DESIGN AND COST STUDY FOR STATE-OF-THE-ART LEAD ACID LOAD LEVELING AND PEAKING BATTERIES

EPRI EM-375
(Research Project 419-1)

Final Report

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NOTICE

ABSTRACT

This design and cost study has applied state-of-the-art tubular positive lead-acid battery technology to estimate the selling prices for one 2500 cycle 10 MW 100 MWhr load leveling battery and two 2000 cycle 20 MW peaking batteries delivering 60- and 100 MWhr. Accessories for the batteries judged vital to meeting the EPRI performance and life requirements are described and priced. These prices, including transportation and installation, are respectively \$62, \$65, and \$73/kWhr for the first battery purchased, but are reduced by salvage-reuse credits to \$29, \$30, and \$33/kWhr for the second battery purchased. Amortized in the price is a battery manufacturing plant investment of 14.4 million for a three-shift operation producing 1000 MWhr/yr.

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Section 1

EXECUTIVE SUMMARY

ESB Incorporated was awarded EPRI Contract RP419-1 to perform a design and cost study of lead-acid batteries for utility load leveling and peak power applications. Three batteries were designed to meet specified power and energy requirements -- 10 MW 100 MWhr, 20 MW 60 MWhr and 20 MW 100 MWhr -- and the life requirements of 2500 cycles for the 10 MW unit and 2000 cycles for the 20 MW units.

Prices for each of the three batteries were estimated for a production rate of 1000 MWhr per year. Accessories, recommended to assure conformance to EPRI battery performance and life specifications, were also designed and priced. Total battery prices including transportation (500 miles), and installation of batteries and accessories are summarized below:

	Installed Price*, $/kWhr		
Discharge Time (Rated), Hrs	3	5	10
Power (Rated), MW	20	20	10
Energy Delivered (Rated), MWhr	60	100	100
Battery Cells	55.65	51.03	48.77
Shipping	2.52	2.33	1.88
Installation	0.87	0.76	.73
Cooling (With Back-Up Equipment)	9.92	7.88	7.65
Air-Lift Stirrers	0.64	0.54	.50
Monitoring	1.65	1.10	1.05
Connectors	1.73	1.64	1.57
Total Selling Price	72.98	65.28	62.15

* Lead at 20¢/lb; antimony at $2.00/lb.

For this lead cost and rated cycle life the stored energy price for the first battery purchase is 3.6 and 3.3 cents per kWhr per cycle for the 3- and 5-hour batteries and 2.5 cents for the longer cycle life 10-hour battery. ESB anticipates greater cycle life than rated cycles giving promise of a further reduction in energy price per cycle.

When lead cost is increased from 20 to 25 to 30 cents per pound, the cell prices (and battery prices) increase $4.45 - $4.95/kWhr per 5 cent increase in lead cost.

Battery cell prices were also estimated for production rates of 500 and 4000 MWhr/year. For the case of 20 cents per pound lead cell prices change with production rate as follows:

Battery Type		Cell Price, $/kWhr		
Power MW	Energy MWhr	500 MWhr/yr	1000 MWhr/yr	4000 MWhr/yr
20	60	56.26	55.65	52.87
20	100	51.60	51.03	48.49
10	100	49.31	48.77	46.33

A 10 percent increment in the cost of material or the cost of purchased parts (cell jar and cover, the major item) causes a 4 percent increase in the cell price -- almost twice as much as the increase in cell price from a similar 10 percent increment on any other component in the cell price structure, i.e., labor, overhead, G & A and profit.

Salvage and reuse credits were estimated for plate lead, antimony, the cell jar and cover and hoops assembly, and terminal copper inserts. The total credits which can be applied to the purchase of a second battery and the second battery cell prices were found to be (for the case of 20 cent lead and 1000 MWhr/yr):

Battery Type		Cell Prices, $/kWhr		
Power MW	Energy MWhr	First Battery	Salvage-Reuse Credit	Second Battery
20	60	55.65	22.85	32.80
20	100	51.03	20.96	30.07
10	100	48.77	20.06	28.71

Cells of the three batteries contain ESB tubular positives and pasted negative plates with a long life microporous separator system. Positive spine alloys are lead-antimony with traces of arsenic for increased cycle life. Negative grid alloys are lead-calcium. The three-hour cell has 43 plates while the 5- and 10-hour cells each have 45 plates. Negative to positive active material ratios are 0.8 by weight. Overall cell dimensions are 56.5" x 21.8" x 21.8" (143.5 cm x 55.2 cm x 55.2 cm) for the 5- and 10-hour cells; the 3-hour cell length is 0.8" (2.0 cm) less.

Detailed weight analyses are reported for each cell. Cell discharge capacities are projected for the 1, 3, 5, 7, 10 and 13-hour rates; however, rated capacities are 8845 Ahr (3-hr), 9756 Ahr (5-hr) and 10,000 Ahr (10-hr) respectively for the three cell types.

EPRI guidelines for a constant power 7-hour charge with a 2-3 hour taper have been met by a recommended modified constant voltage charge (2.32 volts per cell) with the initial current limited to 1100 (or 1200) amperes per cell and constant for seven hours. In a final 2-hour taper the current falls exponentially to a finishing current of 400 amperes. An input of 103% of the previous output is recommended.

ESB proposes to ship cells completely assembled, but dry and uncharged, to the site; unpackage and inspect; install, formation charge with low cost utility power, and run through one complete cycle. Cell designs provide a low cost self-supporting cell jar-cover-hoop assembly to simplify movement of cells without damage to cell or plates. ESB engineers will supervise the installation of the battery and the accessory systems for cooling the cells, electrolyte agitation, and monitoring of cells electrically for voltage, capacity and temperature.

Battery array designs were investigated on single and multitier levels. ESB selected close packed single level arrays. These array designs and resulting energy density are summarized below:

Battery Type		Cells	Cells	Strings	Building	Energy Density
Power MW	Energy MWhr	per Battery	per String	in Parallel	Room Area ft^2	of Array $kWhr/ft^2$
20	60	3756	939	4	22,600	2.65
20	100	5484	914	6	32,600	3.07
10	100	5250	525	10	29,190	3.43

At an estimated building cost of $36/ft the battery buildings would range in cost from 0.8 to 1.2 million dollars.

The need for cooling the batteries has been substantiated by analyses of cell temperature rise during daily cycles and a weekend equalization charge. Water-cooling was selected as the best method of cooling cells equally independent of location in the array. See Appendix A. The cooling system adds $8 - $10/kWhr to the battery system price but this investment is returned as longer operating life.

A maintenance program for the battery and accessory systems includes a semiannual and an annual inspection plus routine watering of cells. The maintenance cost to the utility is estimated to be 0.2 mills per kWhr of delivered energy during a year of operation.

Details of battery design, cost, operation and safety precautions are given in the sections to follow.

Section 2

PROJECT OBJECTIVES AND GUIDELINES

PHASE I OBJECTIVES AND MAJOR ACCOMPLISHMENTS

ESB Incorporated was awarded EPRI Contract 419-1 to perform a design and cost study on a 1000 VDC, 10 MW, 100 MWhr, 10-hour rate lead-acid load leveling battery to deliver 2500 rated capacity discharge cycles in 10 years of service life.

Initial battery performance objectives were to meet any of the following options:

Performance Objective	Option 1	 2	 3	 4
Discharge Rate, hrs	4	7	10	13
Charge Rate, hrs	5	7	10	
Cell Life, years	5	10	20	
Energy Efficiency, %	65	75	85	

ESB was directed to evaluate the tubular positive cell design vs. pasted positive plate cell design and to determine which approach offered the best chance of meeting the design criteria at minimum cost. ESB's choice was the tubular positive approach based on the cost saving in active material, excellent performance at all specified rates, and the cycle life history of similar cells in submarine service.

ESB designed a 45 plate cell to deliver 12,500 Ahr at an average voltage of 1.905 volts per cell (10,000 Ahr rated capacity) at the 10-hour rate. Engineering drawings were prepared and used to obtain initial estimates of cell manufacturing costs.

A 1000 VDC, 10 MW, 100 MWhr battery was then designed and its performance projected for discharge rates of 1, 3, 5, 7, 10 and 13 hours and charge rates of 5, 7, and 10 hours. This battery contained 5250 cells in an array of 10 parallel strings -- each string having 525 cells in series.

Accessory systems were also designed and costed. These systems performed the following functions:

- Electrical monitoring of individual cell voltages, string current, capacity and the temperature of pilot cells.
- Stirring of cell electrolyte with an air-lift pump in each cell.
- Water-cooling of each cell.
- Exhausting of hydrogen and noxious gases from the battery room.

Reclaim values of the lead, antimony and copper in the battery cells were estimated. Reuse rates and values were also estimated for the cell jars, covers, supporting hoop assembly and certain other cell parts and applied as a credit to the cell price of the second battery.

The impact of this new market for lead and antimony was evaluated in comparison to the present U. S. production rate and world reserves. See Appendix B.

These early design studies and battery prices were reported by Dr. D. T. Ferrell, Jr. at the Palo Alto Lead-Acid Workshop, November 18-19, 1975 and in the Phase I Semi-annual Report issued in December 1975(1).

Phase II contract guidelines were changed to increase emphasis on 20 MW 3-hour and 5-hour batteries to operate in the voltage range 1500 - 2000 VDC at minimum cost and battery footprint. Cycle life was decreased to 2000 minimum cycles in 10 years at 200 cycles per year. Charge time was set at seven hours constant power followed by a 2 - 3 hour taper charge to a manufacturer specified finishing current. ESB was also requested to provide design, performance and cost information on each battery to the Bechtel Corporation for their total system cost studies.

To stay within the funding limitations of the contract work on assessing safety and environmental problems, cell arrangement and system size optimization and the sensitivity analysis was deemphasized.

Cost reduction was given a very high priority in the ESB approach to Phase II -- particularly in cell design and battery footprint. Phase I conclusions pointed out that major savings could only come from:

- Reduction in active materials and inactive materials not needed in 3-hr or 5-hr batteries;
- Increase in utilization of active materials;

- Increase in electrolyte specific gravity;
- Lower cost cell jar and cover;
- Elimination of unnecessary safety factors in design.

High building costs (\$30-\$35/ft^2) also suggested savings could be made from a smaller battery footprint. Work was therefore directed at cell arrays having denser cell packing, less aisle space and multitier racking of cells.

The Phase II design and cost studies, cell and battery performance projections, manufacturing processes descriptions, capital investment estimates and maintenance and operating-safety practices are summarized in the following sections of this report. At opportune times the final lower cost 10 MW 100 MWhr battery is compared to the 20 MW 60 and 100 MWhr batteries in terms of performance and price. Battery prices in each case contain in the overhead component of direct costs amortization for a manufacturing plant required to manufacture 1000 MWhr per year and a profit to assure the minimum return on investment required for the load leveling market venture.

Section 3

CELL, BATTERY DESIGNS AND PERFORMANCE PROJECTIONS

BATTERY DESIGNS AND RATIONALE

ESB reviewed past experience with large batteries -- submarine and telephone standby -- and concluded that the performance and economic requirements and potential production quantities could be best met by tubular-positive plate cells manufactured under mass production methods equivalent to automotive battery production. ESB supplied tubular positive plate batteries for U. S. Navy submarines requiring excellent cycle and service life. One of the last life tests on ESB tubular-positive cells was stopped when the Navy Material laboratory was closed in 1962. At that point in time three cells were about 11 years old and had delivered 3400 lab cycles equivalent to 1850 Navy cycles -- a finite charge capacity -- and still retained 95% of rated capacity(2). These cells were based on 1950 technology. Newer alloys for positive plate spines now promise a 50-100% increase in cycle life to ultimate failure by positive grid corrosion.

Three batteries were designed and costed in detail. Each battery has cells with the following common design features:

- Tubular-positive plates having a lead-antimony spine alloy with an arsenic additive and machine pasted negative plates having lead-calcium alloy negative grids;
- Electrolyte stirred by a compressed air system and air-lift pumps in each cell;
- Long life microporous separators;
- Free standing, self-supported plastic cell jar and cover;
- Visual float type electrolyte level monitoring devices;
- Alumina flame arrestors in each cell vent;
- Two (2) positive and two (2) negative cell terminals, each having water-cooled straps and copper inserts to reduce IR losses;
- Lead plated copper intercell connectors -- 2 each -- bolted with two through bolts and nuts on each terminal.

Table 3-1 summarizes the major battery design features and performance projections for the three batteries: the Phase I 10-hour 100 MWhr and the two Phase II 3-hour and 5-hour 20 MW (60 and 100 MWhr) units.

Each battery array of cells in series in strings and strings in parallel will be equipped with an electrical monitoring system, an electrolyte stirring system, and a water-cooling system. The battery room would in addition require a ventilation system. ESB is convinced that under a routine cycling regime of 5 cycles per week (3- or 5-hr discharges and the 7-9 hour charge) Monday through Friday followed by topping-off charges on Saturday and Sunday, each of these systems will be needed to obtain maximum battery life and minimum cost per kWhr per cycle delivered. Each of these accessory systems will be described in more detail in Section 6.

Figures 3-1 and 3-2 show a typical layout for the 3-hr and 5-hr 20 MW batteries. Cells are close packed in series strings with minimum aisles between strings. Obvious advantages are reduction in I^2Rt energy loss in intercell connections, reduction in building floor space and associated building cost, and reduction in accessory system parts cost (cooling system plastic pipe and electronic monitoring system wiring). A key disadvantage is the difficulty of maintenance of cells in central rows. See Section 7, Operation and Maintenance.

Cell Design and Projected Discharge Characteristics

Each tubular positive plate cell has been designed for manufacture using state-of-the-art methods currently in practice, or demonstrated in earlier production contracts. Figure 3-3 is the VLL45 cell assembly used in both the 10 MW 100 MWhr and the 20 MW 100 MWhr batteries. The VLL43 cell assembly designed for the 20 MW 60 MWhr battery is identical except for length which is reduced 0.85 inches.

In the Phase II development of these designs, cost reduction efforts were concentrated on the quantity of active and grid materials; cell jar, cover and reinforcing hoops; strap and terminal design; and electrolyte composition. The prime goal was maximizing energy output per unit cost during cell service life.

Ratios of negative active to positive active material were reduced to minimum values. Grid alloys and grid weights in the positive plates were set at compositions and weights to provide a reliable delivery of the specified energy (60 or 100 MWhr) on the 2000th cycle. Positive active material reserves were based on operating at

Table 3-1

Battery Design and Rated vs. Actual Performance

Power Rating	MW	10	20	20
Energy Output				
Rated	MWhr	100	60	100
Actual	MWhr	125	68	120
Discharge Time (Rated)	Hrs	10	3	5
Number of Cells	Each	5250	3756	5484
Number of Strings		10	4	6
Cells in Series Each String		525	939	914
Operating Voltage	Volts			
Equalizing Charge Cut-off		1391	2488	2422
Daily Cycle " "		1234	2207	2148
Full Charge Open Circuit	Volts	1100	1995	1942
Initial Discharge Voltage	Volts	1058	1794	1801
Average Discharge Voltage	Volts	1000	1696	1708
Discharge Cut-off	Volts	885	1502	1502
Actual Capacity	kAhr	125	40	70
Discharge Current	kA	12.5	13.3	14.0
Power, Actual	MW	12.5	22.7	24.0
Cell Footprint	ft^2	2.67	2.54	2.67
Cell Displacement Area	ft^2	3.28	3.13	3.28
Battery Displacement Area	ft^2	17,220	11,756	17,988
Charge Time, Less 2-Hr Taper	Hrs	7	7	7
Turnaround Energy Efficiency	%	82	81	85
Rated Cycle Life	Each	2500	2000	2000
Life (250 cycles/yr)	Years	10	8	8

Cells in Battery	3756
Cells in Section	939
No. Sections*	4

Safety aisle between half sections.

Cells are self-supporting standing on concrete floor.

One-half inch space between cells.

Area Analysis - Wall-to-Wall

Cells only	11,756 ft^2
Aisles	11,039 ft^2
Total	22,795 ft^2

Overhead crane spans each 2 sections

Energy/Unit Area	KWhr/ft^2
Building	2.6
Cells only	5.1

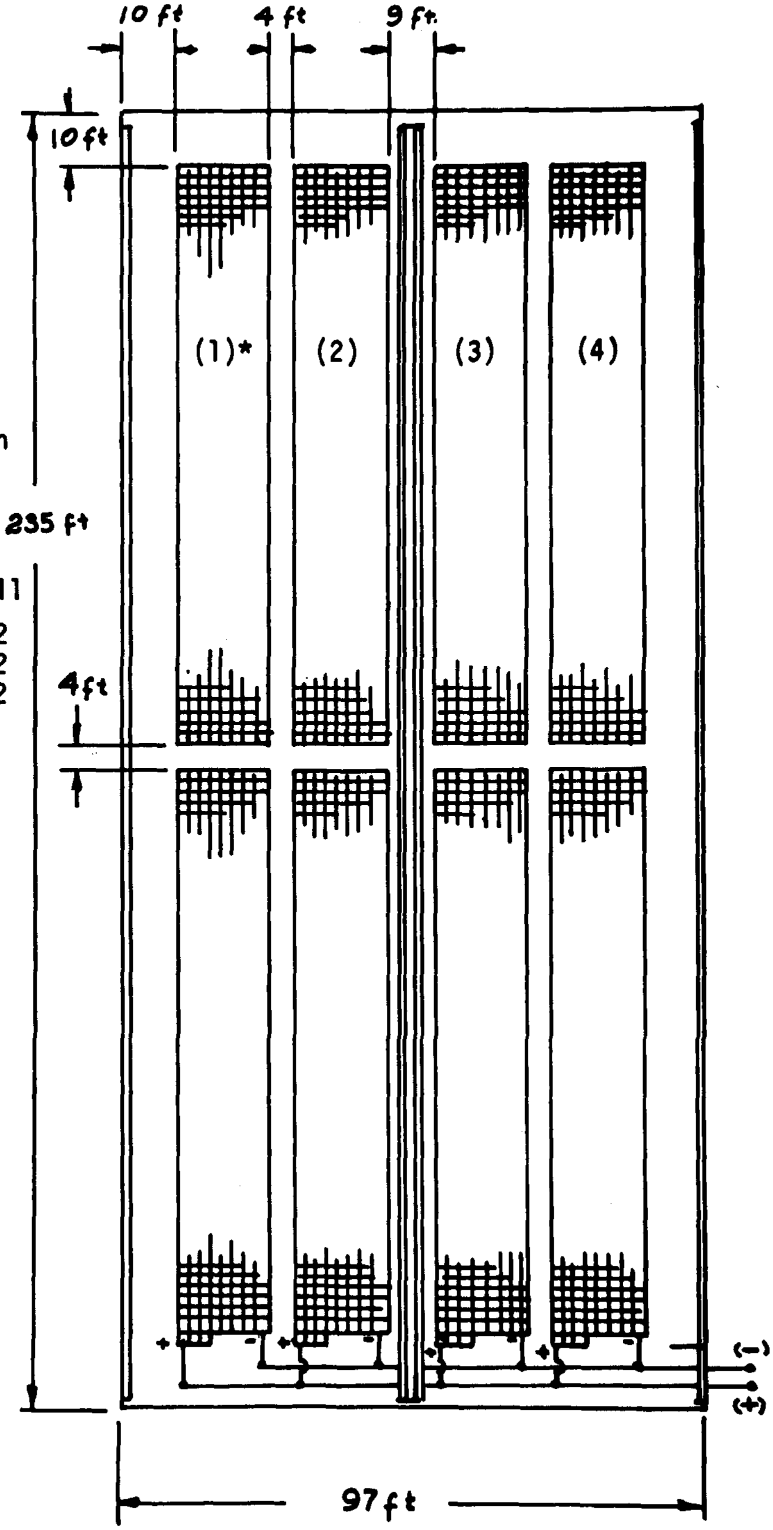


Figure 3-1. Layout of 20 MW 60 MWhr Lead-Acid Battery.

Cells in Battery	5484
Cells in Section	914
No. Sections	6

Safety aisle between half sections.

Cells are self supporting standing on concrete floor.

One-half inch space between cells.

Area Analysis - Wall-to-Wall

	Ft^2
Cells only	17,988
Aisles	13,502
Total	31,490

Overhead crane spans each 3 sections.

Energy/Unit Area

	KWhr/ft^2
Building	3.2
Cell only	5.6

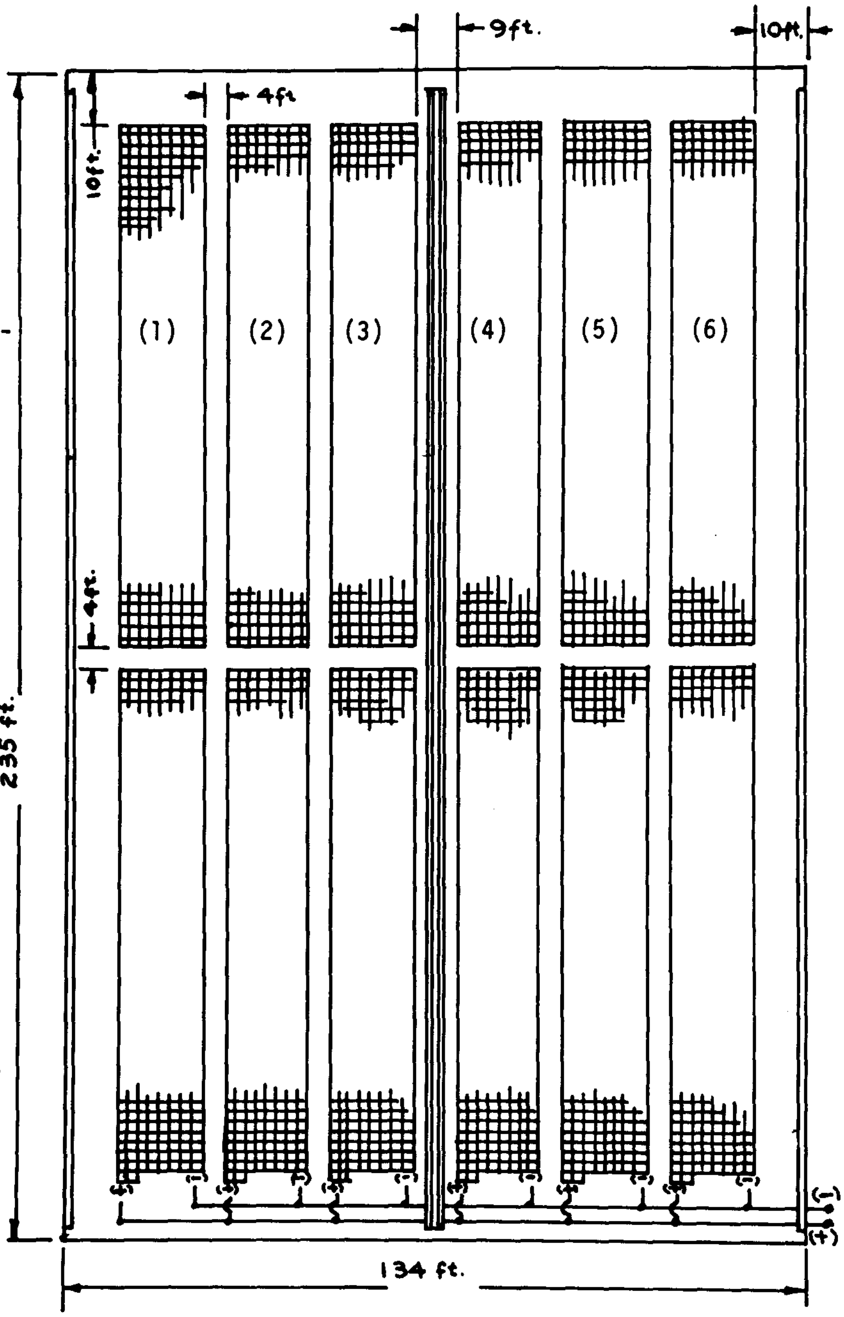


Figure 3-2. Layout of 20 MW 100 MWhr Lead-Acid Battery.

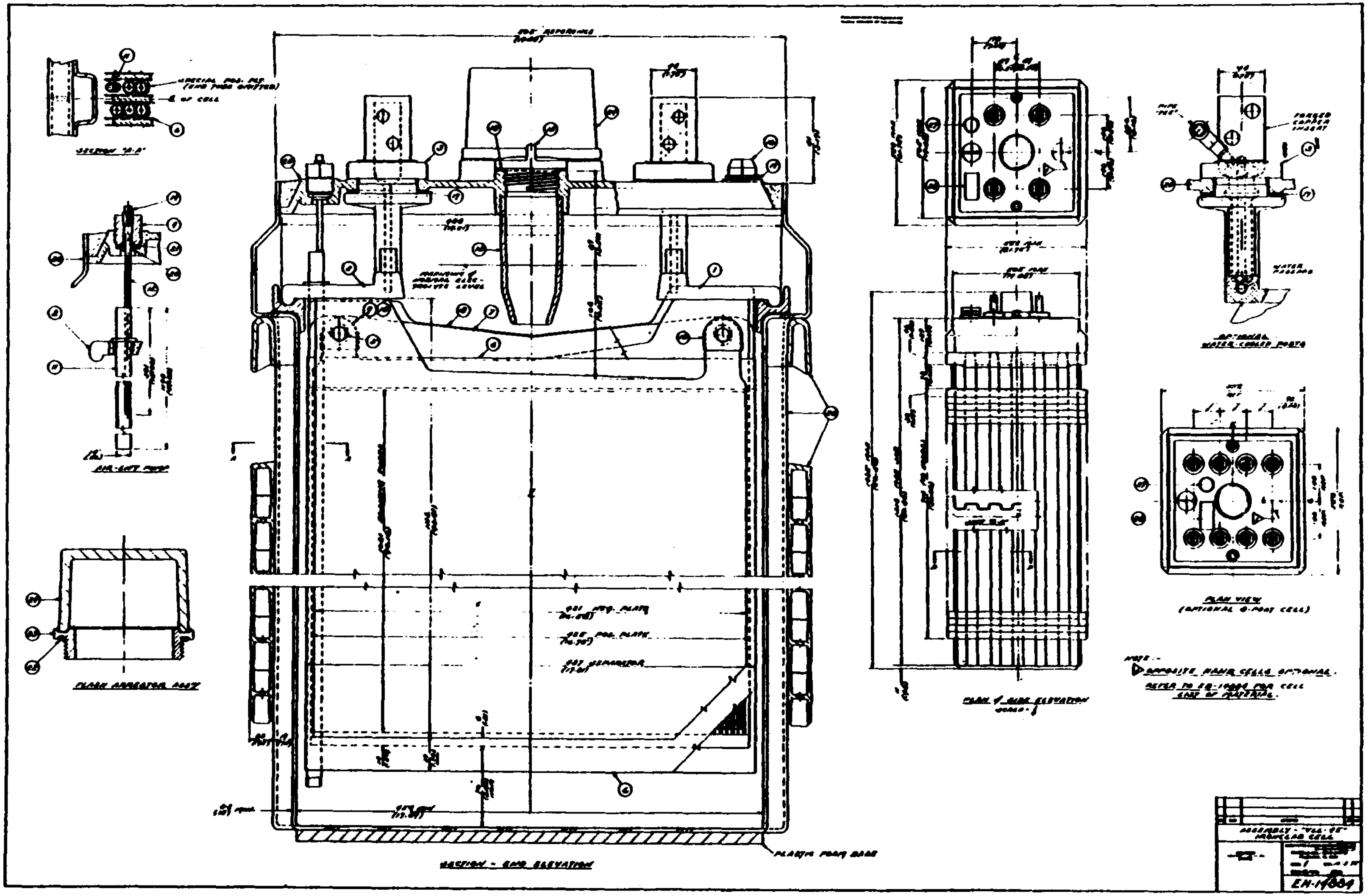


FIGURE 3-3. ASSEMBLY "VLL-45" IRONCLAD® CELL

90% and 85% depth of actual energy output when delivering the 60 MWhr and 100 MWhr (3-hr and 5-hr) discharge cycles respectively. Plate complements selected for the cells are as follows:

- VLL45 Cell: 22 positives, 16.8 x 41.8 inches; 23 negatives 16.6 x 41.8 inches;
- VLL43 Cell: 21 positives and 22 negatives with the same dimensions.

Microporous Daramic® sheet separators (17.2 x 42.6 in.) were specified for all cells. Microporous rubber separators would be preferred but U. S. suppliers cannot now manufacture sheets greater than 13.5 inches in width.

Originally 1.250 s.g. electrolyte was selected for the 10 year 2500 cycle 100 MWhr battery; however, by increasing to 1.280 s.g. capacity was increased 7.7% while reducing life only 4.5% in both 20 MW battery cells.

A substantial cost reduction in cell jars was made possible by a material change. The new jars will be lightweight low-cost plastic with a combination of deep vertical corrugations to support the weight of the plates and injection molded hollow bands to support hydrostatic and plate expansion forces.

The cell cover will be injection molded and has a seal design which will permit removal of the cover and reuse of the cell jar and cover through at least two battery lifetimes. This cover design provides for the alumina flame arrestor assembly, the electrolyte fill port, the air-lift pump assembly, a cell identification plate, and two each positive and negative terminal to cover seals.

Table 3-2 is a weight analysis for the three cells in their final study design. Energy densities of 9-11 watt-hour per pound are projected.

Figure 3-4 is a photograph of a typical Exide® cell with the projected design features.

Cell Performance Projections

Based on ESB Exide Power Systems Division experience with tubular positive plate submarine batteries and the popular industrial truck motive power battery line, performance projections were made for the high specific gravity VLL43 and VLL45 cells for the 3-hour and 5-hour 20 MW batteries and for the low specific gravity

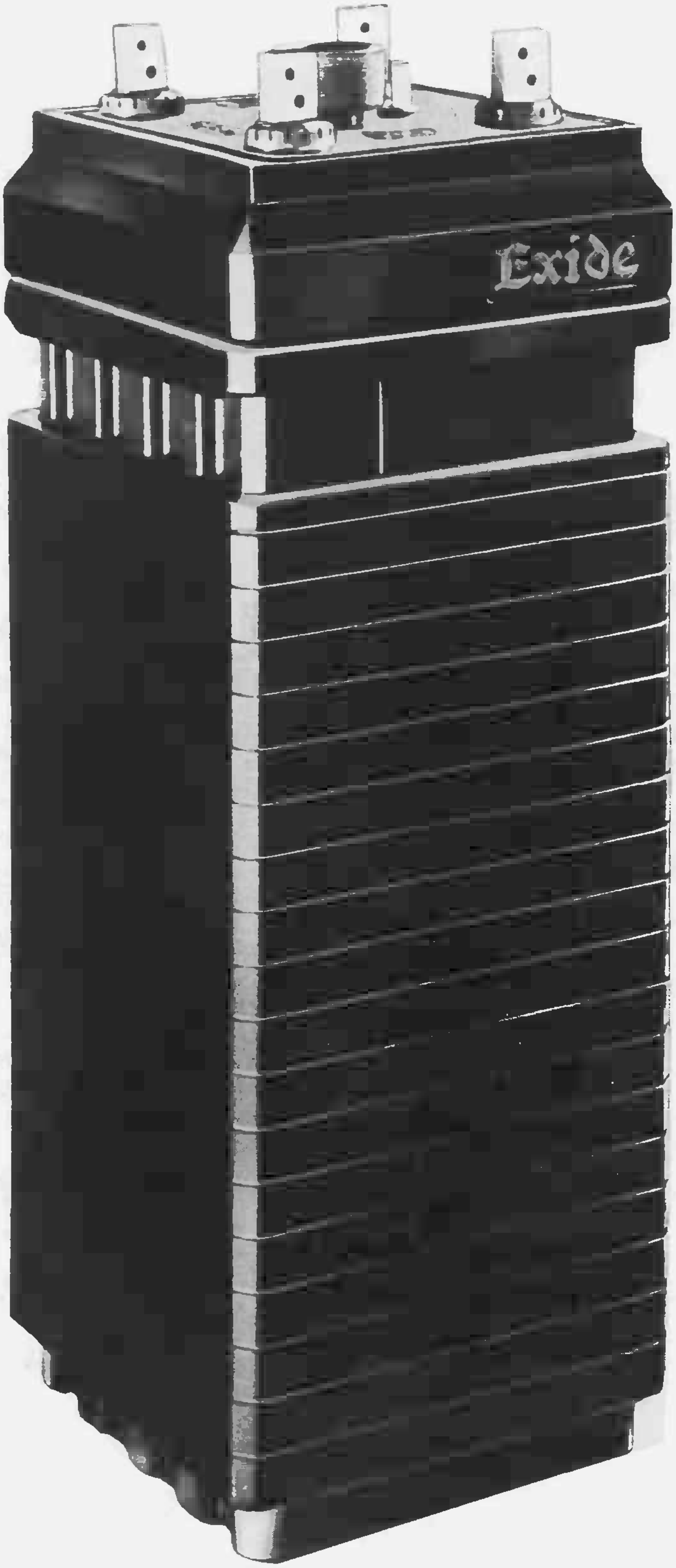
Table 3-2

Cell Type and Weight Analysis - Pounds

Battery	100 MWhr	100 MWhr	60 MWhr
Application	10 MW	20 MW	20 MW
Cell Type	VLL45(LSG)	VLL45(HSG)	VLL43(HSG)
Positive Plates			
Grid Pb	358	358	336
Grid Sb	22.8	22.8	21.5
Active Material	423	423	390
Negative Plates			
Grid Pb	217	217	208
Active Material	338	338	312
Terminal Posts	(2x2)*	(2x2)	(2x2)
Pb	62.5	62.5	59.7
Insert Cu	10	10	10
Electrolyte (s.g.)	503 (1.250)	515 (1.280)	495 (1.280)
Cell Jar, Hoops, Cover	76	76	74
Miscellaneous	80	80	80
Total Estimated Weight - lbs	2090	2102	1986
Rating Hrs	10	5	3
Energy Output kWhr	23.81	21.9	18.3
Energy Density, Whr/lb	11.4	10.4	9.2
Capacity, kAhr	12.5	11.7	10.0

* Cell with 1-hour rate spinning reserve capability would require eight (4x2) posts doubling this weight.

Figure 3-4. Photograph of Typical Exide® Load Leveling Cell



VLL45 cell for the 10-hour 10 MW battery. Table 3-3 summarizes 1, 3, 5, 7, 10, and 13 hour rate discharge currents, capacities, initial, average, and final cell voltages, and output power and energy for the VLL45 high specific gravity cell. Table 3-4 provides similar data for the VLL43 high specific gravity cell. Table 3-5 gives similar projections for the low specific gravity 2500 cycle VLL45 cell. The voltages include a voltage drop for the intercell connectors in a series string estimated for the respective design discharge rates.

Rated cell capacities, calculated as the cell capacity delivered on a battery specification discharge in percent of the actual capacities expected at the design rates, are as follows:

Battery Power MW	Battery Energy MWhr	Cell Type	Design Rate Hrs	Rated Capacity, % Design Target	Rated Capacity, % Design Achieved	Rated Capacity, % 10-Hr Rate
20	60	VLL43 HSG	3	90	88	69
20	100	VLL45 HSG	5	85	83	72
10	100	VLL45 LSG	10	80	80	80

These safety factors are considered adequate to assure rated battery energy being delivered on the 2000th cycle for the 20 MW batteries and on the 2500th cycle for the 10 MW battery.

Battery Performance Projections

Using the above cell data, battery discharge performance was projected at each of the tabulated rates for the battery arrays chosen for the final designs and specified below:

Rated Battery Power MW	Rated Battery Energy MWhr	Cells in Series String	Strings in Parallel	Total Cells in Battery	Rated Discharge Capacity - kAhr String	Rated Discharge Capacity - kAhr Battery
20	60	939	4	3756	8.85	35.4
20	100	914	6	5484	9.76	58.6
10	100	525	10	5250	10.0	100

Figures 3-5 and 3-6 are the projected battery discharge curves of battery voltage vs. discharge capacity at the 1, 3, 5, 7, and 10-hour rates at 85°F initial electrolyte temperature after a full charge. One-hour rate discharge curves are shown as an optional spinning reserve capability for batteries having cells with eight rather than four terminals each cell and eight rather than four intercell connectors. This capability was deleted as a cost reduction step in the battery designs costed in Section 4.

Table 3-3

VLL45 Cell Performance Projection
(20 MW, 100 MWhr Battery Cell)

Discharge Rate	Current	Capacity	Cell Voltage Initial	Cell Voltage Average	Cell Voltage Final	Output Energy	Power
Hrs	amperes	Ahr	volts	volts	volts	kWhr	kW
1 (3)	7,700	7,700	1.730	1.625	1.431	12.51	12.5
3	3,500	10,500	1.912	1.808	1.600	18.98	6.3
5 (4)	2,342	11,712	1.970	1.869	1.643	21.89	4.3
7	1,820	12,740	1.987	1.882	1.662	23.98	3.4
10	1,347	13,465	2.016	1.905	1.688	25.65	2.6
13	1,099	14,280	2.040	1.920	1.740	27.42	2.1

Notes: (1) Electrolyte 1.280 s.g.

(2) 22 positives; 23 negative plates.

(3) One hour spinning reserve available in 8-terminal cell design.

(4) Design discharge rate 5 hrs. Design cycle life 2000 plus cycles.

(5) Rated capacity at 5-hr rate:

$$\text{Rated capacity, Ahr} = \frac{100{,}000 \text{ kWhr}}{5484 \text{ cells} \times 1.869 \text{ V/cell}} = 9{,}756 \text{ Ahr}$$

$$= 83\% \text{ actual 5-hr rate capacity}$$

$$= 72\% \text{ actual 10-hr rate capacity}$$

Table 3-4

VLL43 Cell Performance Projection
(20 MW 60 MWhr Battery Cell)

Discharge Rate	Current	Capacity	Cell Voltage Initial	Cell Voltage Average	Cell Voltage Final	Output Energy	Power
hrs	amperes	Ahrs	volts	volts	volts	kWhr	kW
1 (1)	7,350	7,350	1.730	1.625	1.431	11.94	11.9
3 (2)	3,341	10,023	1.911	1.806	1.600	18.10	6.0
5	2,236	11,180	1.970	1.869	1.643	20.90	4.1
7	1,737	12,161	1.987	1.882	1.662	22.89	3.3
10	1,285	12,853	2.016	1.905	1.688	24.49	2.4
13	1,049	13,631	2.040	1.920	1.740	26.17	2.0

Notes:

(1) One-hour spinning reserve available on cell with 8-terminals only.

(2) Design discharge rate 3 hrs. Design cycle life 2000 plus cycles.

(3) Rated capacity at 3-hr rate:

$$\text{Rated cell capacity, Ahr} = \frac{60{,}000\ \text{kWhr}}{3756\ \text{cells} \times 1.806\ \text{V/cell}} = 8{,}845\ \text{Ahr}$$

$$= 88\%\ \text{actual 3-hr rate capacity}$$

$$= 69\%\ \text{actual 10-hr rate capacity}$$

(4) Electrolyte 1.280 s.g.

(5) 21 positives; 22 negative plates.

Table 3-5

VLL45 Cell Performance Projection
(10 MW, 100 MWhr Battery Cell)

Discharge Rate	Current	Capacity	Cell Voltage			Output Energy	Power
			Initial	Average	Final		
Hrs	Amperes	Ahr	Volts	Volts	Volts	kWhr	kW
1 (3)	7150	7150	1.730	1.622	1.430	11.60	11.6
3	3250	9750	1.912	1.808	1.598	17.63	5.9
5	2175	10,875	1.928	1.854	1.642	20.16	4.0
7	1690	11,830	1.988	1.888	1.660	22.34	3.2
10 (4)	1250	12,500	2.016	1.905	1.686	23.81	2.4
13	1020	13,260	2.060	1.950	1.740	25.40	2.0

Notes:
(1) Electrolyte 1.250 s.g.
(2) 22 positives; 23 negatives
(3) One hour spinning reserve available in 8-terminal cell design.
(4) Design discharge rate 10 hrs. Design cycle life 2500 cycles.
(5) Rated capacity at 10-hr rate:

$$\text{Rated capacity, Ahr} = \frac{100{,}000 \text{ kWhr}}{5250 \text{ cells} \times 1.905 \text{ V/cell}} = 9{,}999 \text{ Ahr}$$

$$= 80\% \text{ actual 10-hr rate capacity}$$

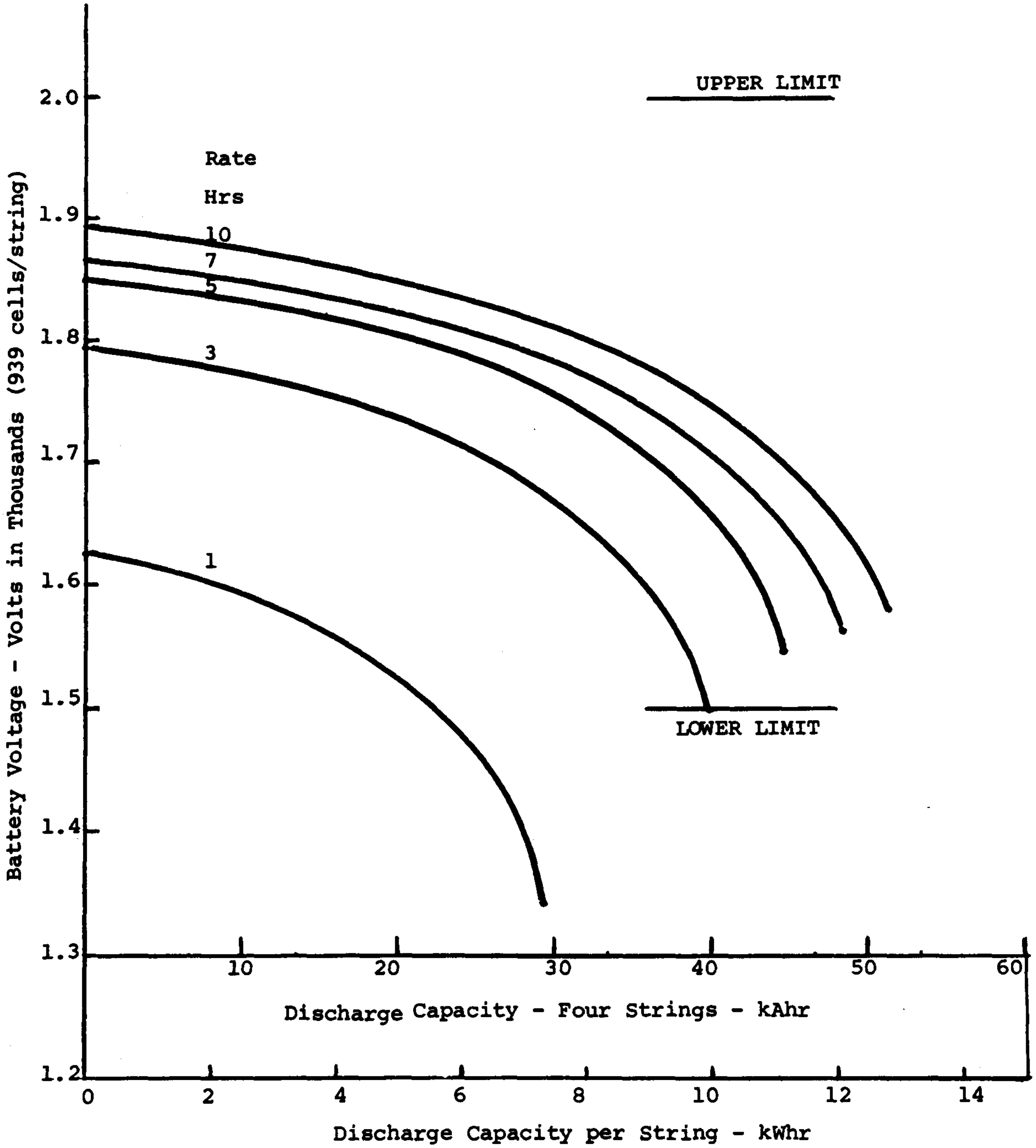


Figure 3-5. 20 MW 60 MWhr Battery Discharge Curves.

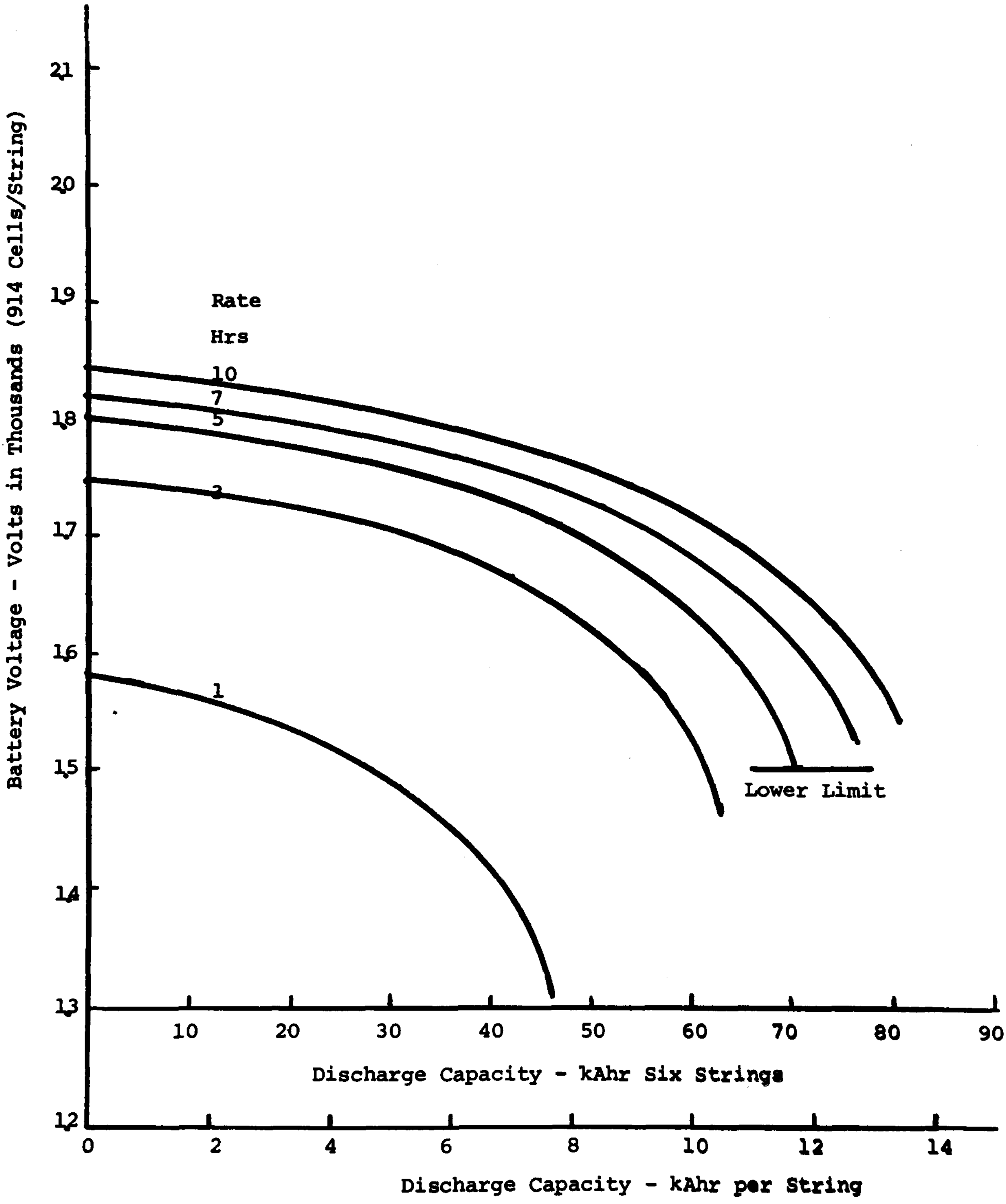


Figure 3-6. 20 MW 100 MWhr Battery Discharge Curves.

Modified constant voltage charge curves of current vs. time are shown in Figure 3-7 for the 3- and 5-hour batteries after a typical daily rated capacity discharge. ESB recommends the lower current charge at 1100 or 1200 amperes rather than the higher current charge which is an emergency option. The lower current bottom curves in the figure are essentially constant power for the first seven hours of charge tapering in 2 hours to a 400 ampere finishing current. This low current modified constant potential charge is recommended to minimize overcharge, heat evolution and water loss, and to extend cell life. See Section 8, Operation, Maintenance and Safety.

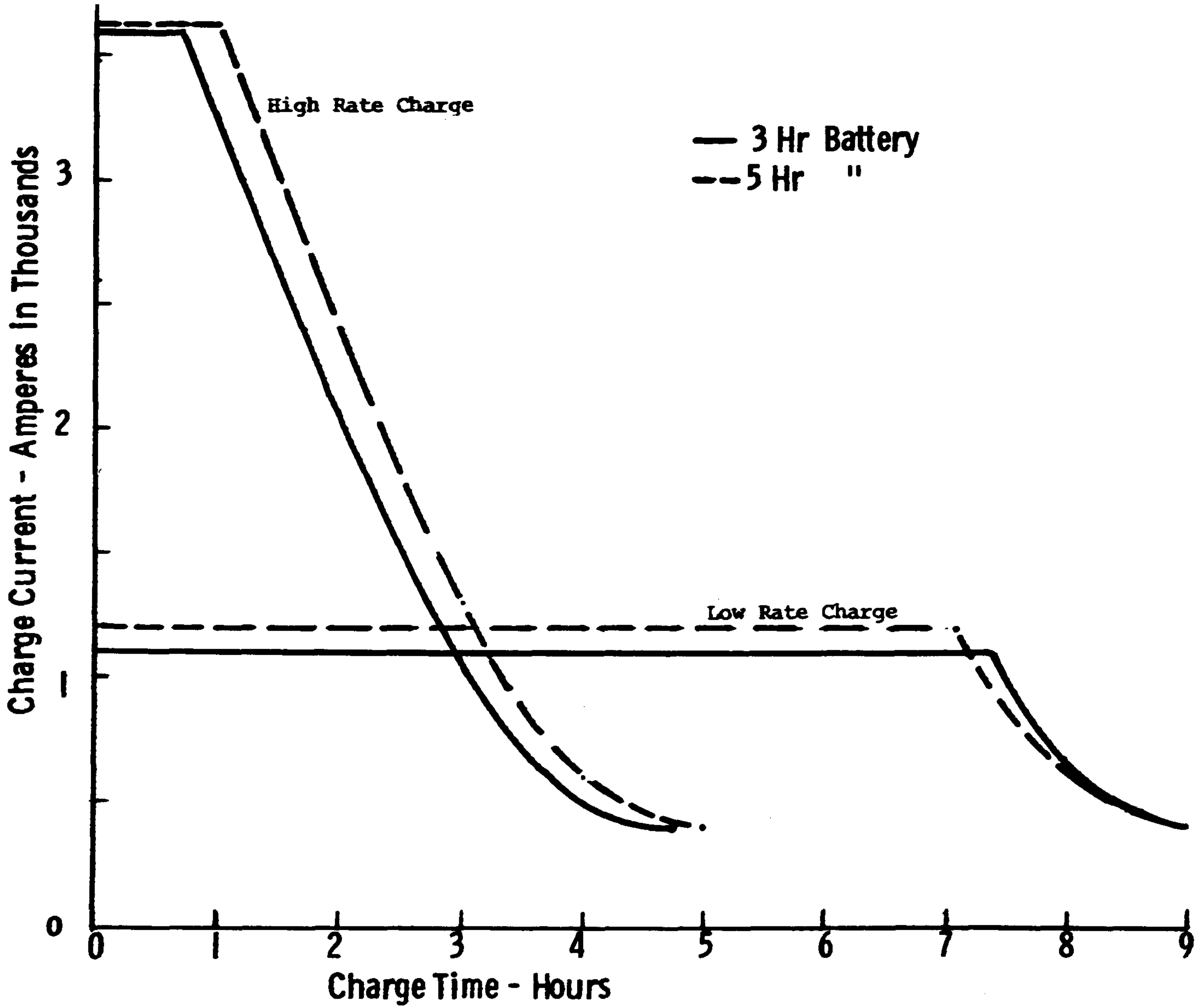


Figure 3-7. Modified Constant Voltage Charge of 3 and 5 Hour Batteries.

Section 4

CELL BATTERY PRICE AND SALVAGE VALUE

First Look Cost Estimates

During the Phase I study cost estimates for 10 MW_e 50 and 100 MWhr batteries were projected on the basis of a production rate of 1000 MWhr per year 3-shift operation. These first look estimates were direct costs only and did not include general administrative, selling and warranty costs or profit to assure an acceptable return on investment. Material costs were based on 20 cents per pound lead and $2.00 per pound antimony, and the amount of material was based on an 80% depth of discharge to deliver rated capacity. In summary, these direct costs were as follows:

Cell or Cost Component	10 MW 50 MWhr Battery 3072 Cells $/kWhr	10 MW 100 MWhr Battery 5250 Cells $/kWhr
Grids and Active Materials	21.50	18.30
Separators	3.07	2.60
Jar & Cover	11.01	8.81
Copper Inserts in Terminals	1.23	1.00
Other Materials and Purchased Parts	9.78	8.31
Total Materials and Parts	46.59	39.02
Direct Labor	6.39	5.42
Overhead	12.55	10.66
Total Direct Costs	65.53	55.10

Cost Reduction Study

In Phase II increased emphasis was directed toward price reduction, a deletion of the emergency spinning reserve one-hour rate capability, and designs for 3- and 5-hr 20 MW batteries. Cycle life was reduced from 2500 to 2000 rated capacity cycles in 10 years. Price reduction was the number one priority.

ESB's price reduction effort during the Phase II study was directed at all cost components but particularly the elimination of excess active and inactive material. Terminals and cell straps were redesigned to eliminate lead not needed to meet the revised performance specification. With the spinning reserve one-hour rate capability deleted the eight terminal cell design was transformed to a four terminal cell design with a corresponding reduction in intercell connectors.

An increase in energy output per unit weight of plate active material was achieved by increasing electrolyte specific gravity from 1.250 to 1.280, gaining 7.7% in capacity and energy output for a 4.5% loss in cycle life (2500 to 2400)(3). A decrease in the ratio of negative to positive active material reduced negative active material by 19% in both cell designs.

A new cell jar and cover design and material was selected for a reduction in jar, cover and supporting hoop price of 40%.

The ratio of rated capacity to actual delivered capacity was increased from 80% to targets of 90% for the 3-hour battery and 85% for the 5-hour battery. Two plates were deleted from the 5-hour battery cell to meet the specification for the 3-hour battery cell, reducing one cell dimension by the combined thickness of the 2 plates and separator. Minor price reductions were also achieved in the other parts and hardware items of each cell design.

The results of these price reduction efforts are the cell, grid, active material, and terminal material price estimates given in Table 4-1 for the 3-, 5-, and 10-hr cells. Table 4-1 is based on 20 cents per pound lead.

When the price of lead is inflated from 20 to 25 to 30 cents per pound, the total materials price for the batteries increases as follows:

		Price of Plate Grid, Terminal and Active Materials		
Battery	Lead Price ¢/lb	$/Cell	$/kWhr	Δ($/kWhr)/c
20 MW 60 MWhr	20	309.15	19.36	
	25	374.33	23.44	
	30	439.81	27.54	.81
20 MW 100 MWhr	20	330.57	18.14	
	25	400.70	21.98	
	30	470.88	25.83	.77
10 MW 100 MWhr	20	329.50	17.30	
	25	399.67	20.98	
	30	469.58	24.65	.74

Table 4-1

Plate Grid, Terminal and Active Material Price Estimates
for VLL45 and VLL43 Cells

Item	20 MW 60 MWhr Battery 3756 Cells			20 MW 100 MWhr Battery 5484 Cells			10 MW 100 MWhr Battery 5250 Cells		
	$/cell	$/kWhr	lbs/kWhr (Rated)	$/cell	$/kWhr	lbs/kWhr (Rated)	$/cell	$/kWhr	lbs/kWhr (Rated)
Positive Grid: Pb	67.20	4.21	21.0	71.60	3.93	19.6	71.60	3.76	18.8
Sb	43.00	2.69	1.4	45.60	2.50	1.3	45.60	2.39	1.2
Positive Active Mat'l	78.00	4.88	24.4	84.54	4.64	23.2	84.54	4.44	22.2
Negative Grid	41.60	2.60	13.0	43.42	2.38	11.9	43.42	2.28	11.4
Negative Active Mat'l	62.40	3.91	19.5	67.64	3.71	18.6	67.64	3.55	17.7
Post Terminal Pb	11.94	.75	3.7	12.50	.69	3.4	12.50	.66	3.3
Electrolyte	5.01	.31	31.0	5.21	.29	28.3	4.20	.22	26.4
Total Price	309.15	19.36	114.0	330.57	18.14	106.3	329.50	17.30	101.0
Cell Type	VLL43 (HSG)			VLL45 (HSG)			VLL45 (LSG)		
Rated kWhr (Hr)	15.97 (3-Hr)			18.23 (5-Hr)			19.05 (10-Hr)		
Depth of Discharge %	90			85			80		

Notes: 1. Lead at $0.20 per lb; Sb at $2.00 per lb.

The average increase in the price of plate grid, terminals and active materials per cent increase in the price of lead is thus 0.74 - 0.81 $/kWhr.

Table 4-2 adds the price of purchased parts, the direct labor and the sum of overhead, G & A, and profit to obtain cell selling prices for the case of 20 cents per pound of lead. Calculation of the selling prices for the case of 25- and 30 cents per pound lead leads to the following summary

Battery Type	Lead Price c/lb	Price for Cells (Each) $/Cell	$/kWhr	Δ ($/kWhr)/c
20 MW 60 MWhr	20	888.70	55.65	
	25	967.66	60.59	
	30	1047.00	65.56	.99
20 MW 100 MWhr	20	930.31	51.03	
	25	1015.29	55.69	
	30	1100.32	60.36	.93
10 MW 100 MWhr	20	929.02	48.77	
	25	1014.03	53.23	
	30	1098.75	57.68	.89

The average increase in cell price per cent increase in the price of lead is thus .89 - .99 $/kWhr in the lead price range 20- to 30 cents per pound. The above prices are for a production rate of 1000 MWhr of cells per year.

At lower production rates overhead contributions per cell will be higher. At higher production rates new economies of indirect and direct cost are forecast. Estimates of cell prices at 500, 1000, and 4000 MWhr production rates were made for the case of 20 and 25 cents per pound lead and are shown below:

Battery Type	Lead Price c/lb	Cell Prices, $/kWhr 500 MWhr/yr	1000 MWhr/yr	4000 MWhr/yr
20 MW 60 MWhr	20	56.26	55.65	52.87
	25	61.20	60.59	57.56
20 MW 100 MWhr	20	51.60	51.03	48.49
	25	56.25	55.69	52.91
10 MW 100 MWhr	20	49.31	48.77	46.33
	25	53.77	53.23	50.57

The sensitivity of cell prices to individual 10% increments in each of the main contributors to price was calculated for the 5-hr cell when manufactured at a rate of 1000 MWhr per year:

Table 4-2

Manufacturing Price Estimates for the VLL43 and VLL45 Cells
Produced at 1000 MWhr per Year

Item	20 MW 60 MWhr Battery Cell (VLL43 HSG)		20 MW 100 MWhr Battery Cell (VLL45 HSG)		10 MW 100 MWhr Battery Cell (VLL45 LSG)	
	$/cell	$/kWhr	$/cell	$/kWhr	$/cell	$/kWhr
Purchased Parts						
Separators	36.08	2.26	37.80	2.07	37.80	1.98
Jar & Cover Assembly	101.00	6.32	101.00	5.54	101.00	5.30
Copper Inserts	19.61	1.23	19.61	1.08	19.61	1.03
Other Parts	108.18	6.77	112.30	6.16	112.30	5.90
Total	264.87	16.58	270.71	14.85	270.71	14.21
Scrap & Freight on Parts	13.21	.83	13.50	.74	13.50	.71
Total Purchased Parts	278.08	17.41	284.21	15.59	284.21	14.92
Plate Grid & Active Materials & Terminals	309.15	19.36	330.57	18.14	329.50	17.30
Direct Labor	45.12	2.83	47.22	2.59	47.22	2.48
Overhead, G & A, Profit	256.35	16.05	268.31	14.72	268.09	14.07
Selling Price	888.70	55.65	930.31	51.03	929.02	48.77
Rated Energy (kWhr) (Hr)	15.97 (3-Hr)		18.23 (5-Hr)		19.05 (10-Hr)	
Rated Depth of Discharge, %	90		85		80	

Notes:
1. Lead at $0.20 per lb; antimony at $2.00 per lb.
2. Scrap on purchased parts @ 1.93%.
3. Freight on purchased parts and scrap @ 3.0%.

Cost Element Increased 10%	Change in Price, %
Purchased Parts	3.7
Plate Grids & Active Material	4.3
Labor	2.0
Overhead	1.4
G & A	.5
Profit	1.3

These results predict that future inflation of the cost of purchased parts and materials will have more than twice the effect of any other cost element. Future work should be especially concentrated in simplification and standardization of purchased parts to lower their cost, in obtaining greater utilization of the active material in the plates and in reducing the cost of all electrochemically inactive materials in the cell design.

Salvage and Reuse Credits

When the load leveling battery is replaced at end of life, credits will accrue to the purchase price of the replacement battery because of:

- Salvage value of lead and antimony in cell plates, and lead and copper in the cell terminals.
- Reuse of the cell jar, cover and supporting hoops.
- Reuse of other parts attached to the cell cover and/or terminal hardware.

Table 4-3 lists the estimated credit for each of the three cell types, the reuse rates and the percent recovery based on the original material and purchased parts cost -- assuming lead at 20 cents per pound and antimony at $2.00 per pound initial cost.

Table 4-3

Salvage and Reuse Credits

Cell Component	Reuse Rate	20 MW 60 MWhr Battery Cell $/Cell	$/kWhr	20 MW 100 MWhr Battery Cell $/Cell	$/kWhr	10 MW 100 MWhr Battery Cell $/Cell	$/kWhr
Plate and Terminals Pb, Sb	(.8)	243	15.22	260	14.26	260	13.65
Jar, Cover, Hoops	(.95)	96	6.01	96	5.27	96	5.04
Terminal Copper	(.8)	16	1.00	16	0.88	16	.84
Other Cell Parts		10	.62	10	.55	10	.53
Totals		365	22.85	382	20.96	382	20.06
Rated Output Energy, kWhr		15.97		18.23		19.05	
Original Parts & Material Cost		587		615		614	
Recovery of Original Parts and Material Cost, %		62		62		62	

Similarly, salvage and reuse credits were calculated for the case of 25- and 30 cent lead. These credits are summarized below:

Battery Type	Lead Price c/lb	Salvage and Reuse Credit $/Cell	$/kWhr
20 MW 60 MWhr	20	365	22.86
	25	418	26.17
	30	470	29.43
20 MW 100 MWhr	20	382	20.95
	25	438	24.03
	30	494	27.10
10 MW 100 MWhr	20	382	20.05
	25	438	22.99
	30	494	25.93

Second battery prices will therefore have the above credits which will be a substantial cost saving to the utility. Recycling lead and antimony reserves will also be assured.

Section 5

MANUFACTURING PROCESSES AND PLANT COST PROJECTIONS

TUBULAR-POSITIVE CELL PLATE AND ASSEMBLY PROCESSES

An analysis was made in Phase I to compare manufacturing processes for tubular positive and pasted positive cell designs. The only basic differences occur in the processes, equipment and materials needed for the positive plates. In tubular-positive plates a central lead alloy core or spine is surrounded by active material enclosed by an outer porous plastic tube which retains the active material in intimate contact with the spine and cell electrolyte. A lead alloy top bar parallels all spines into a continuous current collector and becomes the top closure for all tubes. A molded plastic bar closes the bottom of all tubes. In a pasted-positive plate the active material is pasted into an open lattice or grid of lead-antimony alloy and cured. The pasted-positive is then wrapped with layers of glass mat retainers held in place by a perforated vinyl retainer.

Once the positive plates are completed, the other processes, materials, and components are the same for tubular-positive and pasted-plate cell designs. Tubular positive cell assembly is outlined schematically in Figure 5-1.

ESB selected the tubular-positive cell design approach for the following reasons:

- Uses less lead active and inactive material per kWhr of delivered energy at load leveling rates of discharge.
- Service life and cycle life of battery will be increased.

In the past these advantages have been more than offset by the traditional increase in labor costs for tubular positive plates; however, ESB is convinced improvements in processing and equipment can decrease labor costs significantly through automation of spine casting, tube filling operations, and plate assembly equivalent to machine casting of grids and pasting of SLI automotive batteries.

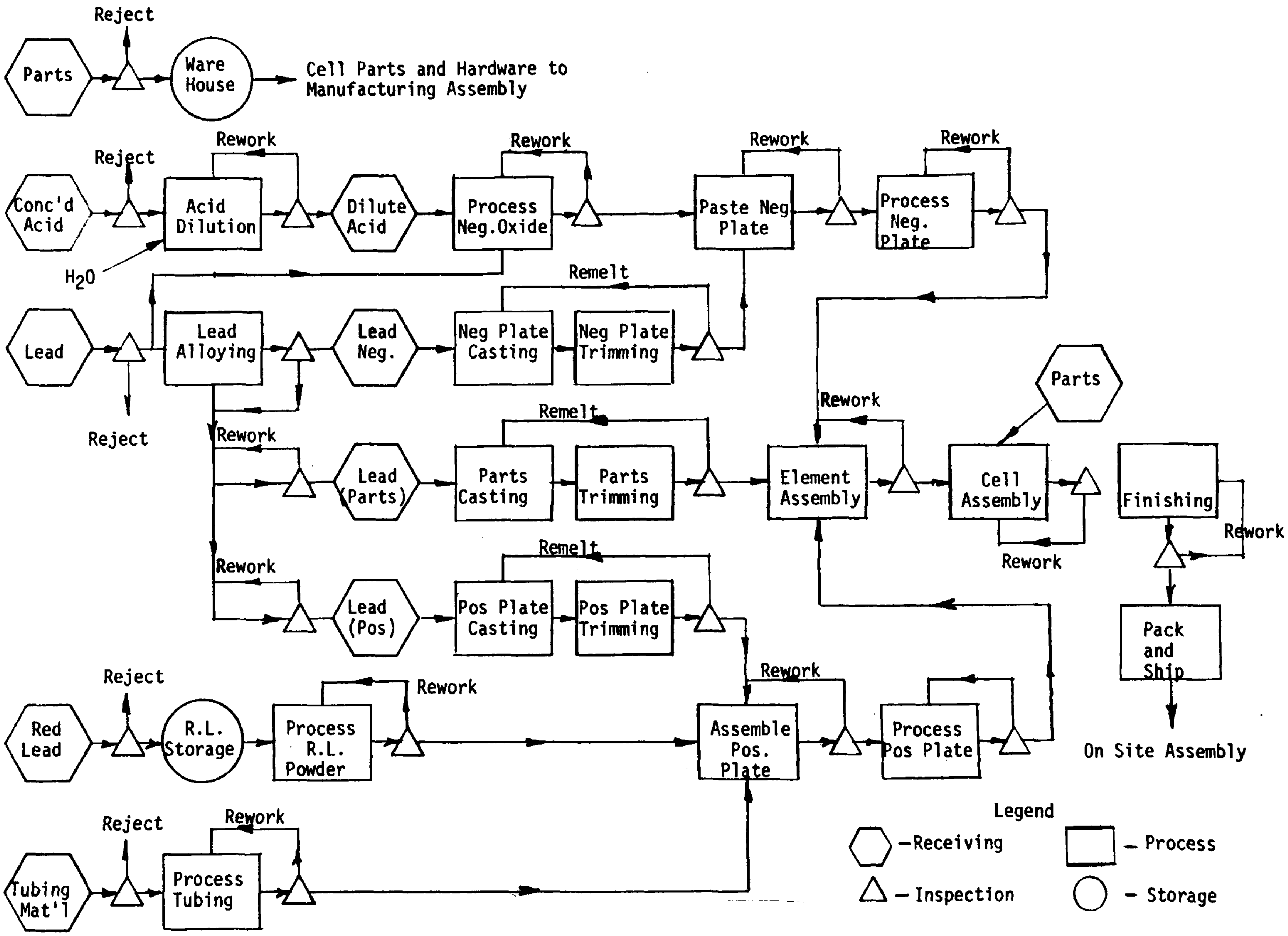


Figure 5-1. Tubular Positive Cell Assembly.

Cell design decisions included design constraints based on producibility, economics and handling. The significant items were:

- Maximum plate dimensions consistent with machine capability.
- Unit cell size and weight consistent with cell container manufacture and in-plant and installation handling operations with industrial trucks and overhead conveyor systems.
- Shipment of dry, unformed units to the utility site for on-site activation and formation with low cost power.
- Use of lead-calcium alloy for negative grids and an arsenic-containing, low antimony lead alloy for the positive spine for low maintenance and long life.

Table 5-1 summarizes the ESB estimates for processing equipment and plant cost for production of 10 each 100 MWhr (20 MW) batteries per year in a 3-shift operation. Equipment cost estimates are based on state-of-the-art machine technology and 1975 quotations. Conversion to a two-shift operation, as may be desirable, will add \$800,000 to the capital costs and 15,000 square feet to the space requirement (200,000 ft^2).

Table 5-1

Plant and Equipment Cost and Manning Estimates - VLL-45 Cell Produced at 54,840 Per Year Three Shift Operation

Operation	No. of Pieces of Equip.	Estimated Total Cost of Equipment	Manning Required	Floor Space Required Sq. Ft.
Oxide Manuf. and Handling	3	1,500,000	4	15,000
Negative Grid Casting	2	300,000	6	7,500
Negative Pasting:				
Mixers	2	270,000	6	2,000
Pasting Machine	1	125,000	12	2,000
Miscellaneous	1	105,000	-	4,500
Positive Grid Casting	4	500,000	9	8,000
Positive Tubing Manuf.	1	200,000	5	5,000
Positive Filling Machines	4	600,000	9	12,000
Plate Finishing	1	500,000	26	20,000
Strap Casting and Finishing	2	200,000	28	10,000
Assembly	5	550,000	105	20,000
Finish, pack and ship	1	300,000	38	15,000
Total - Direct		5,150,000	248	121,000
Plant Support		750,000	92	39,000
Services and Office		100,000	50	10,000
Total		6,000,000	390	170,000
Inflation and Contingency @ 20%		1,200,000	-	30,000
Total		7,200,000	390	200,000
Building, all Improvements		7,000,000	-	---
Land, 10 Acres		200,000		
Grand Total		$14,400,000	390	200,000

Section 6

DELIVERY, TRANSPORTATION AND INSTALLATION

DELIVERY OF CELLS TO SITE

Cells will be assembled dry uncharged at the factory and crated one per package for shipment via truck to the utility site. At the site, cells will be assembled by ESB personnel into the battery array of cells in a series string and strings in parallel, activated and formed up to capacity using lower cost utility power.

The shipping package will consist of one cell strapped on a wooden pallet protected by pressed board side and cover sheets and encapsulated in a plastic film. This package will cost $30 per cell and the pallet and protective sheets can be reused 3-4 times.

Shipping via truck is least damaging to the cells and now more economical. Shipping rates are not linear with increasing mileage but change with destination. The table below gives projected shipping rates from Philadelphia for the three batteries based on a minimum load of 30,000 pounds and distances of 100, 200, 300, and 500 miles at 1.15, 1.23, 1.70, and 1.95 dollars per 100 pounds:(4)

Battery Power MW	Battery Energy MWhr	Cells each	Shipping Weight MM lbs	No. Loads each	Projected Shipping Cost, $/kWhr 100	200	300	500 miles
10	100	5250	9.64	241	1.11	1.19	1.64	1.88
20	60	3756	7.74	194	1.48	1.59	2.19	2.52
20	100	5484	11.97	299	1.38	1.47	2.03	2.33

INSTALLATION AT THE SITE

The site will require a concrete floor chemically proofed against acid attack from electrolyte spillage. Floor strength must withstand a loading of 1200 pounds per square foot of cell and accessories when arrayed on a single level. For optimum performance the base of each cell should be level within 0.125" (about 0.4 degree). Rubber pads (0.43" x 18" x 18") will be provided by ESB to protect the bottoms of the cell cases from sharp projections in the floor. Drainage channels in the floor located in aisles would be desirable to wash down acid spills.

Installation of the battery will require the following steps: (1) unpackaging and inspection of cells; (2) movement of cells with a fork lift truck from the shipping platform to their rows; (3) intercell connections including torque on terminal nuts and bolts; and (4) activation. These steps will require 0.50 hours per cell on the average when all cells are on one level. In addition, accessory systems will be installed row by row as the cells are interconnected. See Section 7, Accessory Systems. Prices for the accessory systems include installation and initial check-out. The entire system check-out and formation cycling will require ESB engineering supervision over a period of several weeks. See Section 8, Operation and Maintenance for subsequent schedules of maintenance.

The formation charge of each series string includes the following steps (for the VLL45 cell 12,500 Ahr cell, 10-hr rate):

- Activate cells with 1.035 s.g. electrolyte and stand on open circuit for 1-4 hours.
- Charge 44 hours at 640 amperes. Stand on open circuit 4-6 hours. Input 28,160 Ahr
- Charge 45 hours at 768 amperes. Stand on open circuit 4-6 hours. Input 34,560 Ahr
- Charge 45 hours at 768 amperes. Input 34,560 Ahr

Total formation charge input per series string is therefore: 97,280 Ahr

and the minimum elapsed time for formation charge of the entire battery is 143 hours (6 days), assuming all parallel strings are charged simultaneously.

The capacity of a VLL45 at the 10-hr rate is 12,500 Ahr. The difference (97,280 - 12,500 = 84,700 Ahr per cell) appears as gassing from each cell:

- hydrogen = 35,400 L hydrogen (1250 ft^3)
- oxygen = 17,700 L oxygen (626 ft^3)

Hydrogen evolved from the 5484 VLL45 cells in the 5-hour 100 MWhr battery on formation charge is therefore 6.86 million cubic feet in a period of 134 hours of charge, or an average rate of 51,200 cubic feet per hour. The hydrogen concentration in air should be kept below 3% by volume to prevent explosions. The building exhaust system must exhaust this gas without any volume of air in the battery room reaching 3%. The flow of air required can be estimated from the equation:

$$Q = 0.009\ (I)(N)(K)$$

where I = maximum current flow (768 amperes), N the number of cells (5484), and K the ratio of the maximum hydrogen concentration allowed (3%) at any point in the room to the hydrogen concentration in the exhaust ducts. This value K must be measured at each installation site. For $K = 2$, Q is 75,810 ft^3 per minute. Hydrogen detectors should be installed at the locations where hydrogen reaches its maximum concentration in the battery room when the exhaust fans are on. These detectors should trigger an alarm bell in the control room when hydrogen rises above 2% and turn on the exhaust fans automatically. Concentrations above 3 percent hydrogen in air will explode with increasing violence as hydrogen concentrations rise even further.

Following the formation charge a 10-hour rate capacity discharge is required. All cells should deliver that rated capacity above the specified discharge cut-off voltage. The first service charge would then be performed in accord with operating instructions. See Section 8, Daily Charge of Battery.

In summary, the prices for installation of the three batteries, including assembly into arrays, intercell connections, activation, formation charge, first cycle discharge and recharge are as follows:

Power	MW	10		20		20	
Energy Output	MWhr	100		60		100	
Price		$	$/kWhr	$	$/kWhr	$	$/kWhr
Transportation 500 miles		188,000	1.88	151,200	2.52	233,000	2.33
Installation, formation charge & first cycle		72,670	.73	52,430	.87	75,835	.76
Total Transportation & Installation		260,670	2.61	203,630	3.39	308,835	3.09

Section 7

BATTERY ACCESSORIES

INTRODUCTION

Load-leveling lead acid batteries designed to discharge at the 3, 5, and 10-hr rate and to recharge at the 7 - 9 hour rate for 2000 - 2500 cycles will require accessory systems to stir the electrolyte, to remove excess heat generated in each cell, and to monitor cell, string and battery currents, voltages and temperature. Safe operation will also require the building to have subsystems for removal of noxious gases and for battery heating under extreme northern climates. The rationale for these systems and their estimated prices are given in the following subsections.

COOLING BY CIRCULATING WATER SYSTEMS

Rationale

One of the many criteria in assessing the lead acid battery for load leveling is the determination of the need to remove heat developed during cycling. This heat is generated by three modes: $T\Delta S$, I^2Rt, and polarization (activation and concentration). Depending on the temperature of the battery, heat removal can be achieved by radiation, free or natural convection, and forced convection, or by forced liquid (water) cooling. The removal of this heat is critical because the battery must be maintained below certain limits ($\leq 120^{\circ}F$); otherwise, a deterioration in cell components may limit cell service life.

Once the mode of heat transfer has been established, the equipment required to remove this heat can be selected for its operational performance as well as its practical value. The heat generated in or near cells in normal operation will control the size of the cooling system and its price. This heat has the following components: (1) I^2Rt resistive heat where I is current, R the internal cell resistance (or the intercell connector resistance), and t the time of charge or discharge; (2) polarization heat resulting from slow steps in the reaction path;

and (3) TΔS heat. Intercell connector heat is small and can be calculated from the known resistance of the copper connectors. The sum of the remaining cell heat components can be estimated by integration between the cell charge or discharge voltage and the thermoneutral voltage (TNV) plotted vs. capacity. The thermonautral voltage is governed by the ΔH for the reaction controlling the charge or discharge, i.e.,(5)

$$\text{TNV} = -\frac{\Delta H}{nF}$$

Normally for lead-acid cells the governing reaction is:

$$Pb + PbO_2 + 2H_2SO_4 \rightleftarrows 2PbSO_4 + 2H_2O \quad \Delta H_{25^\circ C} = -95.3 \text{ Kcal/mole (s.g. 1.280)}$$

and TNV = 95.3 Kcal/2 x 23.07 = 2.065 volts

for a fully charged cell with 1.280 s.g. acid at 25° C. Figure 7-1 gives the values of TNV as a function of acid specific gravity at 25° C (or state of charge).(6) The table below shows how these values change with the state of charge.

State of Charge (%)	S.G.	$\Delta H_{25^\circ C}$	TNV, 25°C Volts per Cell
100	1.280	95.3	2.06_5
75	1.240	93.2	2.01_9
50	1.200	91.4	1.98_1
25	1.160	89.6	1.94_2
0	1.120	88.3	1.91_4

A load leveling week will consist of daily discharge and recharge cycles Monday through Friday with an equalization charge on Friday night. Assume discharges of 10,000 Ahr each day and recharges at the 7-hour rate with a 2-hour taper each night. The heat evolved on the 5-hour rate discharge, assuming no heat from the external load diffuses back into the battery, is given by integration of the area between the curves of Figure 7-2, i.e., between the thermoneutral voltage plotted vs. discharge capacity and the closed-circuit cell voltage vs. discharge capacity. This area corresponds to 1280 Whrs to a cut-off of 10,000 Ahrs. The temperature rise Δt for this cell is:

$$\Delta t_D = \frac{Q}{mC_p} = \frac{1280 \text{ Whr x } 3.413 \text{ Btu/Whr}}{2102 \text{ lbs x } .204 \text{ Btu/lb}} \ {}^\circ F$$

$$= 10.2^\circ \text{ F, assuming no external cooling system.}$$

During the subsequent charge (modified constant voltage) the current holds constant for seven hours at 1200 amperes and then decays to a finishing current of

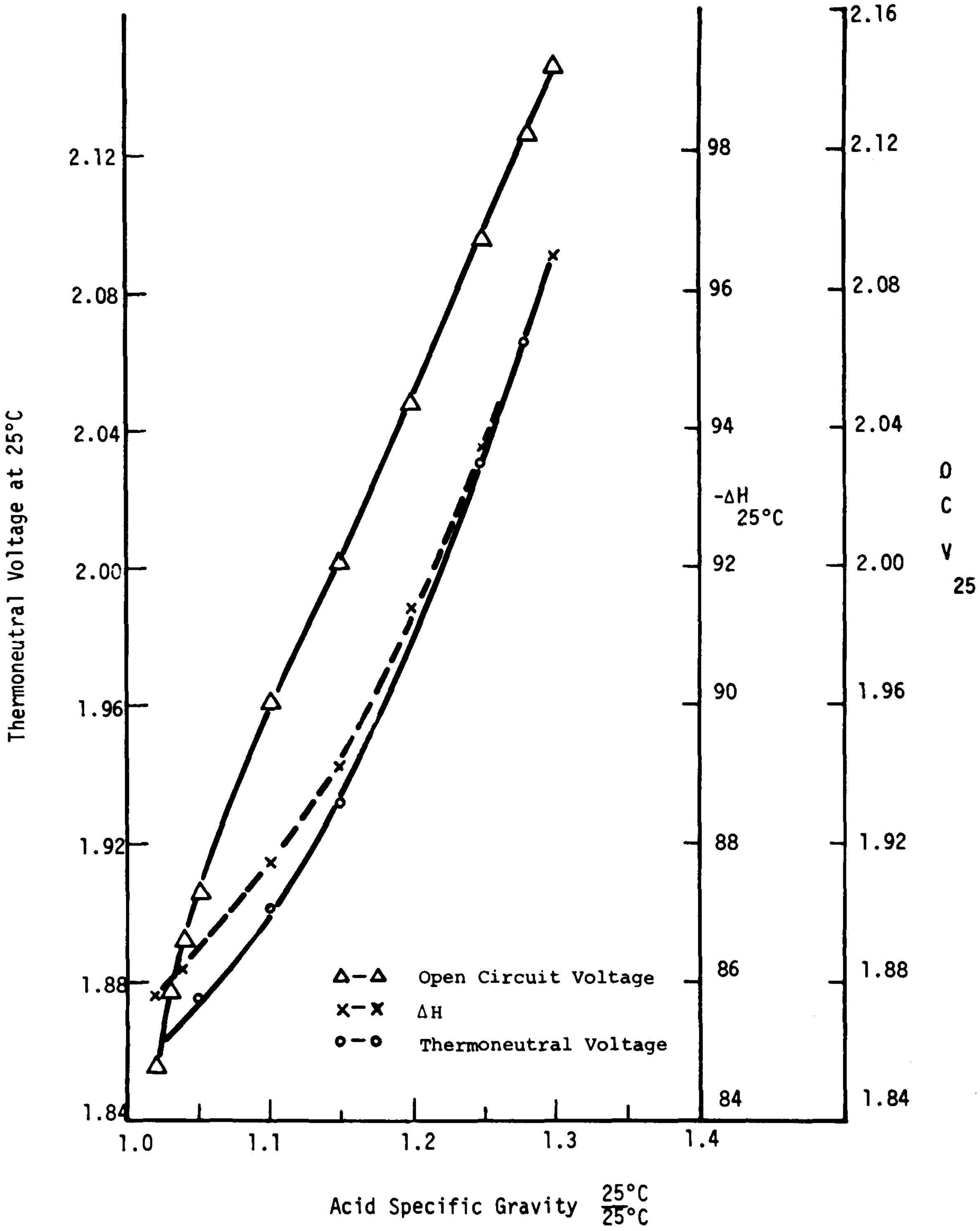


Figure 7-1. Thermo-Neutral Voltages vs. Specific Gravity.

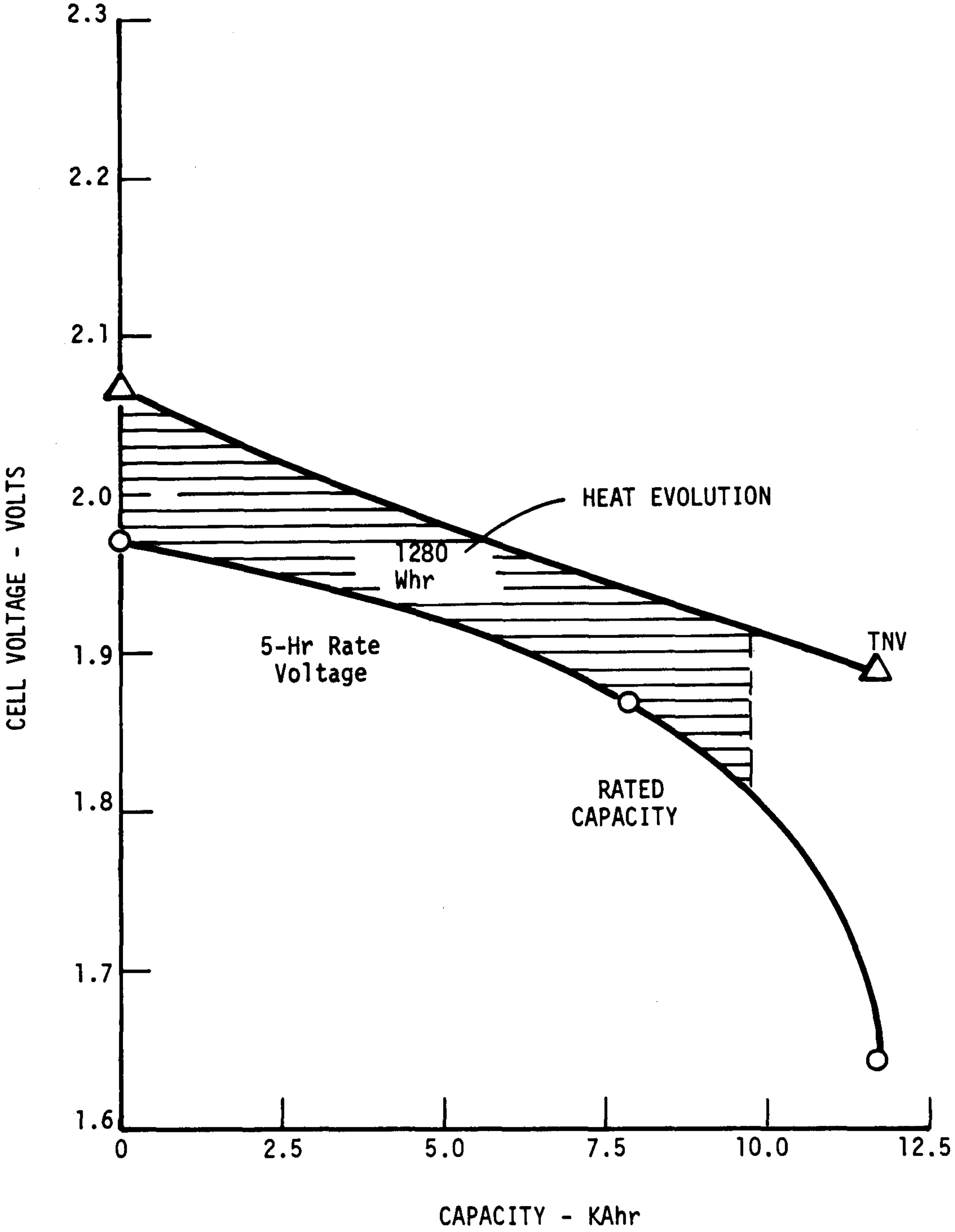


Figure 7-2. Heat Evolution in Discharging VLL45 Cell at 5-Hour Rate.

400 amperes in two hours, returning 10,000 Ahrs plus 3%. The heat evolved is the area between the curves of Figure 7-3, i.e., between the closed circuit charge cell voltage and the thermoneutral voltage. This area corresponds to 2144 Whr; and the calculated temperature rise is 17.1° F, assuming no external cooling system.

Each Friday night the battery will be overcharged to equalize the charge state of all cells in each series string. During this "equalization" charge 120% of the Friday discharge will be returned to the cell, i.e., the first 103% a normal daily recharge finishing at a constant current of 400 amperes - the so-called finishing current. The last 17% of the charge capacity is returned at this constant current. The voltage will rise to about 2.65 volts and remain constant for most of the equalization charge time gassing freely.

Above the gassing potential the thermoneutral voltage is governed by the electrolysis of water and the constant value at 25° C is given by:

$$H_2O \rightarrow H_2 + 1/2\ O_2 \qquad \Delta H_{25^oC} = 68.32 \text{ Kcal/mole}$$

$$\text{TNV} = 68.32/2 \times 23.07 = 1.481 \text{ volts per cell}$$

The heat evolved is now the integrated area between the overcharge voltage 2.65 volts and the much lower thermoneutral voltage for the electrolysis reaction 1.48 volts. The increased heat evolved is shown in Figure 7-4.

ESB projects finishing charge and equalization charge currents of 400 amperes for each of the three batteries. Heat evolution at this current is:

$$q = I\ (V\text{-TNV}) = 400\ (2.65-1.48) = 468 \text{ watts per cell.}$$

Increasing the current will increase the charge voltage and further increase heat output.

During equalization of the 100 MWhr battery a cell discharged Friday for 10,000 Ahr would have 12,000 Ahr returned. During the last 5 hours of charge at the 400 ampere equalization rate the heat evolved in each cell would be:

$$Q = 400 \text{ A} \times 5 \text{ hours} \times (2.65-1.48) = 2340 \text{ Whr}$$

and the rise in temperature without cooling would be:

$$\Delta t = \frac{Q}{mC_p} = \frac{2340 \text{ Whr} \times 3.413 \text{ Btu/Whr}}{2102 \text{ lbs} \times .204 \text{ Btu/lb}}\ ^oF$$

$$= 18.6^o \text{ F}$$

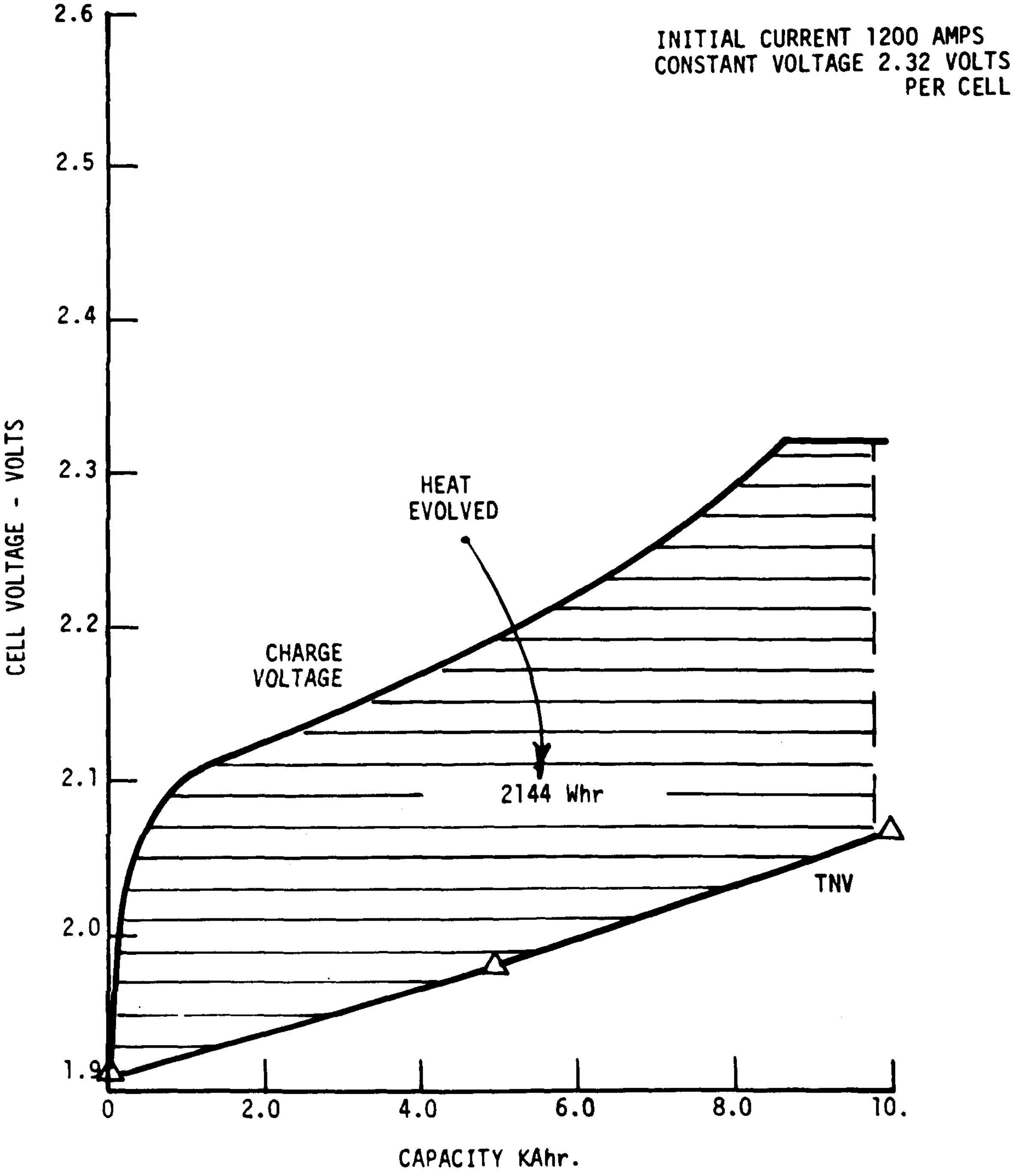


Figure 7-3. Heat Evolution in Charging VLL45 Cell: On Modified Constant Voltage Regime.

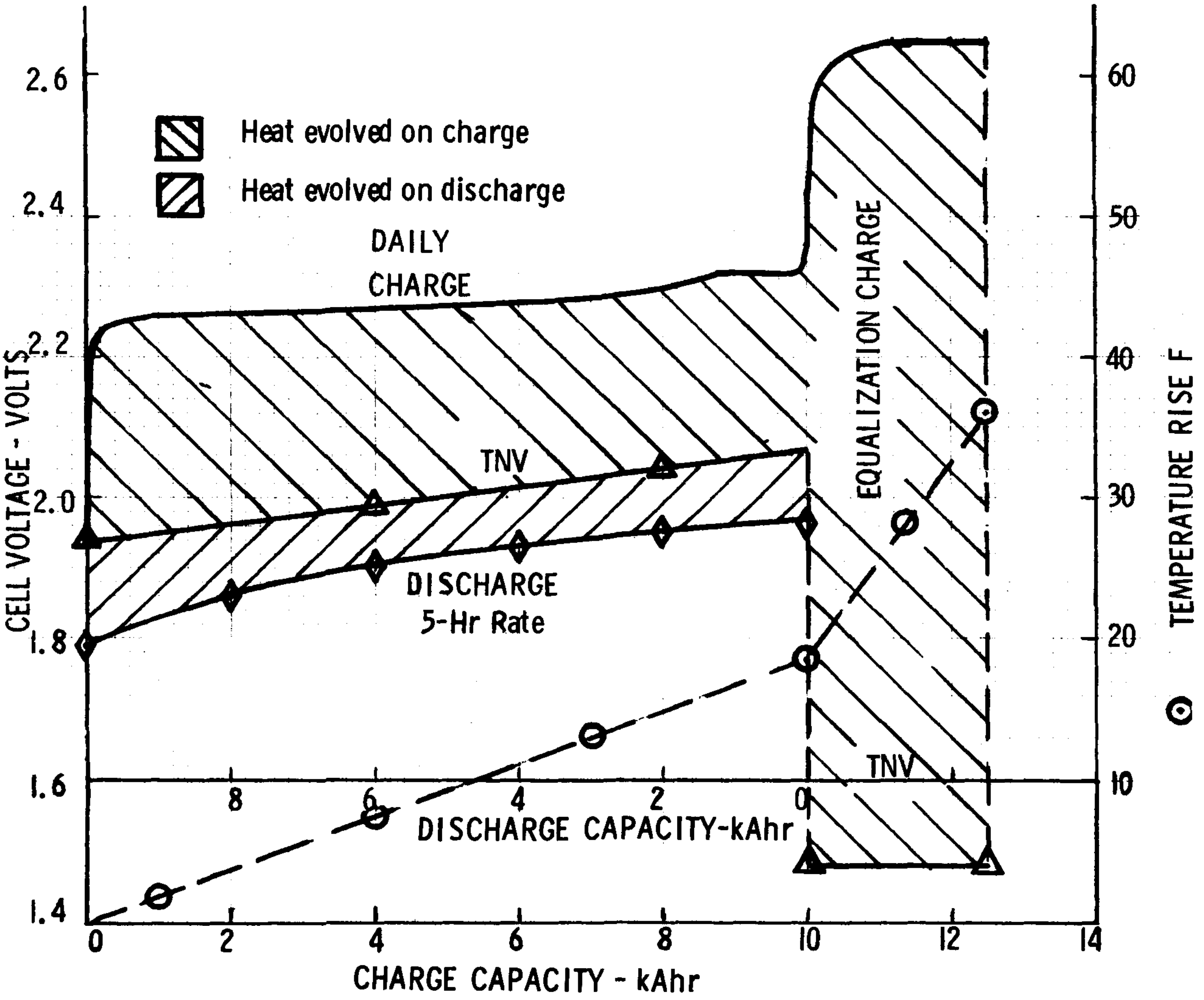


Figure 7-4. Relative Heat Evolution on Daily Discharge, Recharge and Equalization Charge.

Appendix A gives a detailed derivation of the relative capabilities of cooling techniques applied to the close-packed array of VLL45 cells. Cooling rates are shown to be about 10.5 watts for radiation primarily from the tops of cells; about 73.6 watts for the sum of radiation and natural convection; and about 124 watts for forced convection. Using these cooling mechanisms the accumulative effect on the temperature of the 100 MWhr battery cells of daily discharge/charge cycles Monday through Friday and an equalization charge on Saturday would be as shown in the table below.

Day Ending	With No Cooling	Cooling by Natural Convection and Radiation (73.6W)	Forced Convection Cooling (124W)
1	115	101	92
2	142	114	96
3	169	128	100
4	196	141	104
5	223	154	108
6	242	159	103
7	242	145	79

Thus for the 100 MWhr 5-hour battery, forced convection cooling might be able to supply adequate cooling; however, the major problem would be to cool each cell equally.

ESB concluded water cooling through the straps in each cell would be a preferable approach, soundly based on submarine battery experience.

Table 7-1 summarizes the calculated heat evolution and temperature rise for each battery cell during daily cycling. It leads to the conclusion that for the most probable utility loads and ESB's recommended charge rate, the minimum cooling rate required for 24-hour operation is 508 Btu/hr (149W) and the maximum rate of heat evolution is 2080 Btu/hr (609W) during the 3-hour discharge.

Table 7-1

Daily Cycle Heat Evolution and Temperature Rise in Load-Leveling Battery Cells

	Test Condition	Units	20 MW 60 MWhr Battery Cell	20 MW 100 MWhr Battery Cell
A.	Rated Capacity Discharge;			
	1. Time	Hrs	3	5
	2. Internal cell heat	Whr	1697	1280
	3. Intercell connector heat	Whr	131	107
	4. Total heat evolved	Whr	1828	1387
	5. Temperature rise (no cooling)	°F	13.9	11.0
B.	Recharge 103%			
	1. Time at constant I	Hrs	7.4	7.0
	2. Time in taper	Hrs	1.6	2.0
	3. Total charge time	Hrs	9.0	9.0
	4. Initial charge current	Amperes	1100	1200
	5. Finishing current	Amperes	400	400
	6. Internal cell heat	Whr	2135	2144
	7. Intercell connector heat	Whr	37	42
	8. Total heat evolved	Whr	2172	2186
	9. Temperature rise (no cooling)	°F	16.5	17.4
C.	Total Daily Heat Output	Whr	4000	3573
		Btu	13,652	12,195
D.	Minimum Cooling Rate Required 24-Hour Cooling Cycle	Btu/hr W	569 167	508 149
E.	Highest Heat Evolution Rate During Day	Btu/hr W	2080 609	948 278

Notes:	(1) Cell weight	lb	1986	2102
	(2) C_p	Btu/lb/°F	.226	.204
	(3) Intercell connectors resistance	(4) micro-ohm	3.9	3.9
	(4) Discharge current	Amperes	3341	2342

Water-Cooling System Price - Installed

ESB's study has developed a water-cooling system which pumps cooling water from a common cold manifold into the positive plate strap and out through the negative plate strap of each cell to a warm water return. Each half of a parallel section of the battery has its own cooling system. A computer study set the water flow rate at 250 lb/hr as optimum. At this rate a cell should never see a temperature higher than 106° F during normal operation. Redundancy has been included in pumps and in cooling tower capability. See Appendix A-1-C.

In very cool climates the cooling system can be used to heat the battery, provided a steam source is available, simply by addition of a steam heat exchanger to the inlet side. Heat rate is a function of hot water temperature and cell temperature. For 130° F hot water and a start cell temperature of 45° F about 1.8 hrs would be required for warm-up of the 3-hour battery to 60° F at a flow rate of 250 lb/hour (30 gal/hr).

The price for the cooling systems is tabulated below -- with and without the back-up equipment:

Cooling System	20 MW 60 MWhr Battery		20 MW 100 MWhr Battery	
	K$	$/kWhr	K$	$/kWhr
Without Back-Up Components				
Ion exchanger	24	.40	24	.24
Cooling towers	225	3.75	275	2.75
Pumps, valves, piping	69	1.15	103	1.03
Assembly labor	56	.93	75	.75
OH, G & A, Profit	163	2.72	217	2.17
Price	537	8.95	694	6.94
With Back-Up Equipment				
Ion exchanger	24	.40	24	.24
Cooling towers	250	4.17	300	3.00
Pumps, valves, piping	92	1.53	141	1.41
Assembly labor	57	.95	82	.82
OH, G & A, Profit	172	2.87	241	2.41
Price	595	9.92	788	7.88

All components are high quality with a lifetime of 20 years under normal operation. Maintenance will require only inspection for leakage at hose to cell and hose to manifold connections, and repair; also, routine resupply of pure salt to regenerate the ion exchange columns.

AIR-LIFT STIRRER SYSTEM

Each cell has one air-lift stirrer to circulate electrolyte and maintain a uniform acid concentration. Without the stirrer the output energy and energy efficiency would be decreased significantly and service life would be less reliable. This system requires a compressed air supply piped to each cell at a flow rate of 0.03 ft^3/minute which is vented through the cell vent in normal operation.

The price of this system for the two batteries is:

Component	20 MW 60 MWhr Battery		20 MW 100 MWhr Battery	
	K$	$/kWhr	K$	$/kWhr
Rotary vane compressor	2.0	.10	3.0	.03
Piping, valves, flowmeters, filters	2.0	.10	3.0	.03
Assembly labor	10.0	.17	13.7	.14
OH, G & A, Profit	24.6	.41	33.9	.34
Price	38.6	.64	53.6	.54

ELECTRICAL MONITORING OF CELLS AND BATTERIES

In the study close monitoring of cells was first considered a luxury; however, electrical scanning capability is becoming less expensive, and a knowledge of individual cell voltages can permit effective preventive maintenance as well as provide prior warning of the need for service.

In the final study of the monitoring system the following services were included and costed out: (1) monitor individual cell voltages scanning each 15 minutes; (2) monitor buss voltages and current in each series string, assuming each string can be charged independently; (3) monitor temperature at 100 points (each 40 - 50 cells); (4) provide a computer system to identify and warn of cells outside of allowable voltage tolerances; (5) accumulate daily energy and capacity output and input in each string; and (6) calculate energy turnaround efficiency.

The price for these two systems is presented below:

Electrical System Cost Element	20 MW 60 MWhr Battery		20 MW 100 MWhr Battery	
	K$	$/kWhr	K$	$/kWhr
Hardware, parts, etc.	31.7	.53	40.2	.40
Computer	16.5	.28	16.5	.17
Assembly labor	13.3	.22	13.7	.14
OH, G & A, and Profit	37.0	.62	39.4	.39
Price	98.5	1.65	109.8	1.10

This price includes system engineering, program development to make maximum use of the computer, and the cost of installation.

INTERCELL, INTERROW AND INTERSECTION CONNECTORS

The cells of each battery will be connected by lead-plated copper bars 0.25" x 2.25" x L where L is the overall connector length. Buss bars are also flat and are clamped between bolted aluminum plates at right angle turns. Buss bars will connect the parallel sections to the control room. ESB recommends a switching capability to segregate parallel battery sections from each other for maintenance down time and for charging sections separately.

The price for intercell, interrow and buss connectors is given below and does not include installation:

Component	20 MW 60 MWhr Battery		20 MW 100 MWhr Battery	
	K$	$/kWhr	K$	$/kWhr
Intercell, interrow connectors and buss bars	104.0	1.73	163.9	1.64

Section 8

OPERATION, MAINTENANCE AND SAFETY

DAILY CHARGE

Utilities prefer constant power charging. ESB experience leads to a recommendation for modified constant voltage charge. The first portion of the charge is limited to a preset maximum constant current, followed by an exponential tapering current to a preset finishing current.

EPRI guidelines recommended 7 hours for the constant current (almost constant power) and 2 to 3 hours for the taper. ESB recommends that daily charges be performed to return 103% of the daily discharge capacity in ampere-hours. The accumulated output and input would be a direct read-out from the electrical monitoring system.

Figure 8-1 depicts typical charges of this type showing charge current vs. time and battery voltage vs. time. Cell voltages would not rise significantly above gassing potentials during these daily recharges -- holding to a minimum the consumption of water and the evolution of gases as well as heat.

Recommended charge conditions Monday through Friday are therefore:

Item or Instruction	20 MW 60 MWhr Battery	20 MW 100 MWhr Battery
Number of cells in string	939	914
Number of strings in series	4	6
Initial charge current		
Amperes/String	1100	1200
Amperes/Battery	4400	7200
Finishing current		
Amperes/String	400	400
Amperes/Battery	1600	2400
Voltage limit in taper		
Volts per cell	2.32	2.32
Volts per string	2178	2120

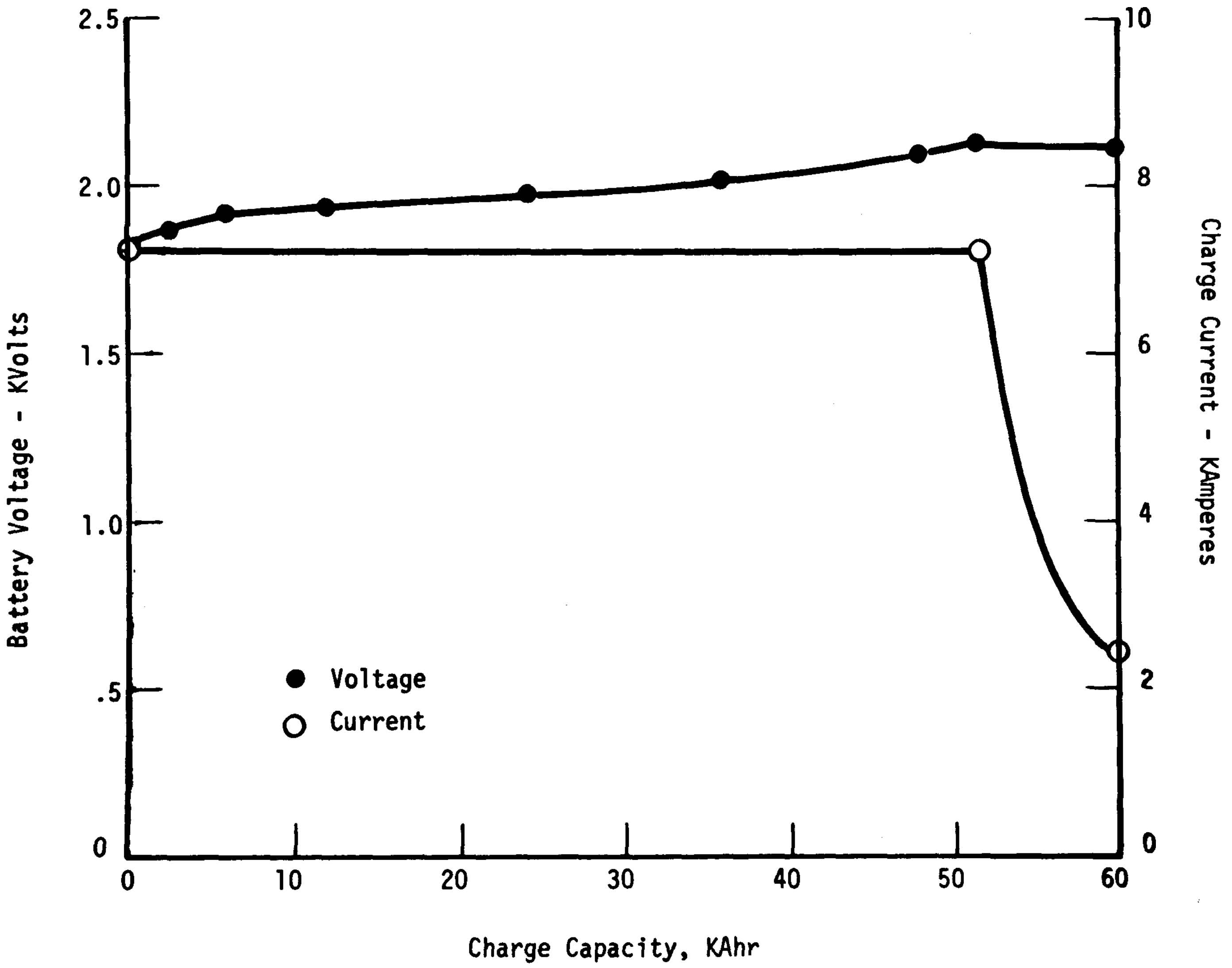


Figure 8-1. Modified Constant Voltage Charge 20 MW 100 MWhr Battery.

Item or Instruction (cont'd)	20 MW 60 MWhr Battery	20 MW 100 MWhr Battery
Hours at limiting current	7.4	7.0
Hours in taper	1.6	2.0
Total charge time - hrs	9.0	9.0
(for previous rated capacity discharge of: Ahr/String	8,845	9,756
Ahr/Battery)	35,380	58,536
Battery voltage at 103% cut-off: (2.35 V/cell) volts	2,207	2,148
Constant power setting for charge (est.) MW (first 7 hrs. only)	9.6	15.2

EQUALIZING CHARGE

An equalizing charge should be performed weekly to equalize the state of charge of all cells in a series string. Service life will be extended and turnaround energy efficiency improved during cycling.

Charge each battery at the 400 ampere finishing rate until 120% of the preceding cycle discharge capacity has been returned. For the 100 MWhr 20 MW battery assume a rated capacity discharge of 9,756 Ahr per string has been delivered on the Friday cycle. Friday night a routine weekly charge would be required to return 100% (9,756 Ahr) and another 20% (1951 Ahr) equalizing charge at 400 amperes constant current would complete the charge. Total time required would be about 9 hrs + 5 hrs = 14 hours.

During the equalization charge cell voltages will rise quickly from 2.45 volts to 2.65 volts per cell and remain constant at that value. Thus the equalization charge is a constant power charge, and the power settings are predictable and are 400 A x 6 strings x 914 cells/string x 2.65 volts/cell = 5.8 MW for the 20 MW 100 MWhr battery and 4.0 MW for the 20 MW 60 MWhr battery.

ESB's heat evolution study predicts Friday's heat load on the battery will be particularly severe because of the combination of a normal discharge/recharge cycle plus equalization. Assuming only radiation and natural convection cooling, ESB estimates a cooling rate of 251 Btu/hr, or 73.6 W, and this rate will allow a repetitive increase in battery temperature. The calculated heat generated in the battery partially compensated by radiation and natural convection cooling can be shown to be:

Heat Source (Each cell & intercell connector)	Heat Absorbed (or Cooling), Whr/Cell 20 MW 60 MWhr	 20 MW 100 MWhr
Friday discharge (rated capacity)	1828	1387
Friday recharge (103% rated capacity)	2172	2186
Equalizing charge @ 400 A	2071	2287
Cooling during discharge, recharge and equalization:	(1192)	(1384)
Cooling during next 24 hrs (Saturday)	(1766)	(1766)
Cooling during next 24 hrs (Sunday)	(1766)	(1766)
Residual heat: Monday A.M.	1347 Whr	944 Whr
Weekend temperature rise, °F	10.2	7.5

ESB's water cooling system thus would be operated on Friday and Saturday as a mandatory procedure until cell temperature is cooled down to 88°F. Failure to cool would increase the high temperature exposure and the high degree-days would decrease service life.

ESB recommends the cooling system be operated thermostatically -- automatically on when the temperature exceeds 95°F -- so that cooling is available 7 days a week.

MAINTENANCE ON 20 MW 60 MWhr and 100 MWhr BATTERIES

ESB's overall system design aims for a goal of minimum maintenance. Three maintenance requirements must be met. Electrolyte levels and specific gravity must be maintained by reliable and effective watering of cells. Electrolyte or cooling water leakage must be cleaned up. Intercell connections must be maintained at proper torque.

Water levels should be monitored visually once each two months after an equalizing charge. Pure water will be added to bring low levels up to the full mark on the cell float-type indicator. Evaporation losses are minimized by the cell vent and cover design; however, water loss during overcharge is estimated to be 15,500 and 24,900 liters per month respectively for the 60 and 100 MWhr batteries, assuming rated capacity discharges 5 days a week and a weekly equalizing charge. As the batteries near end of life, these rates of water loss will increase up to 23,700 liters/month and 38,200 liters/month.

For most of the battery life cells will require an addition of 4.1 and 4.5 liters per cell per month respectively for the 60 MWhr and 100 MWhr batteries. The volume of electrolyte in the cells between the full level and minimum level (about 15 liters) is sufficient to extend service between waterings to 3-4 months when utility cycling routines are reduced. This maintenance can be simplified by a walk-over bridge which will permit a battery section to be treated row by row (8 cells at a time) from above while the bridge advances stepwise down the section.

Reliable automatic watering of cells has not been demonstrated to date. See Section 9. Such a device must be diverted to future development, test and reliability assessment. One failing float valve in any one of the 4-5,000 cells could give a flooded cell and a short to ground.

Intercell connection maintenance may be necessary to eliminate high resistance "hot" connectors which have low torque on the terminal post bolts. Cold flow can occur at connectors until high spots are reduced, and all these bolts must be retorqued to the specified value. These cells with high intercell resistances can be identified by low closed circuit voltages on the scanner print-out and a rise in temperature above average. After the first torque check at installation + 6 months, intercell connectors will remain tight for the life of the battery.

Leakage of electrolyte between jar and cover seals may occur as a random event. Jar covers are sealed to the jar with a flexible cement to permit disassembly and reuse of the jar cover in the replacement battery. Such leaks are easily repairable. Leaks may also occur at cover to gasket seals around the flame arrestor and four cell terminals. Leakage can be detected by ground detectors in each section. This function is a part of the ESB electronic-scanning system. Tightening up retaining nuts on gasket seals will stop these leaks. This inspection is performed at installation + six months also.

Jar leakage through case failure from rough handling in transit or during installation is detected by air pressure leakage tests prior to activation of the cell. Leaking jars will be replaced.

Maintenance of the cooling system consists of a visual inspection for leaks at flexible tube connections to each cell and to the water manifolds. These connections are sealed with plastic cement and when made properly will not leak thereafter during battery life. Repair of leaks is readily performed with more cement with the system turned off on a particular "half-section" of the battery. Ion exchange column regeneration is automatic; however, salt reservoirs must be replenished quarterly.

Maintenance of the electronic scanning system will include calibration checks of temperature and voltage outputs semiannually.

Summarizing, the recommended inspections are:

Semiannual Inspection

- Intercell connections. Cleanup, dry-out and coat with protective grease. Check torque if cell has low voltage on discharge or is running hot.
- Add water to specified high electrolyte level mark.
- Check for leakage in cooling system connections, cell jar to cover seal, and terminal to cover seals. Repair seals, retorque as needed. (First semiannual inspection only).
- Clean and dry cell cover and alumina vent.
- Check calibration of temperature read-out in pilot cells of each section.

Annual Inspection

- Conduct semiannual inspection.
- Monitor end-of-charge voltages on each cell at end of equalization charge.

The annual price of the above inspections is estimated as follows (assuming 200 cycles per year):

Inspection Maintenance Price	60 MWhr Battery		100 MWhr Battery	
	$/yr	Mills/kWhr	$/yr	Mills/kWhr
Direct Labor	747	.062	1091	.055
O.H., G & A, Profit	1680	.140	2453	.123
Total	2427	.202	3544	.178

SAFETY PRECAUTIONS

Precautions must be taken against the hazards of electrical shock, chemical acid burns, flammability and explosion of hydrogen, and the toxicity of stibine and arsine evolved from the batteries during equalization charges.

Standard utility station safety practices should be exercised to protect against high voltage direct current electrical shock. These precautions are especially necessary when installing or replacing cells and during normal maintenance. Standard chemical safety practices will be required when handling the sulfuric acid (1.28 specific gravity) electrolyte, i.e., wear rubber aprons, rubber boots, rubber gloves, and face shields to protect skin and eyes from contact with acid.

Hydrogen is evolved from cells during equalization charge in quantities proportional to the charge current and the number of cells in the battery. If a spark were to ignite an explosive mixture (>3% hydrogen), a fire could result. In such a case, stop the charge placing all battery strings on open circuit. Stop the ventilation system. Personnel should leave the area, an automatic CO_2 fire extinguishing system should be activated, and station firemen should be called.

Stibine (SbH_3) and arsine (AsH_3) are evolved from the high cycle life battery when the positive plate alloy contains the elements antimony and arsenic. Antimony at a 4-6% level and traces of arsenic in the grid alloy are essential to meet the 2000-2500 cycle life at 80% depth of discharge. During normal acid corrosion of the positive grid, antimony dissolves in the electrolyte, migrates to the negative, and deposits on its surface. During any charge where cell voltage rises above 2.5 volts stibine and arsine are evolved from the negative plate surface. Each weekly equalization charge at 400 amperes requires under normal ESB procedures about 4-5 hours above 2.5 volts on each battery cell. The estimated toxic gas and hydrogen evolution in this period are calculated below from the experimental data of Ashendorf and Murphy(7):

Gas Evolved During Equalization Charge	Unit	60 MWhr Battery 3756 cells	100 MWhr Battery 5484 cells
Rated Capacity Discharge	Ahr	8845	9756
Overcharge at 120%	Ahr	1769	1951
Overcharge Time	Hrs	4.42	4.88
Hydrogen Evolved (NTP)	ft^3	108,000	173,000
Stibine Evolved (NTP)	ft^3	5.2	8.3
Arsine Evolved (NTP)	ft^3	.083	.13
Room Volume (less battery)	ft^3	405,000	551,000
Ventilation Air Flow Rate	CFM	30,000	40,000

The air flow rate above would prevent the hydrogen concentration from exceeding 1-1/2% and eliminate the hydrogen explosion hazard; however, the concentration of stibine and arsine would rise to 0.7 ppm and 0.01 ppm respectively. Since the present threshold limit values for stibine and arsine are 0.1 and 0.05 ppm(8), the above air flow rate would have to be increased sevenfold to decrease stibine maximum concentrations to permissible levels.

Very little, if any, stibine or arsine are produced at cell voltages below 2.5 volts per cell. Modifying the equalization charge procedure to a constant voltage charge set at 2.50 volts per cell would reduce stibine evolution substantially; however, antimony would accumulate as a deposit on the negative plates of the cell, decrease energy efficiency, and limit the life of the cell. ESB therefore recommends an exhaust gas manifold designed to meet the threshold limiting values of stibine and arsine in the battery rooms while at the same time trapping the stibine and arsine gasses in an air scrubber on top of the building. Washing the exhaust air with an acidic aqueous solution of an oxidizing agent would convert both toxic hydrides to the soluble cation form and permit recovery of Sb and As. The estimated initial weights of metal evolved as the hydrides per weekly equalization charge are:

Metal Evolved As Hydride Per Week	Grams Per 1000 Ahr(7)	60 MWhr Battery (lb)	100 MWhr Battery (lb)
Sb	0.119	1.7	2.8
As	0.0012	.018	.028

These estimates are conservative. The proposed load leveling cells will contain less antimony and arsenic in their positive plate grids than the cells of Ashendorf and Murphy and are not expected to evolve as much stibine and arsine; however, and BEST test of these large lead-acid cells should include monitoring for stibine and arsine at individual cells and in the exhaust manifold.

Section 9

IMPACT OF NEW TECHNOLOGY AND COST REDUCTION OPPORTUNITIES

ESB predicts new technology now in development will impact load-leveling battery costs favorably: (1) by reduction in active and inactive cell materials per kWhr output; (2) by reduction in direct labor required to manufacture plates and assemble cells; and (3) by reduction in annual maintenance required for the battery. The net decrease in cell price will be 10-15% and may cancel the impact of inflation over the next 2-3 years.

New concepts in active material processing will decrease active material densities while increasing utilization. Continuing positive grid alloy investigations will permit a reduction of relatively expensive antimony and yet not increase shelf corrosion reactions. Improvements in tube materials and processing methods will decrease the manufacturing time per tubular positive plate while decreasing the probability of tube failure by expansion of active material during cycling. Machines are being developed to decrease casting times for positive spines and negative grids, and machine pasting of the large plates will more closely approach SLI battery pasting rates.

Present automatic water-filling systems will become sufficiently reliable to install in the large load-leveling batteries. Also electrical monitoring, scanning, and warning of potentially defective cells will be possible from a central control room -- including monitoring for electrolyte level and specific gravity -- offering a further reduction in maintenance costs.

Section 10

RECOMMENDATIONS

As a result of the study of the state-of-the-art lead-acid load-leveling battery design, there are several areas which offer opportunities for cost reduction, or performance and life improvement. These areas are listed below, not necessarily in the order of priority, and are recommended for consideration for future work:

1. Trade-off studies of system voltage, cell size and series - parallel arrangements. There are two inter-related aspects to this analysis:
    a. A reliability study of large arrays of lead-acid cells, using NASA developed techniques, to give a quantitative assessment of the impact of higher system voltage with many more cells in series versus lower system voltage with more strings in parallel.
    b. A study of the effect of cell and plate size on the overall battery cost. Can the lower production cost of small cells (200-3000 ampere-hours) be effectively carried through to the complete battery installation and result in a viable system at lower cost than the large cells (>10,000 ampere-hours).
2. Carry out heating and cooling tests on large cells to compare actual to theoretical heat evolution. This would provide increased accuracy for the cooling system design and might provide opportunities for system cost reduction.
3. Investigate advanced concepts in design and processing to eliminate or reduce the rate of deterioration with cycling, improve utilization of the active materials and reduce the cost of the inactive materials.

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APPENDIX A

AUXILIARY BATTERY SYSTEMS
FOR
THE LEAD-ACID LOAD LEVELING
BATTERY

By

James B. Doe

TABLE OF CONTENTS

ILLUSTRATIONS

I. AUXILIARY BATTERY SYSTEMS

A. Introduction

One of the many criteria in assessing the lead-acid battery for load leveling is the determination if there is a need to remove heat developed during cycling. This heat is generated by three modes: $T\Delta S$, I^2R, and polarization (activation and concentration). Depending on the temperature of the battery, heat removal can be achieved by radiation, free or natural convection, forced convection, or forced liquid (water) cooling. The removal of this heat is critical because the battery must be maintained below certain limits ($\leq$ 100°F), otherwise, a deterioration in battery performance and battery constituent materials may result.

In any case, once the mode of heat transfer has been established, it is imperative that the equipment required to remove this heat be selected for its operational performance as well as its practical value. Therefore, it is the purpose of the following sections to ascertain the mode of heat transfer, and to delineate the heat removal system requirements for the lead-acid battery load leveling system.

B. Heat Transfer Modes

For the determination of the most important natural mode of heat transfer, it is assumed that the battery is a close packing of cells, that these cells are about 1 inch apart from one another on all sides, except for the perimeter cells, and that all cells are at the same temperature. However, in actual practice, the perimeter cells are cooler and those inside the perimeter are hotter. In any case, the above assumptions are believed to be adequate to describe the overall picture for the battery facility.

1. Radiation

Since it has been assumed that the cells are at the same temperature, there will be no heat transfer via radiation between the parallel jar sides. However, the cell top and the intercell connectors will transfer some heat via radiation. For example, assume that the lead-plated copper intercell connectors are at 110°F and the cell top is at 95°F. Since these areas are small as compared with the totally enclosing air area, one can use(1)

$$Q = F_1 A_1 \varepsilon_1 \sigma_1 (T_1^4 - T_2^4) \tag{1-0}$$

while making the assumption that none of the heat radiated from the cell top or intercell connectors is reflected to it. This is the same as setting the "geometric factor" of F to 1. Other pertinent facts for the calculation are:

Heat receiver: Air

Sources of heat: Intercell connectors and cell top

Q = Heat flow from source, Btu/hr

F = Geometric factor, dimensionless

A = Heat transfer of emitting surface, ft^2

ε = Emissivity, dimensionless

σ = Stefan-Boltzmann constant,
0.173×10^{-8} Btu/(hr)(ft^2) (°R^4)

T_1= Temperature of source, °R

T_2= Temperature of receiver, 545° R (85°F)

	Cell Top	Intercell Connectors
A_1:	2.6 ft^2	1.47 ft^2
ε_1:	0.945	0.281
T_1:	555° R (95°F)	570° R (110°F)

Substituting these values into (1-0)

$$Q_R = 36 \text{ Btu/hr} \tag{1-1}$$

Thus, the heat transfer via radiation (uncorrected for reflection) is not very large; and this is not surprising as energy exchange by radiation is predominantly heat transfer at high temperatures, because the rate of heat transfer depends upon the fourth power of the absolute temperature.

2. Free or Natural Convection

With air flowing around the sides of the cell and over the cell top, it is a distinct possibility that free or natural convection could transfer sufficient quantities of heat. In attempting to analyze the heat transfer situation for the cell, it has been assumed that there is not much mixing of air currents between cell sides and that the surfaces (cell and connector) under evaluation are with free edges. The "surfaces" are separated into vertical and horizontal flat surfaces which are exposed to the surrounding air.

For the trial calculations to ascertain the amount of free convection heat transfer, the following values were assumed:

- The temperature of the surrounding air was 85°F.
- The temperature of the cell container was 95°F.
- The temperature of the intercell connectors was 110°F.

These values could be typical of either the 3- or 5-hour rate cell and are chosen to facilitate the calculations which follow. Under the conditions selected for the calculation, it was ascertained that the heat transfer to air from either a vertical or horizontal surface was laminar. An equation applicable for heat transfer from horizontal surfaces under laminar conditions is:

$$Q = \frac{(0.54)A(t_s-t_a)}{H}\, k_f \left[\left[\frac{g\beta\rho^2 H^3 (t_s-t_a)}{\mu^2}\right]_f \left[\frac{C_p\mu}{k}\right]_f \right]^{1/4} \qquad (1\text{-}2)$$

where

Q = Heat rejected, Btu/hr

A = Horizontal area, ft^2

t_s = Surface temperature of source, °F

t_a = Temperature of air, °F

k_f = Thermal conductivity of air, $\frac{\text{Btu}}{\text{hr-ft-°F}}$

g = Gravitational constant, 4.17×10^8 ft/hr^2

β_f = Coefficient of volume expansion, 1/°F

ρ_f = Density of air, lb/ft^3

μ_f = Viscosity of air, lb/hr-ft

Cp_f = Heat capacity of air, Btu/lb-°F

H = Represents the smaller of the two horizontal dimensions of a rectangular surface, ft.

Whenever a physical property is subscripted by an "f," it means that the property was evaluated at T_f or $T_f = \frac{ta + ts}{2}$. This is commonly called the "film" temperature.

The valid region for this formula is:

$\left[N_{GR}\right]\left[N_{PR}\right]$ region is 10^5 to 2×10^7

where

$$N_{GR} = \text{Grashof Number} = \left[\frac{g\beta\rho^2\ (t_s - t_a)H^3}{\mu^2}\right] \qquad (1\text{-}3)$$

$$N_{PR} = \text{Prandtl Number} = \left[\frac{Cp\mu}{k}\right] \qquad (1\text{-}4)$$

Formula (1-2) was derived from

$$h_c = (0.54)\ \frac{k_f}{H}\left[\left[\frac{g\beta\rho^2 H^3\ (t_s - t_a)}{\mu^2}\right]_f \left[\frac{Cp\mu}{k}\right]_f\right]^{1/4} \qquad (1\text{-}5)$$

and $h_c = \frac{Q}{A(t_s - t_a)}$ (1-6). The h_c is the average free-convection heat transfer coefficient, Btu/hr-ft^2-°F.

Similarly, an equation applicable for heat transfer from vertical surfaces under laminar conditions is:

$$Q = \frac{0.53A\ (t_s - t_a)\ k_f}{H}\left[\left[\frac{g\beta\rho^2 H^3\ (t_s - t_a)}{\mu^2}\right]_f \left[\frac{Cp\mu}{k}\right]_f\right]^{1/4} \qquad (1\text{-}7)$$

but for this equation

H = Vertical height of heat transfer surface, ft

and A = Vertical area, ft^2.

The valid region for this formula is

$$10 < \left[N_{GR} N_{PR}\right] < (2 \times 10^9).$$

Formula (1-7) was derived from

$$h_c = \frac{0.53\ k_f}{H}\left[\left[\frac{g\beta\rho^2 H^3 (t_s - t_a)}{\mu^2}\right]_f \left[\frac{Cp\,\mu}{k}\right]_f\right]^{1/4} \qquad (1\text{-}8)$$

and $h_c = \dfrac{Q}{A(t_s - t_a)}$ (1-6).

The preceding equations were taken from General Electric's Heat Transfer Data Book, G504, pp. 4-8, (1976). The physical properties of air can be taken from this source, G513 pp. 2a-2c, or from the Appendix of Kreith's Principles of Heat Transfer (2nd Edition). A treatment of similar equations was by I. S. Klein of ESB in his paper "Heat Removal From Large Batteries for Load Leveling," 9th IECEC (San Francisco, 1974).

Substituting the values for the vertical and the horizontal areas into the appropriate equations, one obtains a total heat rejection rate of 215 Btu/hr for free convection.

3. Forced Convection

Similarly, for the trial calculation to ascertain the amount of forced convection heat transfer, the following values were assumed:

- The temperature of the surrounding air was 85°F.
- The temperature of the cell container was 95°F.
- The temperature of the intercell connector was 110°F.
- The cooling air velocity was 20 ft/sec (14 mph)(2) and was directed along the length of the cell row, and, thus, only some plate surfaces were considered to be parallel to the air flow. Hence, some surfaces were considered to be under free convection control because of their inherent orientation.

These values could be typical of either the 3- or 5-hour rate cell and were chosen to illustrate the calculations which follow. Under the conditions selected for the calculation, it was ascertained that the heat transfer to air flow from the cell and intercell connector plate surface was laminar. Equations(3) applicable for heat transfer from plate surfaces under forced air convection are:

$$Re_x = \frac{U_\infty X}{\nu} \qquad \underline{\text{Reynolds number}} \qquad (1\text{-}9)$$

$$Nu_x = \frac{h_x X}{k} = 0.332\ Re_x^{1/2}\ Pr^{1/3} \qquad \underline{\text{Nusselt number}} \qquad (1\text{-}10)$$

$$h_x = Nu_x \left(\frac{k}{x}\right) \qquad \underline{\text{Local heat transfer coefficient}} \qquad (1\text{-}11)$$

The average value of the heat-transfer coefficient ($\bar{h}$) is twice h_x or

$$\bar{h} = 2\ h_x \qquad (1\text{-}12)$$

The heat flow is

$$q = \bar{h}A(T_w - T_\infty) \qquad (1\text{-}13)$$

and the above equations apply up to $Re_x = 5 \times 10^5$. Some of the nomenclature above are as follows:

Pr = Prandtl number

U_∞ = Air velocity evaluated at free stream conditions, ft/sec.

X = Length of plate surface, ft.

ν = Kinematic viscosity, ft^2/sec.

k = Thermal conductivity, Btu/hr-ft-°F

A = Plate area, ft^2

T_w = Plate surface temperature, °F

T_∞ = Air temperature, °F

The physical properties above were evaluated at the "film" temperature which is

$$T_f = \frac{T_w + T_\infty}{2}$$

Substituting the appropriate values in the preceding equation, one obtains a value of 425 Btu/hr for forced convection. However, additional heat is transferred by other modes under these conditions, such as free convection and radiation; and this amounts to an additional 134 Btu/hr. Thus, the combination of these two totals results in 559 Btu/hr being rejected from a cell.

Even though this may appear to be a reasonable heat transfer mode, the application of this approach to multi-cells (battery) is dubious. The "dumping" of heat into the battery facility room could lead to room temperature stability problems, large amounts of external cooling air would be required or air-conditioning requirements for the facility would be substantial, large fans would be required to circulate air over the cells, and finally, expensive duct work over the cells may be required to directly control the flow of air over the cells. The forced convection approach was not considered practical for these reasons.

In conclusion, one can readily see that the sum total of the heat rejected for radiation and free convection is about 251 Btu/hr for a cell operating under a set of typical operating conditions. Since the heat rejection rate must be between 800 to 2,000 Btu/hr under cycling, it is apparent that other means of effectively removing heat must be evaluated.

One means of removing heat from the lead-acid cell is by forced liquid (water) cooling of the internal terminal structure. This approach has been successfully utilized for 25 years in lead-acid submarine cells. The next section will detail a similar cooling system for the lead-acid battery proposed for EPRI.

C. Water-Cooling System

1. Description of System

From the preceding section, it has been ascertained that forced liquid (water) cooling of the cell internal structure (terminal strap) would be the most expedient procedure for heat transfer. To develop a relationship between time, cell temperature, heat transfer rate, and cooling water outlet temperature, the following system is delineated.

A lead-acid cell, equipped with two "cored" terminal straps, is to be cooled or heated by pumping a heat-transfer liquid (deionized water) through the "cored" terminal straps at a constant flow rate.

The resulting equations apply to either cooling or heating, and they are applicable if there is no change of phase in the heat transfer medium (water). A model of the lead-acid cell heat transfer system is in Figure A-1. The following equations were developed in Thane R. Brown's article in Chemical Engineering (28 May 1973, pages 99-104) for batch processes and were subsequently adapted to the lead-acid cell.

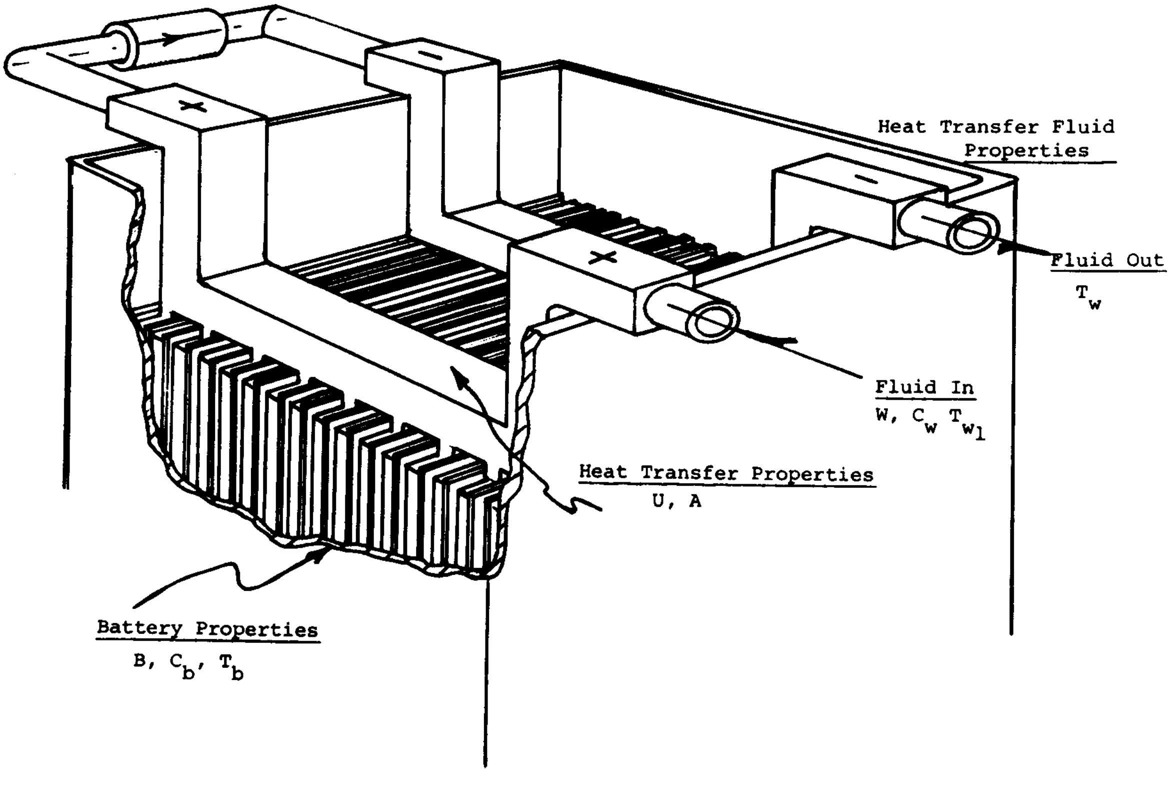


Figure A-1. Model of Heat Transfer System for a Lead-Acid Load Leveling Cell.

A heat balance across the "cored" terminal straps gives:

$$q = UA\Delta T_{1m} = WC_w (T_w - T_{w_1}) = BC_b \left[\frac{-dT_b}{d\Theta} \right] \tag{1-14}$$

Other equations associated with (1-14) are

<u>Logarithmic mean temperature difference</u>

$$\Delta T_{1m} \approx \frac{T_w - T_{w_1}}{Ln \left[\frac{T_b - T_{w_1}}{T_b - T_w} \right]} \tag{1-15}$$

<u>Time Θ</u>

$$\Theta = \frac{BC_b}{WC_w} \left[\frac{1}{1-e^{-UA/WC_w}} \right] Ln \left[\frac{T_{b_1} - T_{w_1}}{T_b - T_{w_1}} \right] \tag{1-16}$$

<u>Temperature of battery at Θ time</u>

$$T_b = (T_{b_1} - T_{w_1}) e^{-K\Theta} + T_{w_1} \tag{1-17}$$

where

$$K = \frac{WC_w}{BC_b} \left[1-e^{-UA/WC_w} \right]$$

<u>Cooling heat transfer rate for battery</u>

$$q = BC_b K (T_{b_1} - T_{w_1}) e^{-K\Theta} \tag{1-18}$$

<u>Heating heat transfer rate for battery</u>

$$q = -BC_b K (T_{b_1} - T_{w_1}) e^{-K\Theta} \tag{1-19}$$

and

<u>Outlet or return temperature of heat transfer media (water)</u>

$$T_w = \frac{q}{WC_w} + T_{w_1} \tag{1-20}$$

The nomenclature for the above equations is:

A = Area of the heat-transfer surface upon which U is based, ft^2

B = Weight of cell, lbs.

C_b = Specific heat of cell, Btu/lb-°F

C_w = Specific heat of heat-transfer medium (water), Btu/lb-°F

T_{w_1} = Temperature of inlet heat-transfer medium (H_2O), °F

T_{b_1} = Temperature of cell, °F

T_w = Temperature of outlet of return heat-transfer medium (H_2O), °F

ΔT_{1m} = Log mean temperature difference, °F

U = Overall heat transfer coefficient, Btu/hr-ft^2-°F

W = Flow rate of heat-transfer medium (water), lb/hr

Θ = Time, hr

The preceding equations were incorporated into a computer program$^{(4)}$, and this program provided the ability to make calculations in a short period of time which is ideal for the study of alternates and for system optimization.

The calculation of certain values used in the above equations deserve comment. The "U" or overall heat transfer coefficient (160 Btu/hr-ft^2-°F) was calculated according to McCabe and Smith$^{(5)}$, and its calculation took into account the geometry of the terminal strap and its relationship to the heat transfer "cored" area. The heat transfer area for both cell terminal straps was 0.348 ft^2, and this area as well as "U" was based on outside areas. The "U" was considered to be constant over the range of cell conditions for these calculations. The cell heat capacity (C_b) was calculated for each cell design, and these values are as follows:

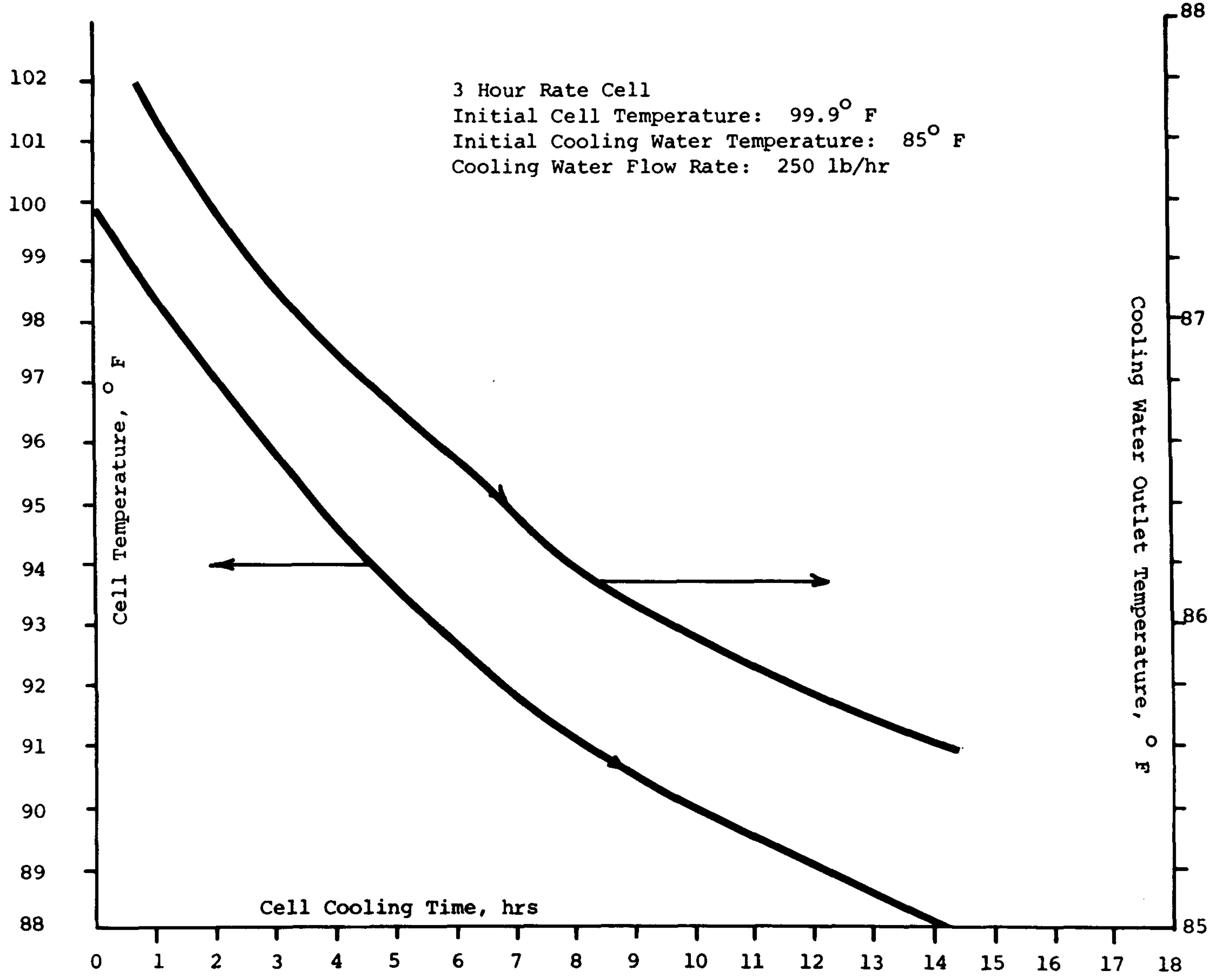
Cell Type	Cell Weight (lbs)	Cell Heat Capacity (Btu/lb-°F)
VLL-45 (5-hr rate)	2102	0.204
VLL-43 (3-hr rate)	1986	0.226

These heat capacity values were essentially constant over the range of cell conditions.

Typical curves generated by the preceding equations via a computer program are in Figure A-2, 3-Hour rate Cell Temperatures Versus Cell Cooling Time and 3-Hour Rate Cell Cooling Time Versus Cooling Water Temperature; Figure A-3, 3-Hour Rate Cell

Heat Transfer Rate Versus Cell Temperature for Various Water Cooling Flow Rates; and Figure A-4, 5-Hour Rate Cell Heat Transfer Rate Versus Cell Temperature for Various Water Cooling Flow Rates.

From repeated calculations for the various flow conditions, it was ascertained that a water cooling rate of 250 lb/hr per cell was ideal. Using this water cooling flow rate, and the cell heat transfer rate at this flow rate and a particular cell temperature, and knowing the applicable heat load, it was possible to develop cell temperature profile curves which could be anticipated during discharge, charge, finishing charge, and equalizing charge periods. In all calculations, it was assumed that the cell was at an average temperature; and no distinction was made for heating zones (for example, the internal current collector region is at a higher temperature than the rest of the cell). Also, for these calculations it was assumed that the heat losses due to radiation and free convection are negligible; and, even though this is not true, one can suppose that adding a touch of "conservatism," i.e., not counting on these modes for appreciable heat transfer, can only assure that the water cooling system will perform adequately. Since the modeling of the water cooling system is based on the individual cell, it is likely that the battery arrangement would perform different from the cell model because as mentioned in I. B. the perimeter cells are cooler then than those inside the perimeter. However, sufficient "conservatism" at appropriate points of the cell model development should keep these differences to a minimum. The above calculations did not consider the heat load from the I^2R heating effects, and again, this heat load is not very large and is balanced by a conservative design approach.



3 Hour Rate Cell
Initial Cell Temperature: 99.9° F
Initial Cooling Water Temperature: 85° F
Cooling Water Flow Rate: 250 lb/hr

Figure A-2. Cell Temperature Versus Cell Cooling Time and Cell Cooling Time Versus Cooling Water Temperature.

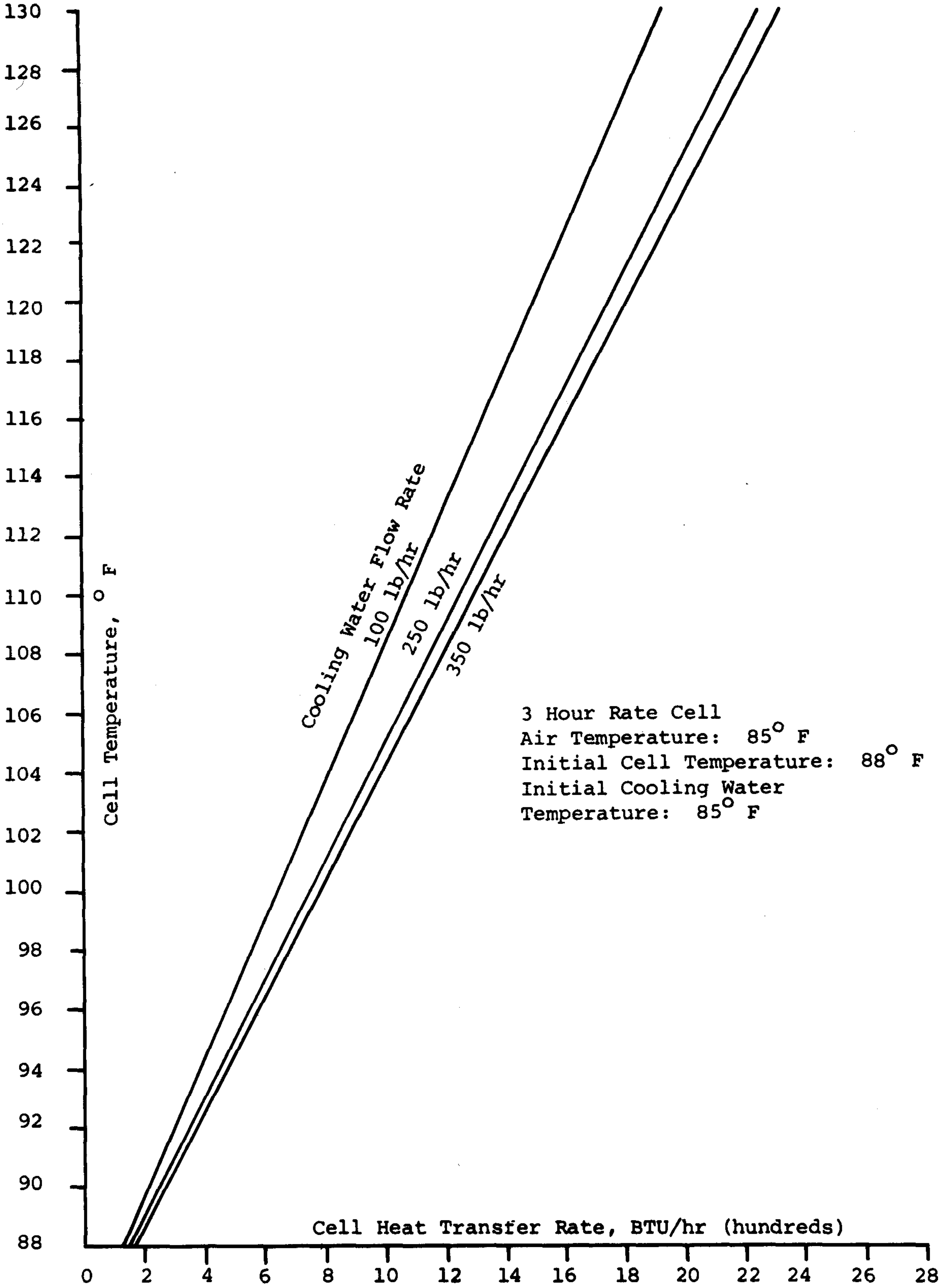


Figure A-3. Cell Heat Transfer Rate Versus Cell Temperature for Various Cooling Water Flow Rates.

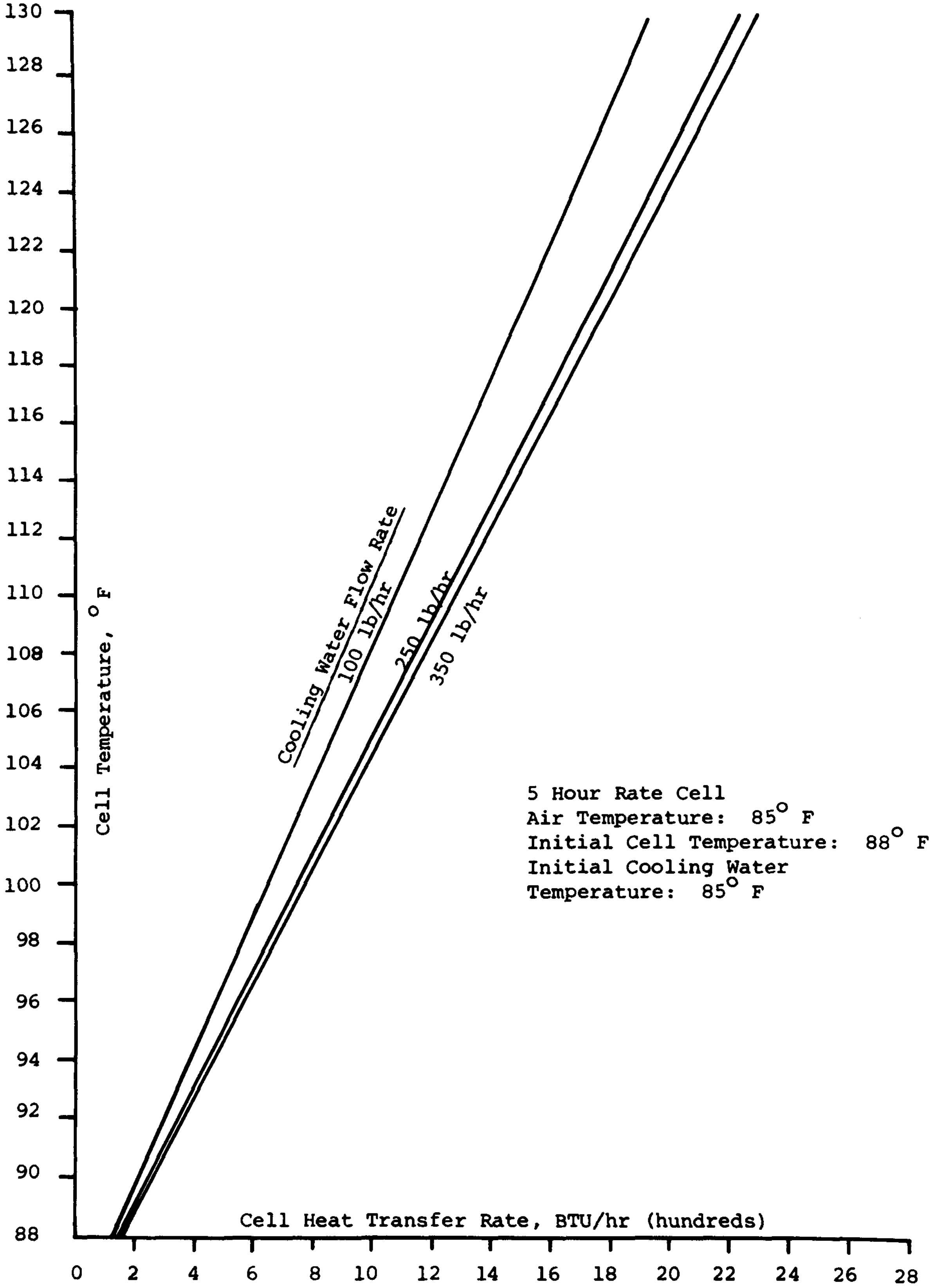
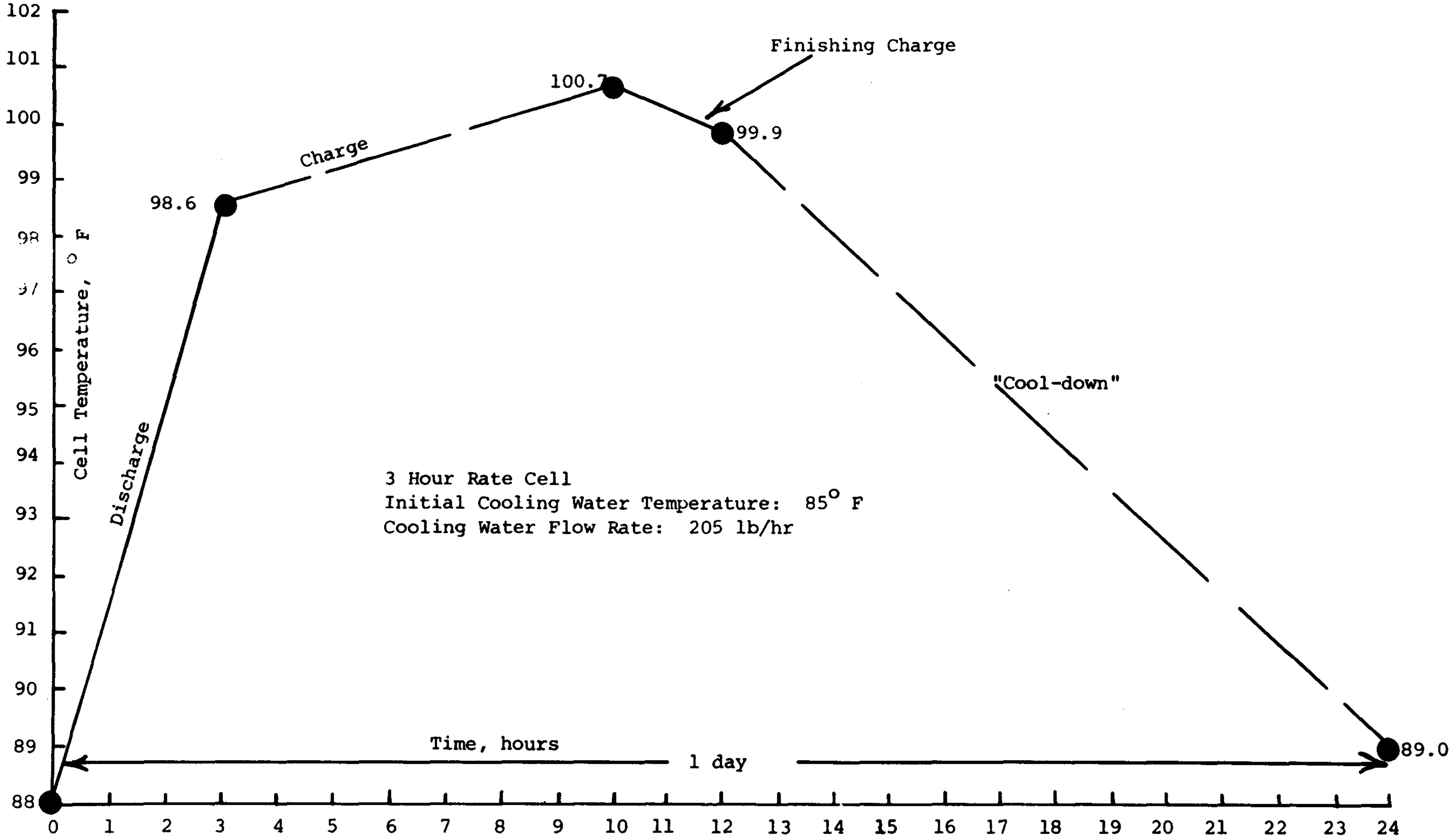


Figure A-4. Cell Heat Transfer Rate Versus Cell Temperature for Various Cooling Water Flow Rates.

Cell (or battery) temperature profiles are given in Figures A-5 to A-7 for the 3-hour rate cell and in Figures A-8 to A-10 for the 5-hour rate cell. An examination of these figures indicates the temperature profile for various periods of operation, such as, discharge, charge, etc. The daily temperature profile for the 3-hour rate cell is in Figure A-5, and for the 5-hour rate cell the profile is in Figure A-8. In either case, there is sufficient time during a daily cycle (24 hrs) to "cool-down" to the initial temperature (88°F). Since the weekend equalizing charge can be applied directly after a finishing charge point or after a battery has equilibrated to room temperature, two battery temperature profiles are possible. Figure A-6 depicts the temperature profile for the 3-hour rate battery when the equalizing charge is applied immediately after the finishing charge period. Figure A-9 depicts the same condition for the 5-hour rate battery. From these plots it is easily seen that even though approximately 106°F is reached during the equalizing charge period, there is sufficient time for the battery to cool down for the remainder of the weekend. For these plots and calculations, it was assumed that the batteries equilibrated to approximately 88°F (where the water cooling system is turned off) before daily cycling and that the room air temperature was 85°F.

A view of a cell top equipped with the auxiliary water-cooling system is shown in Figure A-11. Pumps at opposite ends of a battery section feed cooling water supply headers for each half of a battery section. Each header has a manifold structure from which each cell is supplied with the required cooling water. After a single cell cooling water pass is completed, it is "dumped" into the cooling water return header. From here the return water is pumped up to roof-mounted cooling towers. The heat load is split between two cooling towers, and each are rated at 600,000 lb water/hr for the 3-hour rate battery and 850,000 lb water/hr for the 5-hour rate battery. After the water has been cooled it is pumped into the reservoir which feeds the cooling water supply pumps. A 2% by-pass from this reservoir is passed through ion exchangers (self-contained regeneration units) to remove dissolved impurities which would increase the conductivity of the deionized water. Once the



3 Hour Rate Cell
Initial Cooling Water Temperature: 85° F
Cooling Water Flow Rate: 205 lb/hr

Figure A-5. Cell Temperature Versus Time for a Daily Cycle.

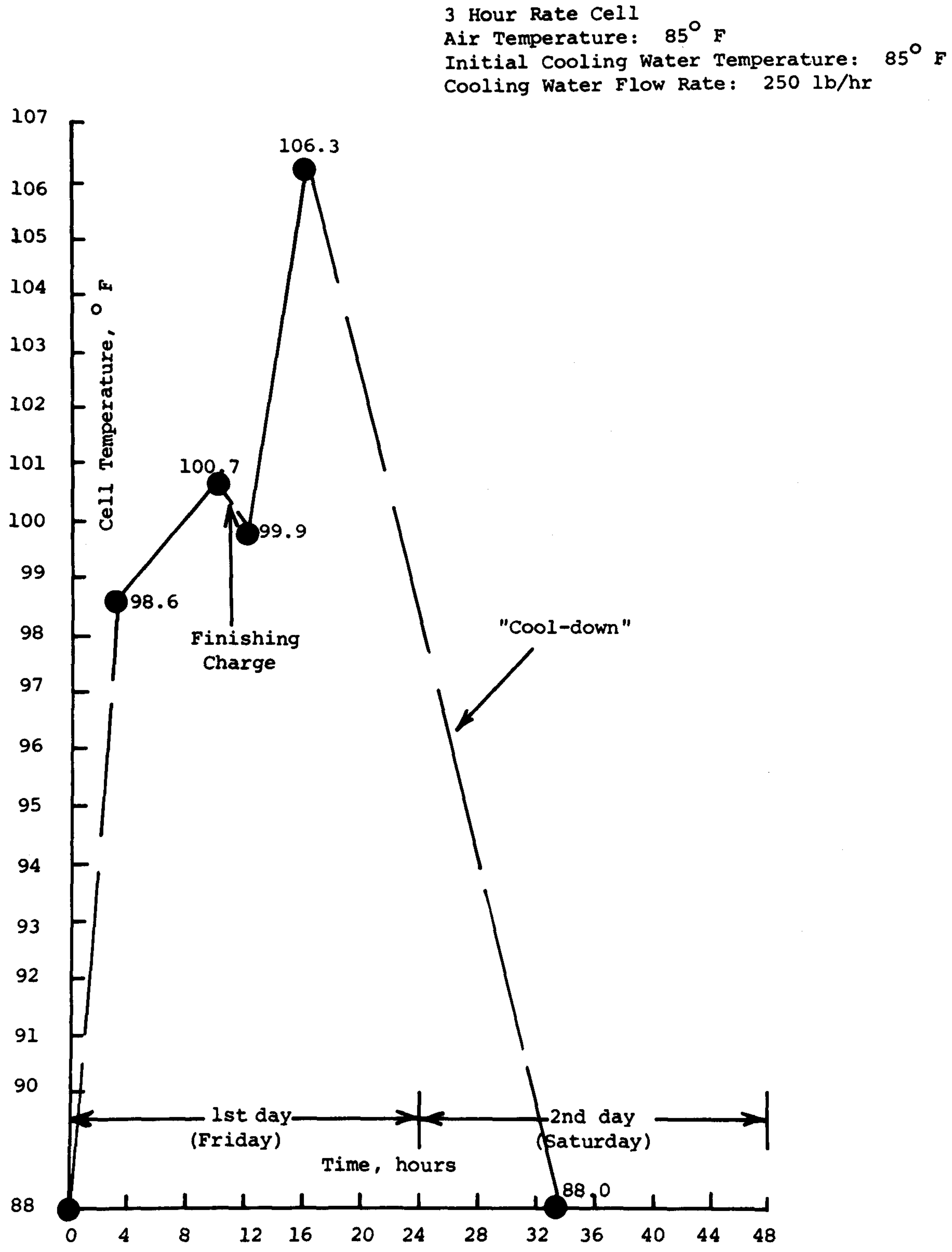
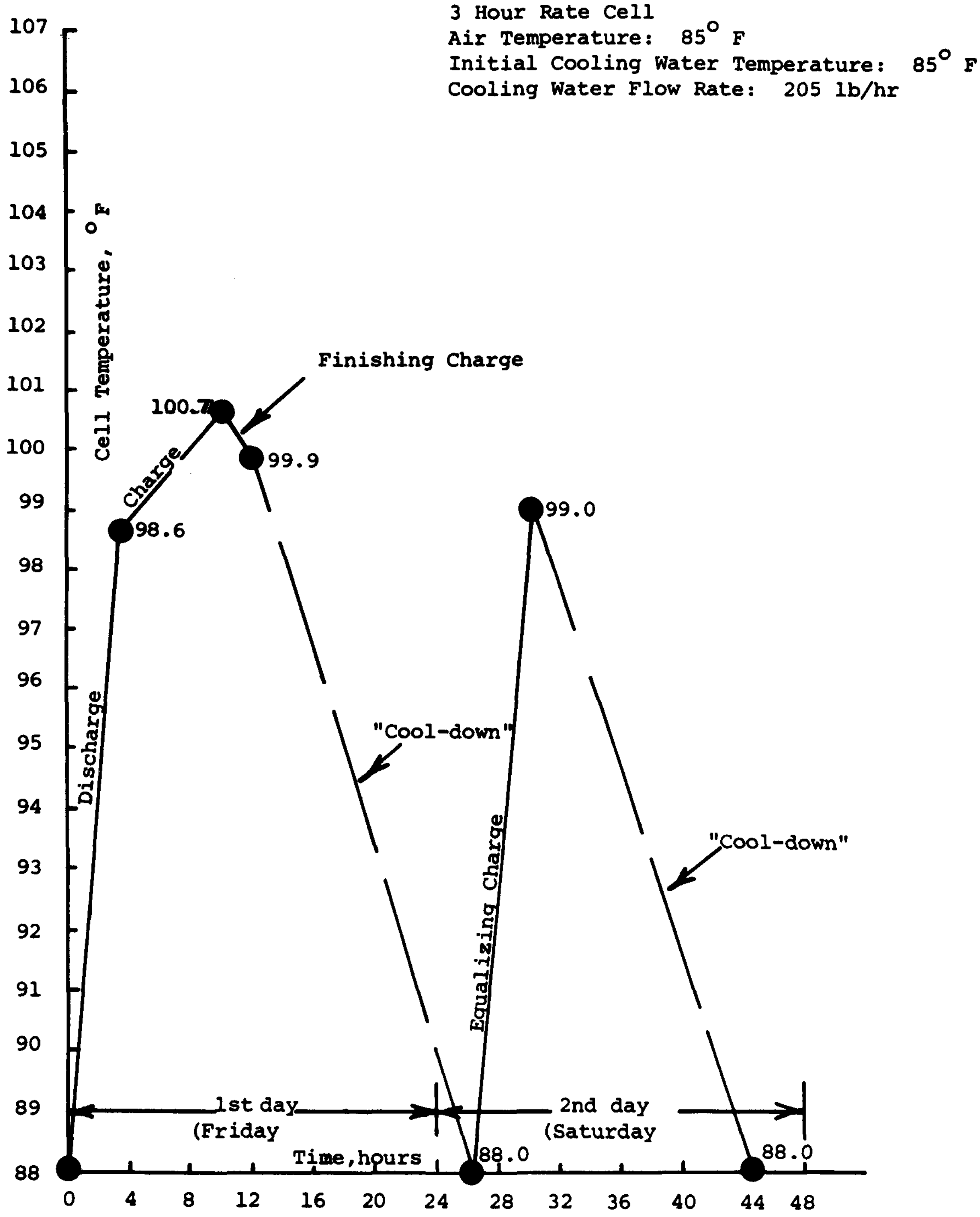


Figure A-6. Cell Temperature Versus Time for Weekend Cycle No. 1.



3 Hour Rate Cell
Air Temperature: 85° F
Initial Cooling Water Temperature: 85° F
Cooling Water Flow Rate: 205 lb/hr

Figure A-7. Cell Temperature Versus Time for Weekend Cycle No. 2.

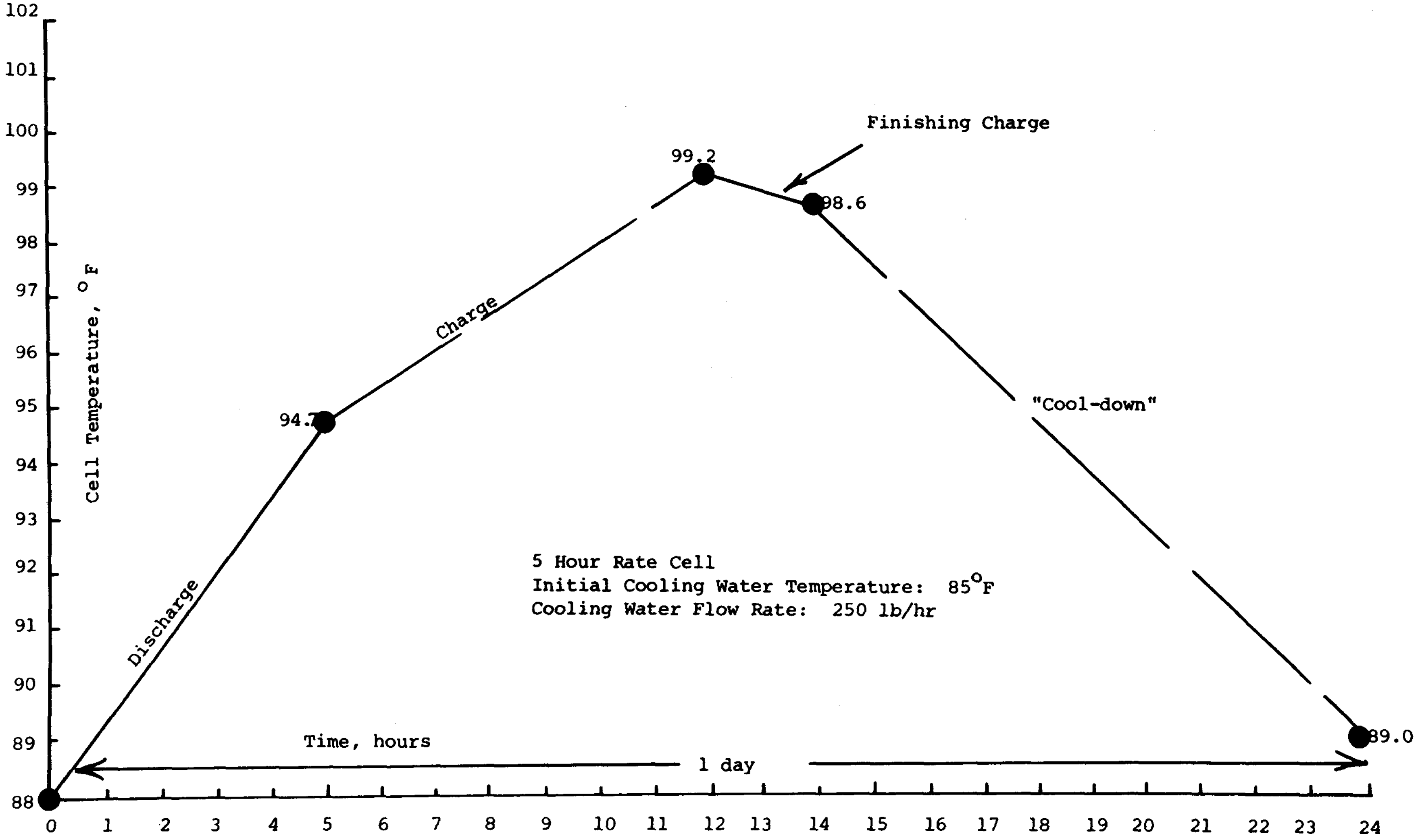


Figure A-8. Cell Temperature Versus Time for a Daily Cycle.

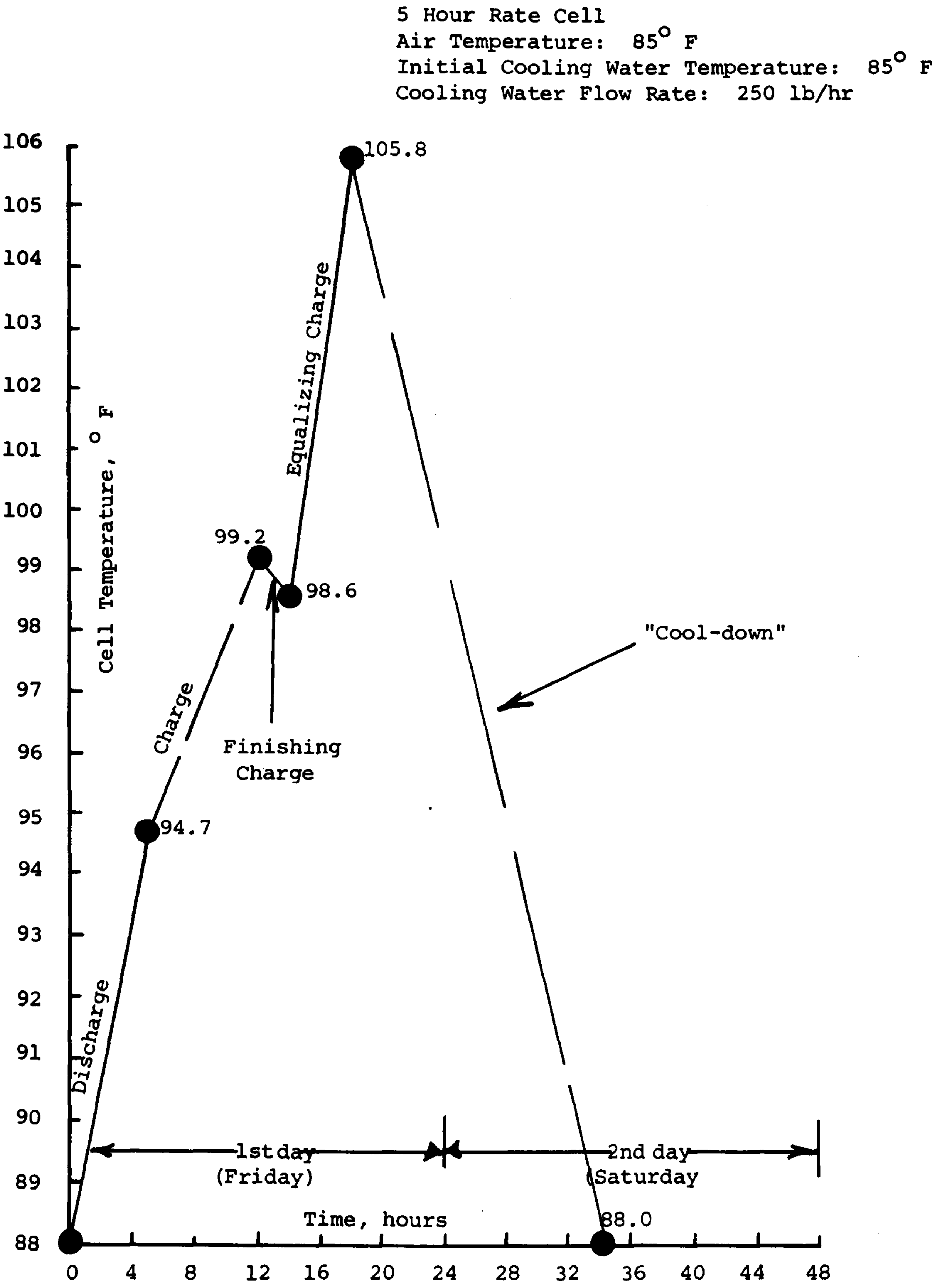


Figure A-9. Cell Temperature Versus Time for Weekend Cycle No. 1.

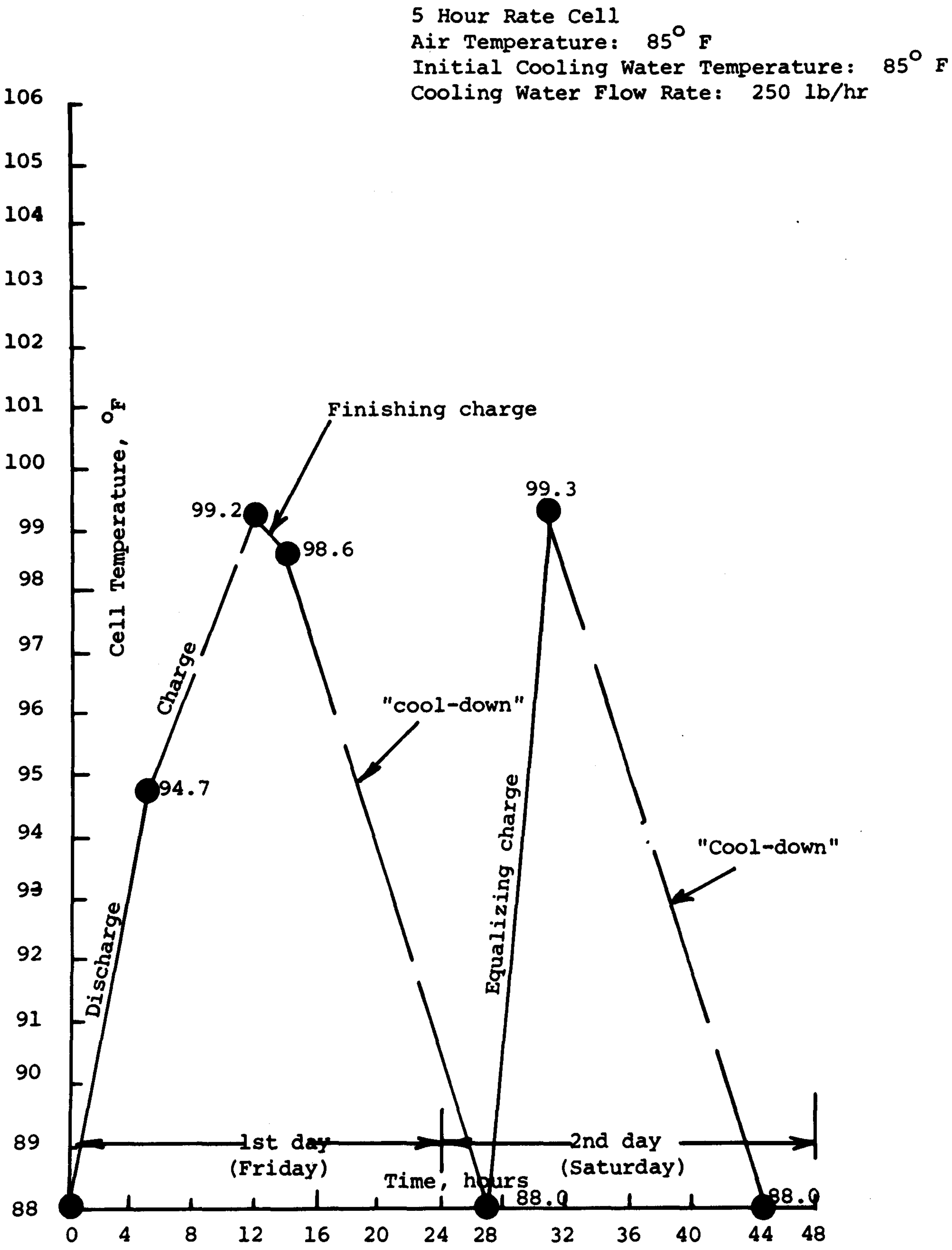


Figure A-10. Cell Temperature Versus Time for Weekend Cycle No. 2.

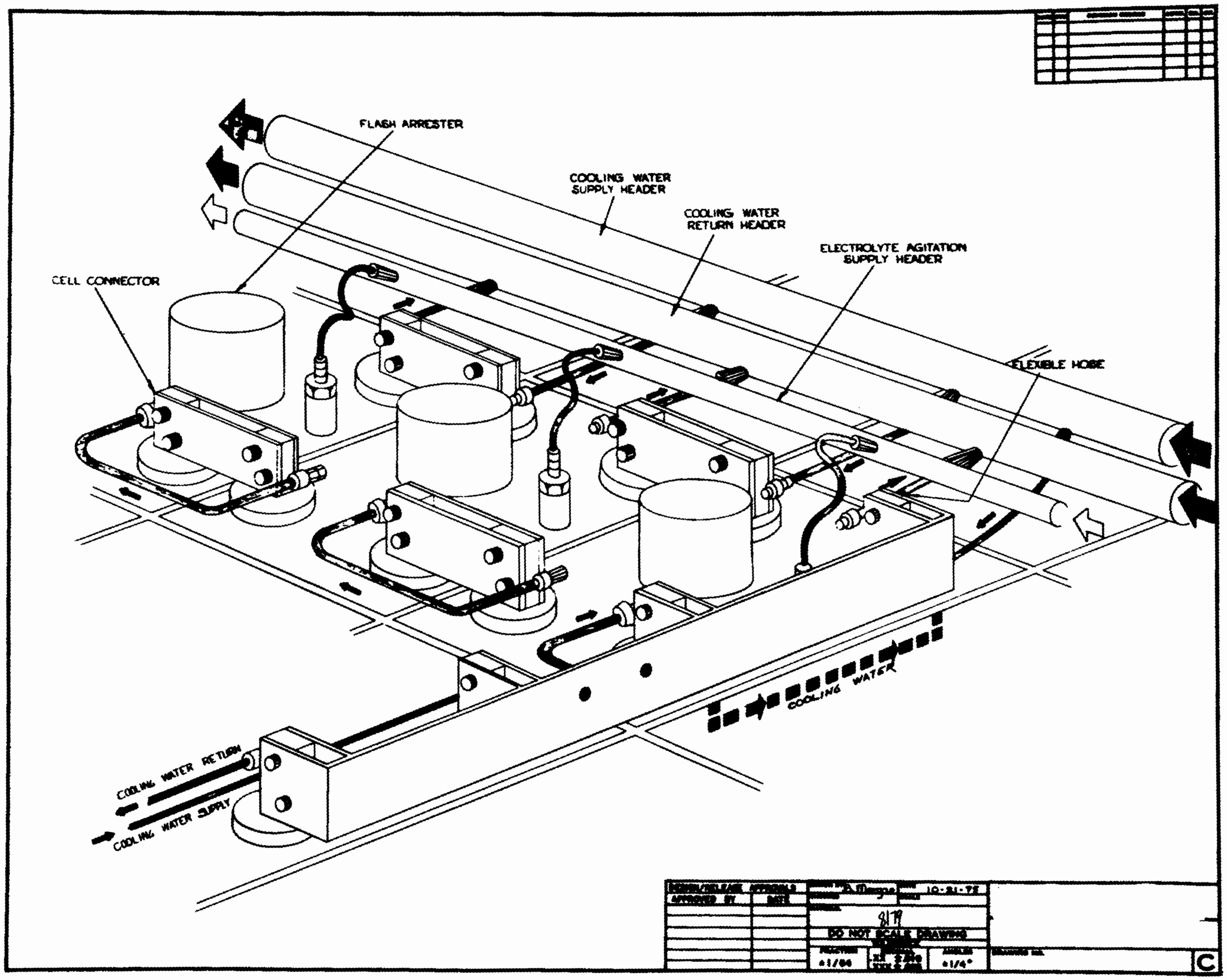


Figure A-11. Cell Cover with Auxiliary Systems.

water has been cleaned of these impurities, it is fed into the cooling water supply system. All components which would come into contact with the deionized water will be plastic or plastic-coated except for the copper heat transfer tubes in the terminal straps and the cooling towers which will have a mixture of plastic and stainless steel components for minimum water contamination and maximum service life. The water cooling system is self-contained for every half battery section. As mentioned previously, the cooling towers distribute the heat load for each half-section between them. The heat rejected from the cooling water could be put to use in heating the battery building under certain conditions, be totally rejected to the environment, or stored for heating the battery in the winter months.

Since the ambient conditions will dictate the cooling tower exit water temperature, it is anticipated that the minimum exit water temperature will be approximately 85°F. Undoubtedly, this exit temperature would be lower in winter; but most of the year 85°F will be a good average temperature.

In extremely cold locations the cooling water sump would be located inside the building to prevent freezing; and a remote sump located inside the building will prevent freezing of the water in the tower pan. Heat load capacity control will also be exercised to prevent freezing while the cooling tower is operating under freezing conditions.

D. Warm-Up System

The present water-cooling system can also be used to circulate hot water to warm up the lead-acid cell to the operational temperature (60°F). Assuming that hot water is available at 130°F and that the initial temperature of the cell is 45°F, it would take the 3-hour rate cell about 1.8 hours to reach 60°F and the 5-hour rate cell about 1.7 hours to reach 60°F. The hot water flow rate for these warm-up cases would be about 250 lb/hr (30 gal/hr).

E. Air-Lift System

The "air-lift" pump agitates the cell electrolyte so that uniform mixing occurs and that a minimum of electrolyte stagnation is prevalent between the top and bottom of the cell. Each cell is equipped with an "air-lift" pump and receives its air supply via a cell manifold system (See Figure A-11). The air is supplied by a low pressure rotary vane compressor, and all air is effectively cleaned of dust, etc. before entering the manifold lines. The system is designed to provide a minimum of 0.03 ft^3/min of air per cell, and is self-contained for every row of cells. The air manifold and air supply lines to the lift-pump are rigid plastic. Installation of the air support lines and connection points are designed to be "fool-proof" in preventing clogged or pinched lines.

II. CELL AND BATTERY ELECTRICAL CONNECTIONS

Each module of cells will have lead-plated annealed copper intercell connectors between terminals. There are two intercell connectors between a terminal, and their current rating is sufficient for that expected during battery operation. Interrow connectors will consist of "U"-shaped lead-plated copper bars joining adjacent cell terminals. The intercell and "U" interrow connectors are pictured in Figure A-11. The two-post terminals do not have the capability of repetitious one-hour rate emergency discharges.

III. LITERATURE CITED

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3. J. P. Holman, Heat Transfer, 2nd Edition, McGraw-Hill, New York, 1968, pp. 118-152.
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5. Warren L. McCabe and Julian C. Smith, Unit Operations of Chemical Engineering, 2nd Edition, McGraw-Hill, New York, 1967, pp. 305-316.

APPENDIX B

LEAD SUPPLY

(Thousand Short Tons)(2)

Lead Supply Source	1971	1972	1973
A. World Mine Production			
U. S.	578	619	603
Rest of world	3165	3145	3203
Total	3743	3764	3806
B. U. S. Supply			
Domestic smelters	1156	1186	1226
Government stockpile release	13	45	211
Imports, metal	193	246	178
Industry stocks	326	247	264
Total	1688	1724	1879
C. U. S. Demand			
Gasoline additives	264	279	274
Transportation(1)	625	668	700
Construction	100	88	86
Paints	81	89	109
Electrical	131	128	135
All other	234	200	294
Total	1435	1452	1598
D. U. S. Primary Demand (Industrial demand minus secondary)	945	954	1059
E. Load Leveling Battery Usage (Projected)	500 MWhr/yr	1000 MWhr/yr	4000 MWhr/yr
100 MWhr battery	19	38	153
60 MWhr battery	12	25	98

(1) Battery industry included.

(2) Bureau of Mines Staff, "Minerals in the U. S. Economy; Ten Year Supply-Demand Profiles for Minerals and Fuel Commodities," 1974, p. 44.