharged and charged states is given in Table 1. These values are theoretical; in a practical cell, additional reactant material is necessary due to incomplete reactions and voltage drops.

Table 1. The Minimum Weights of Reactant Materials for a Li-Al/FeS Cell

Materials	Weight ^a , lb/kW-hr
Uncharged Cell ^b	
Li ₂ S	1.41
Fe	1.71
Al	1.65
Charged Cell ^c	
Li Metal	0.425
FeS	2.69
Al	1.65

^aBased on 100% utilization of reagents at a voltage of 1.33 V.

^bThe reaction is $\text{Li}_2\text{S} + 2\text{Al} + \text{Fe} \rightarrow 2\text{LiAl} + \text{FeS}$.

^cThe reaction is $2\text{LiAl} + \text{FeS} \rightarrow 2\text{Al} + \text{Li}_2\text{S} + \text{Fe}$.

To calculate the material cost for a practical cell, we derived a reference cell design for EV applications based upon recently constructed ANL cells and the multiplate cells fabricated by Eagle-Picher for the Mark IA battery. The reference EV cell consists of three positive electrodes and four negative electrodes and has dimensions of 18.1 x 19.4 x 3.13 cm. The positive electrode has a theoretical capacity of 416 A-hr and contains 50 vol % iron sulfide and 50 vol % LiCl-KCl in dimensions of 17.5 x 17.5 x 0.3 cm. The negative electrode has a theoretical capacity of 458 A-hr and contains 70 vol % Li-Al and 30 vol % electrolyte in dimensions of 17.5 x 17.5 x 0.5 cm. The separator consists of 10 vol % BN felt (0.098-cm thick; 0.16-m² area). The rated capacity for this cell is 333 A-hr at a discharge current density of 50 mA/cm². The design chosen for the SES reference cell was essentially the same as that used for ANL-76-12 except that the separator material was changed from BN felt to MgO powder (0.098-cm thick). The

weights for the materials that would have to be used in the components of the three reference cells are listed in Table 2; both the charged and uncharged

Table 2. Weights of Components in Li/FeS_x Cells

Component	Component Weight, lb/kW-hr						
	SES		EV (FeS)		EV (FeS ₂)		Mark IA
	Unchgd.	Chgd.	Unchgd.	Chgd.	Unchgd.	Chgd.	Chgd.
Electrode							
Lithium	0	0.67	0	0.67	0.06	0.57	0.66
Aluminum	2.52	2.52	2.52	2.52	2.17	2.17	3.10
Li ₂ S	2.22	0	2.22	0	1.69	0	0
Fe	2.20	0	2.20	0	0.94	0	0
FeS	0	3.75	0	3.75	0	0	3.79
FeS ₂	0	0	0	0	0	2.12	0
Electrolyte							
LiCl	2.19	2.19	2.19	2.19	2.08	2.08	2.69
KCl	2.79	2.79	2.79	2.79	1.92	1.92	3.40
Separator							
BN	0	0	0.33 ^a	0.33 ^a	0.33 ^b	0.33 ^b	1.80 ^c
MgO	1.95	1.95	0	0	0	0	0
Neg. Cur. Col.	1.05	1.05	1.05	1.05	1.05	1.05	1.27
Pos. Cur. Col.	1.05	1.05	1.05	1.05	0.33-0.50	0.33-0.50	1.21
Cell Can	3.50	3.50	1.70	1.70	1.70	1.70	2.75
Feedthrough	0	0	0	0	0	0	0
Miscellaneous	2.53	2.53	1.88	1.88	1.47	1.47	1.64
Cell Wt.	22.0	22.0	17.93	17.93	14.08	14.08	22.31
Li Content	1.03	1.03	1.03	1.03	0.91	0.91	1.09

^aUsed 5 ft²/kW-hr (0.066 lb/ft²).

^bUsed 4-5 ft²/kW-hr.

^cBN cloth used as separator: 7.4 ft²/kW-hr at 0.24 lb/ft².

cases have been calculated. In addition, the total cell weight and the lithium content, which is, as shall be shown later, the most expensive cell material, is given for each of the three cell types. As is shown, the lithium content for the EV (FeS₂) cell is lower than that of either the SES cell or the EV (FeS) cell. The LiCl-KCl electrolyte is a significant weight fraction of the cell and varies greatly, depending on the electrode porosity, electrode spacing, separator porosity, and void volume in the cell can. Table 3 lists the amount of electrolyte used per kilowatt-hour for three different ANL cell designs and the Mark IA cell design; also included in this table is the electrolyte weight projected for the EV and SES reference designs. As shown in this table, the salt requirement of the reference design for the EV (FeS) cell and the SES cell, 4.98 lb/kW-hr, is about a 1b/kW-hr less than that of the Mark IA cell.

Table 3. Electrolyte Requirements for Li/FeS_x Cells

Cell Type	Electrolyte Content,
	lb/kW-hr
ANL Type M-MP ^a	9.00
ANL Type PW ^b	6.56
ANL Type K ^c	5.47
Mark IA Cell	6.09
SES Ref.	4.98
EV (FeS) Ref.	4.98
EV (FeS ₂) Ref.	4.00

^aThis is a multiplate cell (three positive and four negative electrodes) with BN felt separators; described further in ANL-79-39, p. 33.

^bThis is a bicell with MgO powder separators; described further in ANL-79-39, p. 32.

^cThis is a bicell with a carbon-bonded positive electrode and BN felt separator; described further in ANL-79-39, p. 32.

The current collector is a significant fraction of the total cell cost, and its weight per kilowatt-hour also varies greatly depending on the cell design. These current-collector weights are listed for three types of ANL cells and the Mark IA cell in Table 4; also included in this table are the

Table 4. Current Collector Weight for Li/FeS_x Cells

Type	Collector Weight, lb/kW-hr	
	Pos.	Neg.
ANL Type PW	2.05	2.05
ANL Type R ^a	1.34	1.60
ANL Type K	2.14	0.86
Mark IA Cell	1.27	1.21
SES Ref.	1.05	1.05
EV (FeS) Ref.	1.05	1.05
EV (FeS ₂) Ref.	0.33-0.50	1.05

^aThis is a bicell assembled uncharged; described further in ANL-78-98, pp. 121-122.

current-collector weights projected for the reference cell designs. Although the weight for the positive current collector of the K-type cells is the highest of the cells listed in Table 4, the weight of its negative current collector is lower than that required for all the reference cells. To date, the only current collector material found to be compatible with the highly

corrosive FeS_2 electrode is molybdenum; it is believed that molybdenum powder formed into an advanced current collector should meet the weight requirement given in Table 4 (0.33 to 0.50 lb/kW-hr). Although molybdenum is an expensive material, its excellent corrosion resistance and high electrical conductivity does, to some extent, compensate for its high cost.

The price of several cell materials produced in low volumes was selected from a list of commodity prices in market publications that had been collected over the past several years. Where a price was obtained earlier than 1979, it was increased by 10% per year to account for inflation. From this list, we selected a high and low estimate for the cell material cost; these values are shown in Table 5. For commercially available commodities in high volume, a single cost was taken from market publications. The costs for BN felt and Li_2S were not available in market literature. Therefore, the cost for BN felt was derived from projections made by Carborundum Corp.* for high-volume production. The cost projections for Li_2S were based upon discussions with knowledgeable individuals in the lithium industry. The low value is the projected cost of Li_2S made from an intermediate product in the production of Li_2CO_3 , and the higher value is for Li_2S produced by the battery manufacturer. The cost of plant equipment and labor for the in-house production of Li_2S would result in increased plant complexity. From the cost data in Table 5, we deduced that LiCl-KCl eutectic (*i.e.*, 44.2 wt % LiCl) would have a cost of \$0.55 to \$0.75/lb and FeS (a mixture of FeS_2 and Fe powder) would have a cost of \$0.10/lb.

From the data in Tables 2 and 5, the cost per kilowatt-hour was determined for the five most expensive cell materials or components. These costs are shown in Table 6. The most expensive material is lithium, the cost of which ranges from \$4.61/kW-hr for an uncharged cell up to \$14.26/kW-hr for a charged cell. Although the weight contribution of the BN felt to the EV cell is negligible, this material is expensive and represents a significant portion of the overall cell cost. Therefore, we estimated the amount of BN felt required in area per kilowatt-hour, and found this value to range from 4 $\text{ft}^2/\text{kW-hr}$ for FeS_2 cells to 5 $\text{ft}^2/\text{kW-hr}$ for FeS cells. Using this data and the BN felt costs given in Table 4, we were able to estimate the cost per kilowatt-hour for BN felt in the EV cell (\$4.00 to 8.50/kW-hr).

B. Costs for Plant, Production Equipment, and Labor

The basic costs for equipment and labor were taken from the earlier cost study (ANL-76-12, pp. 11-12) and then scaled to account for inflation, EV cell size (much smaller than the SES cell), and EV cell plant complexity. A brief summary of the equipment and labor costs (in 1976 dollars) determined for the original plan (1,150 MW-hr/yr) is given in Table 7. It is common industrial practice to use scaling factors to reflect such things as inflation, a change in size, the change in production volume, etc. to provide an updated estimates of costs. Such factors were used to update ANL-76-12. The four scaling factors employed in this report are discussed below.

* Carborundum is fabricating the BN felt presently used in Li/MS cells.

Table 5. A Range of Material Costs for Li/FeS_x Cells

Material	Cost, ^a \$/lb	Source
Li Metal	10.31 (low)	(1975) Foote Mineral Co.
	15.90 (high)	(1979) Chem. Market News.
LiCl	1.20 (low)	Extraction from brines.
	1.65 (high)	(1979) Chem. Market News.
KCl	0.02 (low)	(1979) Chem. Market Reporter.
	0.03 (high)	
Li ₂ S	1.25 (low)	Production from Li ₂ CO ₃ intermediate.
	1.55 (high)	Produced from Li ₂ CO ₃ + H ₂ S.
Li ₂ CO ₃	0.95	(1979) Chem. Market News.
BN Felt	1.00 (low) ^b	Carborundum Corp. estimates.
	1.70 (high) ^b	
MgO	0.25 (low)	Martin-Marietta Corp.
	0.50 (high)	T. Olszanski (ANL).
Aluminum Sheet	0.57	(1979) Minerals & Metals (U.S. Bur. Mines)
FeS ₂ (pyrites, 20 mesh)	0.07	CE Minerals (1975).
Fe Powder	0.175	American Metal Market.
Low-Carbon Steel	0.33	Steel Sales Corp. (1975).
Steel Sheet	0.195	(1979) Min. & Mat'ls, U.S. Bu. of Mines
Mo Powder	4.40	(1979) Chem. Market News.
Fe-5% Mo Sheet	0.70	J. Battles (ANL).
Feedthrough Components	2.40 ^c	J. Battles (ANL).

^aWhere applicable, low and high cost estimates are given.

^bCost given in \$/ft².

^cCost given in \$/kW-hr.

Table 6. Most Expensive Materials in Li/FeS_x Cell

Material	Cost, \$/kW-hr
Li or Li Compounds	4.61-14.26
BN Felt (Separator)	4.00-8.50
Feedthrough Parts	2.40
Mo Powder (Current Collector) ^a	1.45-2.20
Al (Negative Electrode)	1.43-1.66

^aThe estimate given is for molybdenum powder only; the fabrication costs, based upon estimates by Rockwell International, are expected to be a small fraction of the material cost.

Table 7. Equipment and Labor Costs for SES Cell¹ (1976 dollars)

Equipment and Labor	Cost, \$ x 10 ⁶
Production and ancillary equipment	3.204
Land, buildings, and installation ^a	6.408
Inventory and work in progress ^b	1.922
Other cash required	<u>1.000</u>
Total	12.534
Direct labor including fringe benefits ^c	1.404
Indirect labor, and indirect operating costs ^d	<u>2.160</u>
Total	3.564

^aTwice the cost of operating equipment.

^bAbout 20% of the cost of equipment, land, and buildings, which corresponds to approximately one month's supply of raw or converted materials.

^cDirect labor calculated assuming a \$6/hr rate; fringe benefits were assumed to be 30% of direct labor.

^dIndirect labor costs (supervision, clerical, maintenance, etc.) and operating costs (fuel, power, etc.) were assumed to be twice the direct labor cost.

(1) Inflation Factor. The materials costs for the previous cost study was gathered in early 1975, or approximately 4 years ago. Allowing 10% per year for inflation, this factor is (1.10)⁴ or 1.46.

(2) Cell-Size Factor. The effect of the cell size can be approximated by considering some exponential function of cell volume. Because the cell size is thought to have only a small effect on production equipment and labor, the equation $f = (V)^{0.2}$ (where V is the cell volume) was utilized to determine the cell size factor. Since the EV reference cell is about 50% less in volume than the SES reference cell used for ANL-76-12, then the cell-size factor for the EV cell is $(0.5)^{0.2} = 0.87$.

(3) Cell-Production-Rate Factor. The number of cells produced per unit time has a significant effect on the cost of production equipment and labor. A plant producing cells of a large size would have a smaller number of unit operations and would, therefore, be expected to have a lower equipment and labor cost than that of a plant producing smaller cells. A scaling factor of $(N)^{0.8}$ was used in this study to estimate the increased cost of equipment and labor for an EV cell compared to the 1976 SES cell. For the EV cells, the factor was taken to be $(2)^{0.8} = 1.74$.

(4) Plant Complexity Factor. The plant design described in ANL-76-12 was based upon a production scheme that has been superceded by a much simpler one. In the new scheme, recently developed rolling or pressing operations are used to mass produce electrodes. As a result of the simplifications now foreseen, we estimated a lower limit for plant complexity of 0.75, based upon 1.0 as the normalized value for the 1976 plant. An upper limit for plant complexity of 1.25 was then taken to allow for unanticipated process steps.

For convenience, the scaling factors used to update the equipment and labor costs determined for 1976 are shown in Table 8 for each reference design.

Table 8. Scaling Factors for SES and EV Cells

Scaling Factor	<u>SES Cell</u>		<u>EV (FeS) Cell</u>		<u>EV (FeS₂) Cell</u>	
	Low	High	Low	High	Low	High
Inflation	1.46	1.46	1.46	1.46	1.46	1.46
Cell size and production rate	1.0	1.0	1.51 ^a	1.51 ^a	1.51 ^a	1.51 ^a
Production complexity	0.75	1.25	0.75	1.25	0.75	1.25

^aFor this factor, the cell size and production rate have been combined (*i.e.*, $0.87 \times 1.74 = 1.51$).

C. Cell Manufacturing Cost

To calculate the total manufacturing cost for a reference cell, the following steps were followed. First, the equipment and labor costs **given** in ANL-76-12 were updated with the scaling factors given in Table 8. Second, the factory cost (\$/kW-hr) was determined by adding together the basic materials cost for the cell (see Section III. A), the assumed material losses during fabrication (10%), and the labor costs. Third, the return on investment was estimated to yield 25% on the capital investment (*i.e.*, equipment, inventory, cash requirements, etc.) before taxes. Finally, the total

manufacturing cost was calculated by adding together the factory cost, return on investment and general and administrative costs (assumed to be 11% of factory cost). Table 9 presents a complete breakdown of these cost components

Table 9. Cost Calculation for EV (FeS) Cell Produced
in a 1.15×10^6 kW-hr/yr Plant

I. Equipment Cost, \$/yr $\times 10^6$	
Production and ancilliary equipment	5.286
Land, Bldgs., Instl. (200%)	<u>10.572</u>
Total	<u>15.858</u>
Depreciation at 7.2%	1.141
II. Labor Plus Overhead Costs, \$/yr $\times 10^6$	
Labor plus overhead ^a (direct, fringes, indirect, supervision)	5.881
Depreciation	<u>1.141</u>
	<u>7.022</u>
III. Factory Cost, \$/kW-hr	
Basic Materials Cost	17.24
Material Losses (10%)	1.72
Labor & Overhead	<u>6.10</u>
Factory Cost	<u>25.06</u>
IV. Return on Investment (ROI), \$/kW-hr	
Investment	
Depreciation Base ^b	15.858
Inventory & work in progress ^c	2.192
Cash Requirements	<u>1.500</u>
Total	<u>19.55</u>
ROI ^d	4.88
V. Wholesale Selling Price, \$/kW-hr	
Factory Cost	25.06
General and Administrative (G&A) ^e	2.75
ROI	<u>4.88</u>
Price	<u>32.69</u>

^aUpdated cost from ANL-76-12, p. 12.

^bThe cost for operating equipment plus the cost for land, buildings and installation.

^cAssumed to be 8.75% of factory cost.

^dTaken to yield a 25% return on capital investment (before taxes).

^eAssumed to be 11% of factory cost.

(low estimate) for the uncharged EV (FeS) cell; this type of EV cell is expected to be commercialized first. As shown, the materials cost for this cell, \$17.24/kW-hr, is about 53% of the manufacturer's wholesale selling price of \$32.60/kW-hr.

A more general breakdown of the cost components for the SES cell and both EV cells is shown in Table 10 on the next page; a low and high cost estimate is made for each cost component. The table shows that the SES reference cell costs about \$24 to 41/kW-hr, the 1976 estimate being about \$29/kW-hr. The estimated cost for the EV cells are about \$31 (uncharged) to \$55 (charged) per kilowatt-hour. The higher manufacturing cost calculated for the EV cells results from the higher cost associated with the BN felt separator (the 1979 SES cell was assumed to have a MgO powder separator) and the higher labor and equipment costs associated with the manufacture of a smaller cell.

Fig. 2 presents bar graphs of the cost data given in Table 10 for the

Fig. 2. Cost Estimates for SES and EV Cells (for each cell type, the column on the left represents the low estimate and that on the right represents the high estimate).

Table 10. Cell Manufacturing Cost Summary

	<u>1976 Estimate^a</u> of SES Cell	<u>Present Estimate</u>					
		SES Cell		EV (FeS) Cell		EV (FeS ₂) Cell	
		<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>	<u>Low</u>	<u>High</u>
Equipment, \$ x 10 ⁶	3.20	3.51	5.85	5.28	8.81	5.28	8.81
Land, bldgs., inst., \$ x 10 ⁶	6.40	7.01	11.69	10.57	17.62	10.57	17.62
Labor, \$ x 10 ⁶	3.56	3.90	6.50	5.88	9.80	5.88	9.80
Total Investment, \$ x 10 ⁶	12.53	13.82	21.69	19.55	31.62	19.44	31.53
Materials Cost, \$/kW-hr	19.02	14.76	25.05	17.24	29.63	16.14	28.64
Factory Cost, \$/kW-hr	26.27	20.88	35.30	27.81	46.86	26.47	45.65
ROI, \$/kW-hr	2.89	3.46	5.42	4.88	7.91	4.86	7.88
Selling Price, \$/kW-hr	29.16	24.34	40.72	32.69	54.77	31.33	53.53

^aManufacturing cost from ANL-76-12.

SES and EV cells. The total materials cost for each cell, also shown in this figure, represents about 52 to 65% of the total cell cost. The most expensive cell materials were found to be lithium (metal and compounds), \$4.61 to 14.26/kW-hr, and BN felt, \$4.00 to 8.50/kW-hr. If the projected cost for lithium of \$4.61/kW-hr can be reached, then the Li/FeS system would be highly competitive with all other advanced battery systems. Consequently, the lithium cost would not be a dominant obstacle to commercialization.

IV. A COMPARISON BETWEEN ANL AND ARTHUR D. LITTLE (ADL) MANUFACTURING COST METHODOLOGY

The Department of Energy has recommended that the ADL manufacturing cost methodology³ be used for estimating the manufacturing costs for advanced batteries for utility load-leveling. Accordingly, the manufacturing cost for the SES reference cell was made by the ADL method and compared with the cost estimated by the ANL procedure. Some of the important features of both methodologies are discussed below.

Material Allowance. Both reports show a 5% material allowance for scrap; however, to be conservative, we have changed this figure to a 10% allowance.

Overhead. In the ANL method, the overhead was determined by adding together the cost for fringe benefits, indirect labor (*e.g.*, supervision, maintenance, clerical) and operating costs (*e.g.*, fuel, power), and depreciation of equipment and buildings. For these cost factors, the fringe benefits were assumed to equal 30% of the direct labor cost; indirect labor and operating costs were assumed to equal twice the direct cost; and depreciation was assumed to be 7.2% of the equipment and buildings. In the ADL method, overhead was calculated by adding up 150% of direct labor cost, 10% of total materials, and depreciation (10% of equipment plus installation costs). The cost of land and buildings was not considered as part of the overhead. To account for land, building and installation, the ADL method includes rental as an operating cost.

Working Capital. The ANL method employed 10.7% of the annual factory cost based upon the expectation that the battery market would be well defined and would require minimal stock inventory. The ADL method employs 30% of annual factory cost for working capital.

Return on Capital Investment (ROI). The two methods are not very far apart on this factor. For the ANL method, a before-tax ROI of 25%, corresponding roughly to 12.5% after taxes, was assumed; the ADL method specifies 15% after taxes. However, the investment base in the ADL method is smaller than that of the ANL method because the cost of land and buildings is not included. The net effect is to make the ROI for the ADL method look larger. However, ADL made no explicit allowance for general and administrative cost.

Production Rate. The production rate used for the ADL method was 2.5 million kW-hr/yr, whereas that of the ANL method was 1.15 million kW-hr/yr. The latter rate was chosen to coincide with that used in ANL-76-12.

Labor Rate. For the ADL method, a labor rate of \$7.50 (in mid-1976 dollars) per hour was determined. At a 10% annual inflation rate, this amounts to a \$6.49 per hour rate for January, 1975, which is the date at which the labor rate was determined for ANL-76-12 (\$6.00/hr). In 1979 dollars, these labor rates are \$8.78/hr and \$9.50/hr for the ANL and ADL methods, respectively.

A comparison of manufacturing costs for the SES cells are shown in Table 11 for both methods; as can be seen, the difference in manufacturer's selling price is minimal, less than about \$1/kW-hr.

Table 11. The SES Cell Manufacturing Cost According to Two Costing Methodologies (1979 Dollars)

Cost Item	ANL Method ²	ADL Method ³
Equipment Cost, \$ x 10 ⁶	4.678	4.678
Depreciation Base, \$ x 10 ⁶	14.03	9.356
Total Investment, \$ x 10 ⁶	17.46-18.05	16.27-18.44
Total Labor, \$/kW-hr	5.20	4.27
Labor & Overhead, \$/kW-hr	6.21	5.20
Building Rental, \$/kW-hr	0	0.27
Mat'ls Cost Range, \$/kW-hr	15.95-22.55	15.95-22.55
Factory Cost plus G&A, \$/kW-hr	24.60-31.92	23.02-30.28
ROI, \$/kW-hr	4.36-4.51	4.88-5.53
Wholesale Selling Price, \$/kW-hr	28.96-36.43	27.90-35.81

V. LITHIUM RESOURCES AND REQUIREMENTS

A. Reserves/Resources Lithium

A classification system designed to express resource data estimates was developed by the Bureau of Mines and the U.S. Geological Survey and published in 1976 in Geological Survey Bulletin 1450-A. This system defines a reserve as that part of a resource for which rank, quality, and quantity have been reasonably determined and which is deemed to be minable at a profit under existing market conditions. A resource is defined as an estimated quantity of a commodity in the ground in such form that economic extraction is or may become feasible. Reserve estimates, based on data from private industry and from the U.S. Geological Survey and other governmental agencies, are given in Table 12. The reserve in Table 12 includes these reserves as well as lithium resources that may be only marginally economic. This table includes only those resources recoverable using existing technology; hypothetical (undiscovered) resources are not included.

Table 12. Identified World Lithium Resources^a

Country	10 ³ Short Tons of Lithium ^b		
	Reserve Base	Other ^c	Total
United States	400	400	800
Canada	200	300	500
Chile, Bolivia, Brazil	1003	3117	4120
Africa, Europe ^d , Asia ^d , Australia	497	2083	2580
World Total	2100	5900	8000

^aBased on information in Ref. 4.

^bLithium contained in ore delivered to the mill head; about 66% of this lithium is recoverable as chemicals.

^cResources recoverable using existing technology; derived in consultation with U.S. Geologic Survey.

^dOrder of magnitude only.

Most of the world's lithium reserve base, totaling about 2.1 million tons of recoverable lithium delivered to a mill head, are in subsurface brines in Chile and in pegmatites in the United States, Canada, Zaire, and the U.S.S.R. The Chilean brines, investigated recently on a pilot scale, represent about one-half of world reserves. Approximately one-sixth of the world's lithium reserve base is in North Carolina, in the Carolina lithium belt. Total estimated world resources are approximately 8 million tons of lithium equivalent. An estimated two-thirds of the lithium contained in the ore delivered to the mill head is recoverable as chemicals.

B. Lithium Requirements

The projected lithium requirements for both conventional uses and Li/FeS batteries are given in Table 13. The annual production requirements between 1986 and 2006 were estimated in five year intervals. The lithium requirements for batteries in each period is estimated from present projections of the state of Li/FeS technology. In the 1986-1990 period, it is expected that a pilot production line at one or two commercial manufacturers will be producing EV Li/FeS batteries for limited markets. In the next period, one or more partially automated plants are expected. In the third period, 1996-2000, several fully-automated plants producing 6000 MW-hr/yr (enough for 200,000 automobiles/yr) are projected. Because the present strategy is to base the development of the SES battery upon EV battery technology, second-generation SES batteries are not expected to emerge until the 1996-2000 period. A plant of 2500 MW-hr capacity could produce 25 SES batteries per year in the period 2001-2005.

As shown in Table 13, the cumulative lithium requirements for batteries and conventional uses are projected to be 275,240 short tons by 2006. This value represents 51% of the total U.S. resources (approximately 100% of the

Table 13. Projected Lithium Requirements for the U.S.A.^a

	1986-1990	1991-1995	1996-2000	2001-2005
SES Batteries (100 MW-hr)				
Number/yr	0	1	3	25
Production Capacity, MW-hr/yr	0	100	300	2500
EV Batteries (30 kW-hr)				
Number/yr	1000	12,000	200,000	1,000,000
Production Capacity, MW-hr/yr	30	360	6,000	30,000
Total Annual Production, MW-hr	30	460	6,300	32,500
Lithium, short tons per 5 yr period				
For Batteries	75	1150	15,750	81,250
For Conventional Uses	30,000	37,500	50,000	66,900
Total per period	30,075	38,650	65,750	148,150

^aBased upon 1 lb lithium/kW-hr for SES or EV batteries.

reserve base) or 5.1% of the known world resource*. Of the total lithium used in battery production, about 93% would go to EV batteries and about 7% to SES batteries. Of the total lithium produced to the year 2006, 33% would be used in battery production, the remaining 67% would be consumed in conventional uses. Based upon this high projected lithium requirement, it is expected that a very large fraction (perhaps >90%) of the lithium in batteries would be recycled.

VI. CONCLUDING REMARKS

The major assumptions that need to be demonstrated to confirm the low cost potential of Li-Al/FeS cells are as follows:

1. that lithium sulfide can be produced at about the same cost as lithium carbonate from a lithium carbonate intermediate product (the production of Li_2S from Li_2CO_3 plus H_2S is another, somewhat more expensive alternative);
2. that low-cost current collectors for the positive electrode in the Li-Al/FeS₂ cell can be manufactured from molybdenum powders or iron substrates coated with a low-cost ceramic material;

*For these calculations, losses of lithium due to conversion to chemicals are included.

3. that BN felt can be produced at about \$1.00/ft² in mass production;
4. that low-cost, long-lifetime, and inexpensive alloys can be developed for the current collectors in the Li-Al/FeS cell and for the cell can;
5. that electrode particle retention can be accomplished by low-cost materials such as photo-etched sheets backed up by BN felt (the present use of screens and ZrO₂ or Y₂O₃ cloth for this purpose is too expensive for commercial application);
6. that the labor and equipment costs are in the range projected by this study (the earliest check of this will be when the Li/FeS cell is manufactured in a pilot plant, but final confirmation will not be possible until a fully automated plant has been built and operated).

For the high estimates of cell cost, certain limited market applications for the Li/FeS battery appear within reach, such as vans, buses, mining vehicles and submarines. The low estimates for both the SES and EV cells are within the cost goals set by DOE and ANL, and, if these costs can be attained, successful commercialization of the Li/FeS battery for stationary and vehicle applications would be expected on a large scale.

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