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REFERENCE DESIGN OF 100 MW-h
LITHIUM/IRON SULFIDE BATTERY SYSTEM
FOR UTILITY LOAD LEVELING

by

S. M. Zivi, H. Kacinskas, I. Pollack,
A. A. Chilenskas, D. L. Barney,
W. Grieve, B. L. McFarland, S. Sudar,
E. Goldstein, and E. Adler

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ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

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S. M. Zivi, H. Kacinskas,* I. Pollack,*
A. A. Chilenskas, and D. L. Barney

Chemical Engineering Division
Argonne National Laboratory

W. Grieve, B. L. McFarland, S. Sudar, E. Goldstein,
and E. Adler

Energy Systems Group
Rockwell International

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*Engineering Division, ANL.

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REFERENCE DESIGN OF 100 MW-h LITHIUM/IRON SULFIDE
BATTERY SYSTEM FOR UTILITY LOAD LEVELING

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S. M. Zivi, H. Kacinskas,* I. Pollack,* A. A. Chilenskas, D. L. Barney,
W. Grieve,† B. L. McFarland,† S. Sudar,† E. Goldstein,† and E. Adler†

ABSTRACT

This report covers the first year in a two-year cooperative effort between Argonne National Laboratory and Rockwell International to develop a conceptual design of a lithium alloy/iron sulfide battery for utility load leveling. A conceptual design was developed for a 100 MW-h battery system based upon a parallel-series arrangement of 2.5 kW-h capacity cells. The sales price of such a battery system was estimated to be very high, \$80.25/kW-h, exclusive of the cost of the individual cells, the dc-to-ac converters, site preparation, or land acquisition costs. Consequently, the second year's efforts were directed towards developing modified designs with significantly lower potential costs.

I. INTRODUCTION

At Argonne National Laboratory (ANL) and the Energy Systems Group of Rockwell International (RI), a cooperative design effort has been under way for the past two years† with the objective of developing a cost-effective stationary energy-storage (SES) battery system, using high-temperature lithium alloy/iron sulfide cells. The major design and cost studies for this system were completed in 1979; the work is documented in three ANL reports. In the first of these reports, ANL-80-16, United Technologies Corp., under contract to ANL, provided an electrical balance-of-plant conceptual design for the lithium/iron sulfide SES battery; this report was originally issued with limited distribution as UT report FCR-1367.

The present report (ANL-80-19) is the second in the series and covers the initial efforts by ANL/RI to develop a conceptual design for a 100 MW-h SES facility, designated the reference design. A cost analysis of this reference design, however, showed that such a facility would be much too expensive. Subsequently, three alternative conceptual designs with lower potential costs were proposed, and these designs are documented in the third report, ANL-80-20.

*Engineering Division, ANL.

†Rockwell International, Energy Systems Group.

‡Funding provided by the Division of Electrical Energy Systems in the Department of Energy.

The RI/ANL reference design of the 100 MW-h SES facility is depicted in Fig. 1. This facility consists of two groups of six SES modules arranged on

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Fig. 1. 100 MW-h SES Facility

either side of an electrical-power processing center. Each module consists of thirty-six Li-Al/FeS or Li-Si/FeS units with a capacity of 240 kW-h each, designated a submodule; nominal dimensions for an uninsulated, assembled module are 12 x 2.8 x 6 m. Each module group has a 10-MW converter; interties permit reassignment of the converters to alternate battery groups. Also in the central area are ancillary buildings which house switchgear, equalizer electronics, and other instrumentation. Centrifugal blowers for the thermal management system are housed in sheet-metal structures on the outside of each module group. The submodules can be trucked to the plant site and brought up to operating temperature in an external furnace on site. The usual electrical measurements such as voltage, current, and power will be provided in conjunction with the converter equipment, along with alarm signals, with suitable interface devices to communicate the battery status to a dispatcher in accordance with standard utility practice. Two-way communications will allow this dispatcher to start, stop, and control the operation of the battery system remotely.

The lithium alloy/FeS cells operate at constant power between 1.0 and 1.8 V from the end of discharge to the end of charge, over 5 h; this gives a nominal voltage for the 12-module system of 1728 to 3110 V. With six modules serving each converter section, the current to each converter at the end of discharge will be 6000 A. Because the charging time will be as long as 7 h, the charging current at constant power at the beginning of charge will be

4134 A from each converter to its operating group of six modules. The battery-system operating efficiency over one cycle per day for 5 days per week is estimated to be at least 75% (assuming a cell watt-hour efficiency of 80%, an equivalent total system resistance of 0.94Ω , and additional losses); cell equalization can be accomplished on the weekends. A detailed description of the facility design and cost is given below.

II. CONCEPTUAL DESIGN OF 100 MW-h FACILITY

A. Cell Design

The SES facility is designed to be capable of accommodating either Li-Al/FeS or Li-Si/FeS cells. The former cells operate within a voltage range of 1.0 to 1.6 V, whereas the latter cells operate within a voltage range of 1.0 to 1.8 V. The voltage range for the Li-Si/FeS cells was used to determine the appropriate size for the power converters.

Cell-size evaluation studies determined that the largest practical cell capacity for this conceptual system is 2.5 kW-h. This was based on projection of the cell state of the art in the early 1980's as well as the impact on cell-size life-cycle costs of the cell external conductor as depicted in Fig. 2. The design and performance specifications for this 2.5 kW-h cell, based on the expected technological status of the Li/FeS system in the early 1980's, are presented in Table 1.

Fig. 2. Cell External Conductor Costs vs. Cell Capacity

Table 1. Design Specifications for the Lithium Alloy/FeS Cell

Maximum Size	0.17 x 0.28 x 0.23 m (6.75 x 11 x 9 in.)
Energy Output at C/5	2.5 kW-h
Charge Output at C/5	2083 A-h
Maximum Weight	43 kg (94.8 lb)
Energy Efficiency	80%
Voltage Cutoffs	
Charge	1.6 to 1.8 V
Discharge	1.0 V
Cell Resistance	0.33 mΩ
Cycle Life	2000 cycles

Some amount of cell thermal stratification due to the operation of the thermal control system is unavoidable during the operation of battery cooling systems; hence, the effect of cell size on the internal thermal stratification was evaluated. The approximate conditions of the problem can be defined by a second-order boundary value solution of the two-dimensional Fourier heat conduction equation in a rectangle ($-a < x < a$) by having a uniform heat generation (Q_0) and heat transfer through surface resistance Y per unit of surface $X = \pm a$ and $Y = \pm a$. The solution

$$\Delta\theta = \frac{Qa^2}{2K}$$

approximates the dependence of the internal cell thermal stratification on the heat generation within the cell (Q), the reciprocal of cell thermal conductivity (K), and the square of the electrode dimension (a). In view of the strong dependence of $\Delta\theta$ on the second power of electrode size and an already significant thermal stratification within the cells of 8 to 23°C (14 to 42°F), it was concluded that electrode dimensions should not exceed 24 cm (9 to 10 in.). As a consequence, increases in cell capacity to reduce the battery system cost will have to be accomplished through an increase in the number of electrode pairs per cell. The designs for Li-Si/FeS and Li-Al/FeS cells both lend themselves to such changes.

B. Submodule Design

1. General Characteristics

The 240-kW-h submodule is the smallest field replaceable unit within the battery system. It will be completely factory assembled and shipped to

the site ready for installation. The basic submodule is depicted in Fig. 3, all submodules being identical. Major physical and functional characteristics of these submodules are given in Table 2.

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Fig. 3. Submodule Design

Table 2. Submodule Characteristics

Height	5.84 m (19 ft 2 in.)
Width	1.8 m (5 ft 11 in.)
Thickness	0.275 m (10-13/16 in.)
Weight	5442 kg (6 ton)
Capacity	240 kW-h (nominal maximum)
Voltage	43.2 V dc [end of charge (EOC)]
Cell Quantity	96
Equalization Circuits	24

The submodule consists of ninety-six 2.5 kW-h cells arranged in rows of eight cells (two groups of four cells) vertically stacked 12 high. Each group of four cells is mounted on a suitably stiffened shelf to which all cell casings (cell negative terminal) are brazed or welded so that contact resistance is minimized. In this arrangement, the shelves perform the dual function of equalization conductor and structural support. The shelves are attached to brackets on vertical frame members and high-strength electrical insulators to assure circuit isolation from ground. The insulated cell positive terminals are connected directly to the casing of the cell on the shelf above (negative terminal) with a short, flexible busbar. The 24 groups of four-cell assemblies are connected in electrical series and have positive and negative terminals at the submodule top. Consequently, two long busbars run the length of the stack and are enclosed within, but electrically insulated from, the center and end box beams. Special bus conductors are required for the topmost connections from the cell positive terminals to the main positive terminal of the submodule.

Submodules are removable from the top of a module. For handling purposes, the frame has two lifting eyes that mate with a strongback (see Fig. 4).

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Fig. 4. Hoist Strongback

Insulated equalization leads from each shelf are routed through the outer box beams of the submodule, while thermocouple leads are routed through the center beam to the receptacle portion of a special electrical disconnect assembly located at the top of the submodule and attached to and between lifting brackets.

2. Electromechanical Design

There will be a periodic requirement to equalize the cells in the submodule individually, which would require a large number of conductors. To reduce the conductor requirements, the cells are connected in parallel groups of four cells each, with 24 parallel groups in series (see Fig. 5). The submodule voltage at the end of charge is 43.2 V for the LiSi/FeS cell. The submodule current at the end of discharge is 2000 A (based on a constant power discharge for 5 h).

As a consequence of the large number of cells (41,472), particular attention has been given to electrical interconnections and devices in order to minimize the total contact resistance, energy losses, and voltage drops.

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Fig. 5. Submodule Equalization Concept

Flexible busbars used for cell interconnections will be braided stainless-steel-clad copper conductors brazed to clad connection pads. Wire will be fabricated commercially for use at elevated temperatures with a high-chrome stainless steel cladding.

a. Basis for Conductor Selection

Materials selected for conductors in power distribution circuits must have high electrical and thermal conductivity. Many combinations of metals are used for bolted connectors, with factors such as temperature, corrosivity, conductivity, and cost affecting the selection. High electrical conductivity is essential to minimum heat generation during the passage of current. Equivalent proportions at low temperature of the leading basic conductor material candidates are listed in Table 3. Resistivity and density factors for the candidate materials are listed in Table 4.

Table 3. Conductor Materials Characteristics (20°C)

Material	Diameter, ^a in.	Conductivity, ^b %	Weight, ^a ratio	Cost (August 1978), \$/lb
Copper (Cu)	1.0	100	3.5	1.44
Aluminum (Al)	1.28	61	1.7	1.5
Sodium (Na)	1.64	37	1.0	0.41

^aFor conductors of equal resistance.

^bFor conductors of equal cross section and length.

Table 4. Conductor Resistivity and Density Characteristics

	Resistivity, mΩ-cm		Density, g/cm ³	
	20°C	500°C	20°C	500°C
Aluminum	2.83	8.6	2.7	2.7
Copper	1.724	5.0	8.9	8.7
Sodium	4.60	27.17	0.968(s)	0.8323(l)
Na/Cu Ratio ^a	2.72	5.43	0.109	0.093
Al/Cu Ratio ^a	1.64	1.72	0.304	0.301

^aThis is a ratio and the numbers given are dimensionless.

All candidate conductor materials require containment, for corrosion prevention as well as structural enhancement. Only stainless steel (SS) and heavy nickel (Ni) were considered; however, nickel exhibits an undesirable migration characteristic at the battery operating temperature. The effect of this migration can be observed in Fig. 6. Figure 7 shows the comparative resistivities up to 500 h at high temperatures for stainless steel (Oxalloy 28), Inconel, and nickel-clad copper wires. While the initial electrical resistivity is higher for the stainless-steel clad material, after exposures up to 300 h, its resistivity is the lowest of the three materials considered. An evaluation of stainless-steel cladding revealed that Types 430 and 446 are candidates for copper wire and bar cladding.

Fig. 6. Time-Dependent Variation of Nickel-Clad Copper Wire Resistivity at Elevated Temperatures

Additional studies revealed that, although aluminum requires an area about twice that of copper for the same resistance, the equivalent mass ratio at 500°C (932°F) is (see Table 4 for density data at 500°C) as follows:

$$\frac{\text{Mass Al}}{\text{Mass Cu}} = \left(\frac{D_A}{D_C} \right) \left(\frac{A_A}{A_C} \right) \frac{1}{1} = 0.301(1.72) = 0.517$$

Using the cost data from Table 4, the cost ratio for any connection of equal length and voltage drop was determined to be

$$\text{Cost}_{\text{Al}} = \frac{1.5}{1.44} (0.52) = 0.54 \text{ Cost}_{\text{Cu}}$$

Fig. 7. Time-Dependent Resistivity Variations of Clad Copper Wire at Elevated Temperatures

These results indicate that aluminum appears to be an attractive alternative to copper; however, operating temperature may be too close to the melting point for safety; and manufacturers have indicated that the ability to maintain good bonds of unoxidized conductor to stainless steel cladding is questionable.

Sodium busbars have found several applications to date and could not be neglected here, despite the fact that sodium enters a liquid phase at 98°C (209°F) and requires a positive containment much like a cladding. In fact, the tensile strengths of aluminum and copper are so low at operating temperatures that structural reliance on cladding could be considered essentially equivalent. Liquid conductors are subject to a "pinch effect"; however, at projected current levels, this is considered a negligible influence.

Five and one-half times the area of sodium is required for the same resistance value; and, consequently, the same voltage drop as that of copper. For equal lengths of busbar, the mass ratio at operating temperature is

$$\left(\frac{D_{Na}}{D_{Cu}}\right)\left(\frac{A_{Na}}{A_{Cu}}\right)\frac{1}{1} = 0.093(5.43) = 0.506$$

or

$$\text{Mass}_{Na} = 0.56 \text{ Mass}_{Cu}$$

With a mass-based cost ratio assumed to be

$$\frac{C_{Na}}{C_{Cu}} = \frac{0.41}{1.44} = 0.285$$

the relative cost for any connection of equal length with equal voltage drop is

$$\text{Cost}_{Na} = 0.285(0.56) = 0.16 \text{ Cost}_{Cu}$$

Although sodium will require one-half the mass at one-eighth the cost of copper or less, the cross-sectional area must be over five times as large. This, coupled with higher projected fabrication costs for special handling, higher volumetric requirements with elevated temperature (internal expansibility of the container), and safety considerations due to the possibility of catastrophic failure, rule out use of sodium at this time. These results are summarized for comparison purposes in Table 5.

Table 5. Conductor Evaluation Data

	Melting Point, °C (°F)	Relative Resistance ^a	Density, ^b g/cm	Cost, 1978\$/lb	Mass Ratio ^c	Cost Ratio ^c
Copper	1065 (1949)	2.9	8.6	1.4	1.0	1.0(clad)
Clad Cu	-	4.3	-	-	-	-
Aluminum	646 (1195)	5.0	2.7	1.5	0.71	0.74
Clad Al	-	13.1	-	-	-	-
Sodium	97.6 (208)	15.8	0.83	0.41	0.42	0.12
Encased Na	-	21.5	-	-	-	-
Iron	1535 (2795)	33.0	7.7	-	-	-

^aDetermined for material of equal size at 500°C.

^bDetermined for material at 500°C.

^cDetermined for material of equal resistance.

b. Submodule Terminals and Interconnections

Submodule terminals will have two degrees of freedom (azimuth and elevation) in order to accommodate dimensional variations in the relative positioning of submodules with respect to one another. Interconnections will be in a disconnectable flat busbar configuration as depicted in Fig. 8.

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Fig. 8. Submodule Busbars

Electrical slip joints rated at 2000 A will be used in order to achieve the flexibility necessary for the desired operability and maintainability, and for protection against earthquakes. A specially shaped, louvered contact spring band made from stainless steel will be used to maintain a low contact resistance. These spring bands (see Fig. 9) from the Multilam Corp. (Los Altos, CA) maintain potential losses on the average to less than 12 mV per joint at rated continuous current and have been used in applications up to 70,000 A.

3. Structural Design

The submodule structure provides the primary support for the cells, and consists of an outer frame and center post in which a series of 24 shelves

Fig. 9. Multilam Components and Connectors

are installed (as depicted in Fig. 3). There are 12 levels of cells, with eight cells on each level. The shelves are electrically insulated from each other and have the cross-sectional shape of a commonly used channel section. This shape will provide good structural characteristics, with adequate rigidity against twisting or excessive deformation. Support connections to the frame will be made by securing the shelf between top and bottom seated clips. Rigid structural insulation will be sandwiched between the shelf and the supporting clips to maintain electrical separation between the shelf and frame.

The frame of the submodule provides the support for the cell shelves and will be the mechanism by which loads will be transmitted to the module frame. The submodule frame includes the vertical side and center posts, the base and top, seven horizontal struts, and six cross braces across one face of the structure. The side posts and top and bottom members are channels, similar to the shelves. The center post is a rectangular tube, and the cross bracing is made of flat bars. The side and center posts carry lateral loads, perpendicular to the face, by their bending capacity. Lateral loads parallel to the face are designed to meet the seismic requirements for a Zone IV site as well as for transportational loading.

4. Handling System

The submodule handling system includes a movable gantry with a special strongback, special tools for busbar and connector connection and disconnection, a warmup and cooldown rack, and a transportation mold.

The gantry will be a structural frame that supports a 15-ton monorail hoist and an operator's cab. The hoist will support installation and removal of all components in the battery system. The gantry will be supported on electrically driven tracked wheels, 21.3 m (70 ft) apart, that straddle the battery modules, as depicted in Fig. 1.

The hoist will be equipped with a strongback (Fig. 4) for attachment to the submodule lifting brackets. The operator will be required to actuate pins on the strongback to enter holes on the lifting brackets for positive connection. Lifting will place these pins under shear loading.

C. Module and Ancillary Equipment Design

1. General Characteristics of Module

The module conceptual design consists of 36 submodules. The battery module, which is depicted in Fig. 10, is partitioned into six compartments, each accommodating six submodules. Submodules will be shipped separately and inserted or removed from the top. Salient physical and functional characteristics of fully assembled modules are given in Table 6.

Modules will be designed to provide physical separation of associated electrical and mechanical support equipment to facilitate assembly and improve safety and maintainability. A thermal control module is attached at one end, while electrical connections are made at the opposite end. The overall battery module includes the major components of the thermal management system, including electrical heaters, hairpin heating and cooling tubes, and inlet and exhaust plenum chambers.

Four factory-assembled, self-supporting trussed frames along with an insulated base frame will be stacked together to form the major structure. Two trussed frameworks incorporate multipurpose partitions, which provide guideways for the submodules, support for electrical cable raceways, and thermal management system hairpin tubes, as well as structural stabilization under transverse loads.

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Fig. 10. Truckable Module Design

Table 6. Module Characteristics

Height	7.0 m (23 ft)
Width	2.9 m (9.5 ft)
Length	15.2 m (45 ft)
Weight	30,000 kg (33 ton) without submodules
Capacity	8.64 MW-h (nominal)
Voltage	1555 V dc (EOC)
Cell Quantity	3456
Submodule Quantity	36
Equalization Circuits	864

Foot pads will be provided for insertion guidance, positioning, and alignment. Insulating panels are to be installed on the exposed sides of the battery module, and six removable hatch covers that are weatherproofed and insulated to be installed on top for maintenance access.

2. Electrical Design

Each module will include 36 submodules (96 cells) for a rating of 8.64 MW-h from 3456 cells. The 36 submodules are connected in series to provide an end-of-charge voltage of 1555 V.

Thermocouple equalization leads will be routed to the electrical end of each module. Wires will be routed in raceways in each of the six aisles between submodule rows above and in line with the cooling tubes.

Submodule power interconnections will be predominately in line from submodule to submodule using special busbars with movable joints. The resulting serpentine connection pattern to connect submodules in series is shown in Fig. 11. A comparison study was made of various submodule interconnection alternatives, and the results are tabulated in the chart shown in Fig. 12. The major alternative was identified as between location of the interconnection terminals on the bottom of the submodule or on the top (*i.e.*, between internal and external module connections). Consideration was given to five applicable terminal contact configurations, depicted in Fig. 13. No apparent advantages were identified for the cone, sphere, or flat terminal types when used in an external-top configuration; and, consequently, no otherwise appropriate comments are shown. All terminal types identified are applicable "internally."

3. Mechanical Design

Because of the predominance of radiation heat transfer between the cells and the heating and cooling tubes, two concentric radiation shields having lengths of 2.9 m (9.5 ft) and 1.8 m (5.9 ft) will prevent excessive cooling and heating of the cells located in the vicinity of the inlet. The radiation shields and the tubes are an integral part of the module structure and, therefore, will be factory assembled and welded to the inlet and outlet plenum tubesheets.

4. Structural Design

Module structural framing will provide the support and stabilization system for the submodules. Nominal overall dimensions for an assembled module will be 13.7 m (45 ft) long by 2.9 m (9-1/2 ft) wide by 6.1 m (20 ft) high. Structurally, a module consists of five principal parts: a base, two main-frame sections, a cover adapter section, sectionalized covers, and a structure for the support of the thermal management system and the air blowers (see Fig. 14). The interior of the battery module is partitioned into six compartments, with each compartment accommodating six submodules. The main frames have partitions, or guide frames, that provide the means for stabilizing the submodules under transverse lateral loads and also provide support for the heating and cooling tubes of the thermal management system.

The internal structural members of the module will be fabricated from material suitable for the high-temperature operating requirements, such as 2-1/4 Cr-1 Mo steel. Where possible, shapes such as tubes, rods, and flat

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Fig. 11. Submodule Interconnections

sheets will be used. The structural framing has been designed to permit as much freedom for thermal expansion as is consistent with the structure's function and integrity. A satisfactory first approach for seismic performance was evaluated using box-type shear wall construction with internal grid members and diagonal bracing to obtain added rigidity and cell stack support.

		LOCATION									
		EXTERNAL - TOP					INTERNAL - BOTTOM				
		PIN	CONE	SPHER.	FLATS	FORK	PIN	CONE	SPHER.	FLATS	FORK
<u>ELECTRICAL PERFORMANCE:</u>											
LOW RESISTANCE (V DROP)		OK	NA	NA	NA	OK	OK	OK	MASS LTD	LO CONT PR	OK
HIGH CURRENT		OK	NA	NA	NA	OK BULKY	OK	OK	OK	OK	OK
CONTACT PRESSURE	CONVENTIONAL MULTILAM	VARIES WITH TEMP., CREEP AND RELAXATION 8 - 10 PSI					1 KPSI MAX. (MASS LTD) 8 - 10 KPSI				
<u>FUNCTIONAL PERFORMANCE:</u>											
SHAPE	MULTILAM CONVENTIONAL	OK	NA	NA	NA	OK	OK CLOSE TOL.	OK CLOSE TOL.	OK OK	OK	OK OK
KEYABILITY		L+S	NA	NA	NA	L+S+O	L+S	L+S	L	L	L+S+O
MAINTAINABILITY		ACCESSIBLE/SM REMOVAL					MANDATORY SYSTEM SHUTDOWN/COOLDOWN + POOR ACCESS				
SAFETY	PERSONNEL	OK/GOOD HI-TENSION PRACTICE					OK/INACCESSIBLE TO SHORTING				
INSERTABILITY/ CONTACTABILITY		OK	NA	NA	NA	OK	CLOSE TOL MECH. ALIGN	CLOSE TOL.	SELF ALIGNING	CLOSE F+P TOL + FREE	MECH. ALIGN
FAILURE MODES	SEISMIC	OK	NA	NA	NA	OK	HI-DYNAMIC LOADING	HI-DYNAMIC LOADING	CONTACT DAMAGE	OK @ HL	HI-DYNAMIC LOADING
	INTERNAL	NA	NA	NA	NA	NA	3 TON + DYNAMIC OVERLOADING CHEMICAL LEAKAGE				
	EXTERNAL	TOOL, SLING AND COVER DAMAGE (DESIGN)					LOOSE PIECE INTERFERENCE DAMAGE AND/OR INSERTION RESTRICTION				
NOTES: NA - NOT APPLICABLE; ML - MULTILAM; SM - SUBMODULE; L - LOCATION; S - SIZE; O - ORIENTATION											

Fig. 12. Chart of Submodule Interconnection Alternatives

Fig. 13. Submodule Interconnection Alternative Shapes

Trade-off studies revealed that the steels listed in Table 7 are generally applicable as structural materials; however, the selection of Cor-ten mild steel, or plain structural steel for structural components is not compatible with the nominal operating temperature of the cell (450°C). During prolonged inactivity of the battery system, all of these materials would be exposed to graphitization, which induces stress corrosion and thermal fatigue; and considerable safety and maintenance problems could arise as a result of system operating transients. The use of alloy (Cr-Mo) steel enhances the maintainability and safety of the system.

5. Thermal Management System

A thermal management system is required for each module to maintain cell temperatures within 420 to 475°C (788 to 887°F); this system must provide

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Fig. 14. Truckable Module Design Concept

the necessary heating or cooling during startup, normal operation, and equalization. The performance specifications for thermal management of the Li-Al/FeS and Li-Si/FeS systems are given in Table 8. The proposed thermal management system consists of 84 hairpin-shaped cooling tubes, inlet and outlet air distribution plenums, two parallel-connected high-temperature (about 500°C) insulated blowers, electrical heaters, an ambient-air inlet with damper, and monitoring and control instrumentation sensors for the overall system.

The thermal control module (see Figs. 15 and 16) is designed to be free standing, yet will be attached firmly to the battery module (interfacing with the intake and exhaust plenum chambers). This unit incorporates two blowers driven by a common 30-hp, three-phase electric motor at a variable speed determined by a controller located within the power processing center. The thermal control module is provided with controls to raise the system temperature to operating temperature after extended shutdown or to minimize temperature variations during the four operation modes--charge, discharge, cell

Table 7. Characteristics of Steels at High Temperatures

Metal ^a Characteristics	302 SS	304 SS	446 SS	C1038	2-1/4% Cr- 1% Mo	Cor-ten-A
Temperature, °F	900-1100	900-1000	900-1100	900-1100	900-1100	800-1000
Tensile Strength, 10 ³ psi	60.0-53.2	60.0-53.2	66-42.5	44.0-25.2	60-41	76.4-52.8
Yield Strength at 2%, 10 ³ psi	18.1-16.4	18.1-16.4	42.2-23.5	21.5-16.3	28-16	39.9-35.2
Creep Stress at 10 ⁻⁴ %/h, 10 ³ psi	23.8-12.0	23.8-17.0	16.4-2.8	10.0-2.1	28-12	44.5-11.5
Stress for Rupture in 1000 h Unexposed, 10 ³ psi	49.0-27.0	49.0-27.0	46.0-12.0	13.7-5.6	41-25	56.8-18.6
Stress for Rupture in 1000 h Exposed, 10 ³ psi	48.0-30.0	48.0-30.0 ^b	47.0-18.8 ^b	11.9-5.2 ^c	32-16 ^d	---
Projected Price in Large Volumes, ^e \$/lb (May 78)	0.92	0.91	1.17	0.16	0.75	0.21

^a1/8 in. sheet cut.^b100,000 h exposure.^c83,000 h exposure.^d10,000 h exposure.^e10⁶ lb.

modes—charge, discharge, cell equalization, and standby thermal equalization. To minimize energy usage during cycling, module temperature will be allowed to fluctuate by 55°C (100°F). Thermal control can be economically achieved with a programmed logic controller (PLC), shown schematically in Fig. 17. A steel sheet metal enclosure will shelter thermal controller components from the elements, provide blower noise abatement, and restrict thermal losses. Large doors will be provided for ease of access during maintenance.

Cooling and heating of the cells is accomplished by circulating conditioned air in ASTM-A-214 steel U-shaped tubes (2.5 in. dia). Since the Li-Al/FeS and Li-Si/FeS cells have different heat generation profiles, the air flow ratio and temperatures will be variable over a range of up to 7200 cfm and 482°C (900°F). When cooling is required, ambient air is mixed with the return air to obtain the desired temperature. The excess hot air is discharged to the surrounding atmosphere through a stack having a 260°C (500°F) discharge damper. When cooling is not required, as during thermal equalization (standby), the ambient air inlet and stack discharge dampers are closed and the fans shut down. Two electrical duct heaters, having a combined heating capacity of 120 kW, provide initial preheating. These may also be used at reduced power, about 15 kW, to provide the required thermal equalization as needed. The use of tubular duct heaters reduces heating system maintenance and provides for a low-cost heating system.

Table 8. Schedule for Thermal Management for Li-Al/FeS and Li-Si/FeS Systems

Cell Design	LiAl/FeS	LiSi/FeS
Preferred Cell Temperature Range, °C	420-475	420-475
Air Flow Rate/Operating Period, (cfm)/(h/cycle)		
Discharge	7200/5	7200/4
Charge	4800/7	---
Thermal Equalization	3600/41	3600/43
Inlet/Outlet ^a Air Temperature, °C/°C		
Discharge	271/380	121/338
Charge	271/392	---
Thermal Equalization	437/427	460/448
Maximum Cell Temperature Fluctuation, °C	43	86
Maximum Cell Temperature Difference at end of a Week, °C	3	8
Air Pressure Drop/Blower Power Requirement, psi/hp		
Discharge	0.36/11.31	0.36/11.31
Charge	0.16/3.35	---
Thermal Equalization	0.095/1.49	0.092/1.45
Air Heater Power Requirement, ^b kW		
Discharge	---	---
Charge	---	---
Thermal Equalization	12.9	14.2
Total Weekly Power Consumption Rate, ^c %		
Due to Pressure Drop	0.80	0.50
Due to Air Heating	1.23	1.41

^aOutlet air temperatures were selected to yield the maximum ΔT (T inlet minus T outlet). When inlet temperature is higher than outlet, heat input by electrical heater will be required.

^bThese are the net heater power requirements only.

^cBased on 8.64 MW-h/cycle total power output per module.

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Fig. 15. Thermal Control Module

In order to reduce the heat leaks through the thermal management module and to comply with applicable OSHA regulations, all components exposed to the hot air are to be insulated with 0.15-m (6-in.) fiberglass insulation. Cooling of the thermal control module is provided by natural convection through door louvers. In order to maintain small cell-temperature differences within the module and to enhance the standby capability of the module, surfaces

Fig. 16. Schematic of Thermal Control Module

exposed to ambient air, such as covers, sides, and the end facing the power processing center, are insulated by 0.45-m (18-in.) thick weatherized fiberglass panels. Insulation between adjacent battery modules sharing a common wall is eliminated to reduce system cost. Structural maintenance work on a module, however, requires the cooling of all adjacent units and results in a 50% capacity loss. Heat losses through the module base represent a sizeable fraction of the overall thermal losses due to the heat leaks through support I-beams and Marinite stringers.

There will be 20 chromel-alumel (shielded, non-grounded) thermocouples per module to monitor cell temperatures. As shown in Fig. 18, eight of these thermocouples are located on the cells closest to each of the module corners, and twelve thermocouples are located in groups of four at three locations along the longitudinal axis of the module, at each end and just off center. To minimize the number of thermocouple channels required in the data acquisition equipment, the readings from four thermocouples at each corner will be averaged, as will the four thermocouples at each of the three other locations; thus, only five channels will be required. In addition to the 20 thermocouples on the cells, seven temperature sensing elements will be positioned in the thermal management system to provide temperature measurements for the PLC; four data channels to the PLC will convey information on the battery operating status [i.e., charge, discharge, thermal equalization (standby), and cell equalization].

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Fig. 17. Thermal Control Programmed Logic Controller

Air flow in each of the parallel air circuits will be measured, along with the suction pressure in the mixer section of the return air plenum, by means of suitable high-temperature transducers. Position monitors on the air inlet damper and on the exhaust-stack discharge damper will complete the information into the PLC for controlling the thermal management system.

6. Cell Equalization

Because of variations in cell capacity and self-discharge rates, it is necessary to provide periodically an equalizing charge to normalize the differences that occur in cell capacity over repeated charge-discharge cycles. A cell equalization concept that was developed for ANL by TRW, Inc., for Li-FeS electric-vehicle batteries, has been adapted for the SES cell. The reference concept uses a small, constant-current power supply for each module, as shown in Fig. 19.

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Fig. 18. Temperature Sensor Locations in Module

Individual, electronically controlled bypass circuits (shunt regulators), shown in Fig. 20, will be used for each group of four cells mounted on a submodule shelf. A germanium power transistor with an emitter-collector saturation voltage (V_{ECO}) with a low value (0.2 V) has been indicated so that greater voltage drops can be tolerated in the long equalization leads from the cells (submodules) through the modules and onto the palletized bypass circuit assemblies.

The main converter provides the bulk charge of constant power until a group of four cells in parallel attains 1.8 V; charging will then be switched to the equalizing charger. The cell monitoring and bypass circuit (Fig. 20) comprises a three-state comparator to indicate cell voltages of >1.8 V, <1.0 V, and between 1.0 and 1.8 V. When the equalizing charger has been energized, the bypass circuit will be energized, thereby causing the charge circuit to bypass any group of cells through a power transistor in parallel whenever cell group voltage exceeds 1.8 V. Circuit IR drops will reduce the apparent cell voltage so that it will be necessary to periodically check the cell voltage by turning off the bypass power transistor (perhaps 10 ms off in a 10 s cycle).

7. Power Processing, Protection, and Controls

Power processing and associated components are to be housed in a central location between two groups of six battery modules as depicted in

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Fig. 19. Battery System Control and Protection

Fig. 1. A two-wall, prefabricated, metal-frame structure houses nonweathered components, which are arranged on modular, factory-assembled pallets. This structure is cost effective and well ventilated. Movable roof panels provide weatherproof shelter and gantry access for installation and replacement of pallets and/or components. Palletized modules provide for groups of components as follows: circuit protectors (circuit breakers and similar), equalization controls, battery controls, thermal measurement, thermal-management power-station communication, and instrumentation. A station service transformer will be included; in addition, space will be allocated for conversion equipment.

An elementary electric power diagram is shown in Fig. 21. Two modules will be connected in series to provide a nominal bus voltage of 3110 V for the converters. The midpoints of the series connections will be solidly

Fig. 20. Cell Monitoring and Equalization Circuit

grounded to limit the maximum voltage to ground to only 1555 V. This will reduce the amount of electrical insulation needed to isolate the cell supporting shelves of the submodules, as well as the electrical insulation of the various conductors and switchgear. The grounded midpoint will also reduce the common mode voltage to ground for the various instrumentation sensors and circuits. The midpoints will be grounded to a grounding grid, which will be buried beneath the structural slab on which the modules rest. This grounding grid will also be connected to the grounding grid of the local utility substation.

Busbar construction will feature cladding for the portion within the module and bus duct construction within the power processing area. A thermal barrier will be included in the busbars at the transition point, which will be a high-resistance plug of stainless steel. In accordance with the schematic diagram (Fig. 22), bus duct will be routed to circuit breakers, which will be floor-mounted on pallets; and the circuit breakers on pallet assemblies will be connected to the converters by means of an enclosed bus duct.

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Fig. 21. Electric Power Diagram

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Fig. 22. Power Processing Interconnections Diagram

III. TEST MODULE FOR BEST FACILITY

A conceptual design was developed for a truckable battery module for testing in the BEST facility.* The battery module is a scaled-down module

*Battery Energy Storage Test Facility. This facility, which is being constructed under joint sponsorship by the U.S. Department of Energy, the Electric Power Research Institute, and the Public Service Co. of New Jersey, will be used to test various types of batteries as load-leveling devices on an electric utility system.

design of the 100 MW-h facility described in Section II. Because of the bridge crane hook height, capacity limitations, and the maximum bus voltage of 1000 V at the BEST facility, the test module will have only half the capacity of the module conceived for full-scale utility applications. The BEST battery test module is shown in Fig. 23. Cell-equalizing charges will be

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Fig. 23. BEST Battery Module Installation

administered on a frequency determined by operating experience. The battery module includes 1728 cells with a capacity of 2.5 kW-h at the 5-h rate, arranged 48 cells to a submodule along with the necessary thermal management system. The 48 cells per submodule are arranged in groups of four cells in parallel, 12 such groups in series, to give a maximum submodule voltage of 21.6 V at the end of charge. The 36 submodules in the module are connected in series to give a maximum module voltage of 778 V at the end of charge. Charge equalization leads will be provided for each group of four cells in parallel.

The thermal management system includes six U-shaped tubes running longitudinally along the module between rows of submodules alongside the cells, for a total of 42 tubes. The ends of the tubes are connected to supply- and

return-manifold chambers or plenums, which are connected to a high-temperature blower located in the thermal control module. The supply manifold duct includes electric heaters and a mixing chamber for the introduction of ambient air into the system. Air is recirculated through the tubes by a blower to provide heating or cooling as required. When cooling is required, some of the recirculated air is exhausted to atmosphere and replaced by a cool mixture of hot and ambient air. During thermal equalization (standby), the ambient-air-inlet damper and stack-discharge damper are closed and the fans shut down. An electrical duct heater having a maximum rated capacity of 60 kW is provided for initial preheating. It is also derated at 7.5 kW to provide the required thermal equalization as needed.

The basic submodule design is schematically represented in Fig. 24 and its characteristics are listed in Table 9. The module will consist of

Fig. 24. BEST Battery Submodule

36 of these submodules (same as for 100 MW-h facility) and will be partitioned into six compartments, each accommodating six submodules. For this module, a single main frame will be used with special high-aspect covers. The submodules will be shipped separately and will be inserted or removed from the top. Salient physical and functional characteristics of fully assembled modules are given in Table 10.

Table 9. Characteristics of BEST Submodule

Height	3.51 m (11 ft 6 in.)
Width	1.8 m (5 ft 11 in.)
Thickness	0.275 m (10-13/16 in.)
Weight	2721 kg (3 ton)
Capacity	120 kW-h (nominal maximum)
Voltage	21.6 V dc (EOC)
Cell Quantity	48
Equalization Circuits	12

Table 10. Characteristics of BEST Module

Height	4.5 m (14 ft 9 in.)
Width	2.9 m (9.5 ft)
Length	15.2 m (45 ft)
Weight	21,315 kg (23.5 ton) without submodules
Capacity	4.32 MW-h (nominal)
Voltage	778 V dc (EOC)
Cell Quantity	1728
Submodule Quantity	36
Equalization Circuits	432

IV. COSTS OF 100 MW-h FACILITY*

A price estimate (1978 dollars) has been prepared for the nominal 100-MW-h SES facility based on the conceptual design described in Section II. For the estimate of this conceptual design, it was assumed that a prime contractor would be responsible for complete turnkey erection of the battery. As a consequence, individual costs have been marked up by 21% to cover 10% general overhead and 10% profit for the prime contractor. The cost estimates given below are based upon an apparent cost basis only, so accuracy is unpredictable.

The most probable costs for components of the 100 MW-h facility are presented in Table 11; these costs do not include the individual cells, the dc-to-ac converters, site preparation, land acquisition costs, or site-specific engineering costs. The total balance-of-plant (BOP) estimate, \$80/kW-h, was based on the construction of 25 batteries per year, and all nonrecurring costs such as development and engineering were assumed to have been written off against prior contracts. A further breakdown of the costs for the submodule is

*The cost analysis for the reference design was funded under contract by the Electric Power Research Inst.

Table 11. Cost Breakdown for BOP of 100 MW-h Facility

Item	Description	Material Cost, \$/kWh	Labor Cost, \$/kWh	Subtotal, \$/kWh	Contractor Overhead, \$/kWh	Contractor Profit, \$/kWh	Total Price, \$/kWh
1	Submodules:						
	Structural Steel	6.96	0.56	7.52	1.70	1.03	10.25
	Copper Components	13.96	1.13	15.09	3.41	2.07	20.57
	Ceramic Insulation	5.08	0.41	5.49	1.24	0.75	7.48
	Miscellaneous	0.98	0.08	1.06	0.24	0.14	1.44
2	Modules:						
	Structural Steel and Sheet Metal	3.80	2.86	6.66	0.67	0.73	8.06
	Thermal Control (Subcontract)	2.14	-	2.14	0.21	0.24	2.59
	Thermal Insulation	0.50	0.38	0.88	0.09	0.10	1.07
	Equalization and T/C Wiring and Connectors	8.85	1.36	10.20	1.02	1.12	12.34
3	Control and Instrumentation:						
	Site Controller	1.50	-	1.50	0.15	0.16	1.82
	Thermal Controllers	0.12	-	0.12	0.01	0.01	0.14
	Circuit Protectors	2.79	-	2.79	0.28	0.30	3.38
	Instrumentation (T/C)	0.36	-	0.36	0.04	0.04	0.44
	Equalization Pallets	1.60	0.54	2.14	0.21	0.24	2.59
4	Ancillary Equipment:						
	Shelter (Hanger)	0.12	0.23	0.35	0.03	0.04	0.42
	Gantry	0.97	-	0.97	0.10	0.11	1.17
	Special Tools and Rack	0.11	0.12	0.23	0.02	0.03	0.28
	Facility Lighting and Power	1.15	0.06	1.21	0.12	0.13	1.46
	Busducts	0.35	0.03	0.38	0.04	0.04	0.46
5	Field Installations:						
	Foundations	0.11	0.31	0.42	0.04	0.05	0.51
	Mechanical Assembly	-	1.53	1.53	0.15	0.17	1.85
	Electrical	-	0.67	0.69	0.07	0.08	0.83
	Startup	-	0.28	0.28	0.03	0.03	0.34
	Equalization Electrical	-	0.63	0.63	0.06	0.07	0.76
6	Total Plant	51.44	11.20	62.64	9.95	7.68	80.25

provided in Table 12. Cell material and fabrication costs are excluded entirely; however, the labor required for attachment of cell interconnectors and installation within submodule assemblies is included. It was assumed that the modules would be fabricated by an independent subcontractor on the basis of competitive bids. The estimated module cost was developed from a material and labor takeoff, which is listed in Table 13. Material costs were based on current catalog prices, and labor was priced using a \$22/h wrap-around rate. In addition, the thermal control modules (blowers) were estimated as part of the installed module costs. The total module price includes the prime contractor's markup of 21%.

The BOP estimate of \$80/kW-h is much too high for a cost-competitive SES system. Therefore, a further cost analysis was conducted to determine what are the primary contributing factors to this high cost. Table 14 shows the percentage material contribution of the various components given in Table 11, and Table 15 shows the cost contribution made to the BOP cost by thermal management, structural components, power components, and equalization. The data from these tables were used to determine what aspects of the conceptual design given in Section II can be modified to lower the BOP cost significantly. The alternatives proposed as a result of this analysis are presented in ANL-80-20.

Table 12. Cost Breakdown of Submodule

Material Item	Material Cost		Labor Cost		Subtotal		Contractor Overhead		Contractor Profit		Total Price	
	\$/Plant	\$/kWh	\$/Plant	\$/kWh	\$/Plant	\$/kWh	\$/Plant	\$/kWh	\$/Plant	\$/kWh	\$/Plant	\$/kWh
Structural Steel:												
Preformed Shapes	175,308	1.690	14,215	0.137	189,523	1.827	42,826	0.413	26,017	0.251	258,366	2.492
Sheets	21,201	0.204	1,719	0.016	22,920	0.221	5,179	0.050	3,146	0.030	31,245	0.301
Plates	74,477	0.718	6,039	0.058	80,516	0.776	18,194	0.175	11,053	0.106	109,763	1.058
Castings (Cr-Mo)	406,871	3.924	32,991	0.318	439,862	4.242	99,394	0.958	60,383	0.582	599,639	5.783
Castings (SST)	44,159	0.426	3,581	0.034	47,740	0.460	10,788	0.104	6,554	0.063	65,082	0.627
	<u>722,016</u>	<u>6.963</u>	<u>58,545</u>	<u>0.564</u>	<u>780,561</u>	<u>7.527</u>	<u>176,380</u>	<u>1.701</u>	<u>107,153</u>	<u>1.033</u>	<u>1,064,094</u>	<u>10.263</u>
Copper Components:												
Busbar (SST Clad)	777,719	7.501	63,061	0.608	840,780	8.109	189,987	1.832	115,419	1.113	1,146,186	11.005
Flex. Str. Wire (SST Clad)	151,430	1.460	12,279	0.118	163,709	1.579	36,993	0.357	22,473	0.216	223,175	2.152
CAWG Wire (SST Clad and Insul.)	158,505	1.528	12,852	0.124	171,357	1.652	38,721	0.373	23,523	0.226	223,601	2.253
Forgoings (SST Clad)	251,783	2.428	20,416	0.197	272,199	2.625	61,508	0.593	37,364	0.360	371,071	3.579
Stampings (SST Clad)	108,235	1.043	8,776	0.084	117,011	1.128	26,440	0.255	16,063	0.155	159,514	1.538
	<u>\$1,447,672</u>	<u>\$13.962</u>	<u>\$117,384</u>	<u>\$1.132</u>	<u>\$1,565,056</u>	<u>\$15.094</u>	<u>\$353,648</u>	<u>\$3.411</u>	<u>\$214,845</u>	<u>\$2.072</u>	<u>\$2,133,549</u>	<u>\$20.578</u>
Ceramic Insulation:												
Plates	51,750	0.499	4,196	0.040	55,946	0.539	12,642	0.122	7,680	0.074	75,268	0.735
Sheets	312,582	3.014	25,346	0.244	337,928	3.259	76,360	0.736	46,390	0.447	463,678	4.443
Blocks	106,852	1.030	8,664	0.083	115,516	1.114	26,103	0.251	15,858	0.153	157,477	1.519
Bushings and Washers	55,468	0.535	4,498	0.043	59,966	0.578	13,551	0.130	8,232	0.079	81,749	0.788
	<u>526,652</u>	<u>5.079</u>	<u>42,704</u>	<u>0.411</u>	<u>569,356</u>	<u>5.490</u>	<u>128,655</u>	<u>1.240</u>	<u>78,160</u>	<u>0.753</u>	<u>776,171</u>	<u>7.486</u>
Miscellaneous												
	<u>101,325</u>	<u>0.977</u>	<u>8,216</u>	<u>0.079</u>	<u>109,541</u>	<u>1.056</u>	<u>24,752</u>	<u>0.238</u>	<u>15,037</u>	<u>0.145</u>	<u>149,330</u>	<u>1.440</u>
	101,325	0.977	8,216	0.079	109,541	1.056	24,752	0.238	15,037	0.145	149,330	1.440
Total	<u>2,797,665</u>	<u>26.981</u>	<u>226,849</u>	<u>2.186</u>	<u>3,024,514</u>	<u>29.167</u>	<u>683,435</u>	<u>6.591</u>	<u>415,195</u>	<u>4.004</u>	<u>4,123,144</u>	<u>39.768</u>

Table 13. Cost Breakdown of Module

Item	Material Cost		Labor Cost		Subtotal (\$/kWh)		Contractor Overhead		Contractor Profit		Total Price	
	\$/Plant	\$/kWh	\$/Plant	\$/kWh	\$/Plant	\$/kWh	\$/Plant	\$/kWh	\$/Plant	\$/kWh	\$/Plant	\$/kWh
Structural Steel:												
2-1/4 Cr - 1 Mo Pipe, Plate												
Bar	169,044	1.63	208,824	2.02	377,868	3.65	37,786	0.37	41,565	0.40	457,220	4.42
Carbon Steel Tubing	72,576	0.70	53,064	0.51	125,640	1.21	12,564	0.12	13,820	0.13	152,024	1.46
Sheet Metal and Misc.	152,616	1.47	34,584	0.33	187,200	1.80	18,720	0.18	20,592	0.20	226,512	2.18
Equalization Components:												
Insulated No. 6 AWG SS												
Clad Wire	792,521	7.64	118,800	1.14	911,321	8.78	91,132	0.88	100,245	0.97	1,102,698	10.62
Connectors	110,143	1.06	17,630	0.17	127,773	1.23	12,777	0.12	14,055	0.14	154,605	1.49
Thermocouple Wiring	14,256	0.14	5,280	0.05	19,536	0.19	1,954	0.02	2,149	0.02	23,638	0.23
Thermal Insulation:												
No. 8 Fiberglass Insulation	51,984	0.50	39,854	0.38	91,848	0.88	9,185	0.09	10,103	0.10	111,136	1.07
Thermal Control Modules:												
Blowers & Motor	66,300	0.64	*	-	66,300	0.64	6,630	0.06	7,293	0.07	80,223	0.77
Heaters - 60 kW	13,200	0.13	*	-	13,200	0.13	1,320	0.01	1,452	0.01	15,972	0.16
Ducting	48,000	0.46	*	-	48,000	0.46	4,800	0.05	5,280	0.05	58,080	0.56
Insulation	21,600	0.21	*	-	21,600	0.21	2,160	0.02	2,376	0.02	26,136	0.25
Structural Enclosure	73,200	0.70	*	-	73,200	0.70	7,320	0.07	8,052	0.08	88,572	0.85

*Subcontract

Table 14. Percentage Material Contribution of BOP Components

	Item %	% System
<u>Submodule</u>	-	49.5
Copper Components	51.8	25.6
Structural Steel	25.8	12.8
Ceramic Insulation	18.8	9.3
<u>Module</u>	-	30.0
Equalization & T/C Wiring	51.3	15.4
Structures	33.5	10.1
Thermal Insulation and Control	15.2	4.5
<u>Control and Instrumentation</u>	-	10.4
Electrical	62.1	6.5
Equalization	30.9	3.2
Thermal	7.0	-
<u>Field Installations</u>	-	5.4
Mechanical Assembly and Foundations	55.0	2.9
Electrical	37.0	2.0
Startup	8.0	-
<u>Ancillary Equipment</u>	-	4.7
Facility Electrical	38.5	1.8
Gantry	30.8	1.5
Miscellaneous	30.7	-

Table 15. Functional Cost Contributions to BOP Component Costs

Item	Description	\$ / kWh	%	\$ / kWh			
				TH	ST	P	EQ
1	Submodules:						
	Structural Steel	10.25	12.8		10.25		
	Copper Components	20.57	25.6			18.32	2.25
	Ceramic Insulation	7.48	9.3			6.31	1.17
	Miscellaneous	1.44	1.8	0.24	0.2	0.7	0.3
	ST	39.74	49.5				
2	Modules:						
	Structural Steel and Sheet Metal	8.06	10.1	2.00	6.06		
	Thermal Control (Subcontract)	2.59	3.2	2.59			
	Thermal Insulation	1.07	1.3	1.07			
	Equalization and T/C Wiring and Connectors	12.34	15.4	0.23			12.11
	ST	24.06	30.0				
3	Control and Instrumentation:						
	Site Controller	1.82	2.3			1.82	
	Thermal Controllers	0.14	0.2	0.14			
	Circuit Protectors	3.38	4.2			3.38	
	Instrumentation (T/C)	0.44	0.5	0.44			
	Equalization Pallets	2.59	3.2				2.59
	ST	8.37	10.4				
4	Ancillary Equipment:						
	Shelter (Hanger)	0.42	0.5		0.42		
	Gantry	1.17	1.5		1.17		
	Special Tools and Rack	0.28	0.3		0.28		
	Facility Lighting and Power	1.46	1.8	0.41		1.05	
	Busducts	0.46	0.6			0.46	
	ST	3.79	4.7				
5	Field Installations:						
	Foundations	0.51	0.6		0.51		
	Mechanical Assembly	1.85	2.3	0.70	1.15		
	Electrical	0.83	1.0			0.83	
	Startup	0.34	0.4	0.34			
	Equalization Electrical	0.76	1.0				0.76
	ST	4.29	5.4				
6	Total Plant	80.25	100.4	8.2	20.0	32.8	19.2

TH = Thermal ST = Structural P = Power Components EQ = Equalization

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