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**ANNUAL REPORT FOR 1980 ON
RESEARCH, DEVELOPMENT, AND DEMONSTRATION
OF LEAD-ACID BATTERIES FOR
ELECTRIC-VEHICLE PROPULSION
Contract No. 31-109-38-4207**

by

Exide Management and Technology Company

ARGONNE NATIONAL LABORATORY, ARGONNE, ILLINOIS
Operated for the U. S. DEPARTMENT OF ENERGY
under Contract W-31-109-Eng-38

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Annual Report for 1980 on
RESEARCH, DEVELOPMENT, AND DEMONSTRATION
OF LEAD-ACID BATTERIES FOR
ELECTRIC-VEHICLE PROPULSION

Prepared for
The Office for Electrochemical Project Management
Argonne National Laboratory
Under Contract No. 31-109-38-4207

by
Exide Management and Technology Company
Yardley, Pennsylvania

March 1981

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1.0 Executive Summary

1.0.1 ISOA Lead-Acid Battery Development

The initial phase of Contract No. 31-109-38-4207 entitled "Improved State of the Art" herein identified as ISOA was divided into two major development efforts. One was the improvement of electric vehicle batteries using flat pasted positive plates and the second was for a tubular long life positive plate.

A factorial experiment FP-1 was designed for the investigation of 32 component variables based on a flat pasted positive plate configuration. The experiment tested 96 - six volt batteries for characterization at 0, 25, and 40°C and for cycle life capability at the 3 hour discharge rate with a one cycle, to 80% DOD, per day regime.

The conclusions of this factorial experiment is under Section 1.1.11 of this report.

The second development effort was a factorial experiment designed to study the relationship of 32 component variables based on a tubular positive plate configuration. This experiment TP-1, required the assembly of 128 - six volt batteries for testing at various discharge rates at 0, 25, and 40°C along with cycle life testing at 80% DOD of the 3 hour rate. Of the 96 batteries under test, 75 remain on cycle life testing with 17 batteries having in excess of 365 life cycles.

Preliminary conclusions indicate:

1. The tubular positive plate is far more capable of withstanding deep cycles than is the flat pasted plate.
2. As presently designed 40 Whr/Kg can not be achieved. 37.7 Whr/Kg was the best tubular data obtained.
3. Electrolyte circulation is impaired due to the tight element fit in the container.
4. A redesign is required to reduce the battery weight which will improve the Whr/Kg value.

This redesign is complete and new molds have been ordered.

Concurrent with the work of FP-1 and TP-1 Exide undertook a computer study of grid designs to reduce the voltage drop across the grid hence achieve a higher battery terminal voltage. Molds were purchased for these new radial designs and plates utilizing these grids are under test.

A subcontract to Battelle Columbus Laboratories has been completed and their report is attached as Appendix I of this report. The contract required an independent study for an optimized grid design. Their study and work has resulted in a unique grid design which has been successfully cast, processed; and is presently undergoing test.

The data obtained from the two grid studies above, along with the analysis of the FP-1 factorial experiment will be used to finalize a flat pasted positive plate design for the ISOA phase.

1.0.2 Advanced Lead-Acid Battery Development

The second major phase of the contract required the design and development of an Advanced Lead Acid Battery for electric vehicle applications. Exide's initial approach was to seek weight reductions of the basic components with emphasis on the negative plate grid structure. Two such developments have been successful to date.

A negative grid has been developed using injection molded plastics as the base structure resulting in a weight reduction of 45% for each grid or a weight reduction of 5% for a 6 volt module. The conductivity of this grid is equal to that of a conventional lead cast grid.

The second development is an electroformed grid structure having a weight 49% less than a conventional lead grid with a conductivity three times as great. A weight reduction of 6% for a 6 volt module will be achieved with this grid.

1.0.3 Battery Subsystems

In addition to the major study phases of the contract, design and development work continued on two related aspects of batteries for electric vehicle applications.

The designs of several electrolyte circulating systems are being tested to determine whether a reduction in overcharge can be achieved without a loss in battery capacity or cycle life.

A report was issued 5 May 1980 entitled "Charging of Lead Acid Batteries for Electric Vehicles" which summaries proper charging procedures. The report, in part, is included under Section 1.6 of this Annual Report.

1.1 ISOA Battery Program

1.1.1 FP-1 Factorial Experiment History

This initial factorial experiment was designed as a screening test to evaluate battery components to aid in the design of a battery which would meet the established goals of the ISOA phase of Contract ANL 31-109-38-4207.

Four positive paste formulations were selected.

1. FP-P1 contained 100% GOX lead oxide.
2. FP-P2 contained 90% GOX lead oxide plus 10% of red lead. A proprietary additive in the amount of 0.5% of the oxide weight was added to reduce the plate weight.
3. FP-P3 contained 100% GOX lead oxide with 0.5% of the additive.
4. FP-P4 contained 100% GOX lead oxide with 0.25% additive.

Two commercially available microporous separators were used in conjunction with a layer of 0.076 mm thick glass mat.

1. Microporous hard rubber (Amerace) supplied by American Hard Rubber Co.
2. Microporous polyethylene (Daramic) supplied by W. R. Grace Co.

Two concentrations of battery grade sulfuric acid were included in the test to determine if an increase in concentration would improve the battery capacity sufficient to offset the added weight of the more concentrated solution.

1. 1.285 sp. gr. (38 Wt %)
2. 1.315 sp. gr. (41.4 Wt %)

Two construction variations were included.

1. Twenty-three plate elements with outside negative plates (12 negative and 11 positive per cell).
2. Twenty three plate elements with outside positive plates (12 positive and 11 negative per cell).

The above design improvements involve parameters of both dependent and independent variables. The program master schedule did not allow sequential testing of variables. A factorial experiment was used to provide data on various components concurrently.

The following tabulations shows the 32 variables that were tested. FP-N1 negative plates were used in all batteries.

<u>Exp. Batt. Spec. No.</u>	<u>Pos. Plate Code</u>	<u>Separator* Type</u>	<u>Construction**</u>	<u>Final Sp.Gr.</u>
5716	FP-P1	R	ON	1.285
5717	"	R	OP	"
5718	"	P	ON	"
5719	"	P	OP	"
5720	FP-P2	R	ON	"
5721	"	R	OP	"
5722	"	P	ON	"
5723	"	P	OP	"
5724	FP-P3	R	ON	"
5725	"	R	OP	"
5726	"	P	ON	"
5727	"	P	OP	"
5728	FP-P4	R	ON	"
5729	"	R	OP	"
5730	"	P	ON	"
5731	"	P	OP	"
5758	FP-P1	R	ON	1.315
5759	"	R	OP	"
5760	"	P	ON	"
5761	"	P	OP	"
5762	FP-P2	R	ON	"
5763	"	R	OP	"
5764	"	P	ON	"
5765	"	P	OP	"
5766	FP-P3	R	ON	"
5767	"	R	OP	"
5768	"	P	ON	"
5769	"	P	OP	"
5770	FP-P4	R	ON	"
5771	"	R	OP	"
5772	"	P	ON	"
5773	"	P	OP	"

*Separator Type

R = Microporous hard rubber supplied by Amerace

P = Microporous polyethylene supplied by W. R. Grace Co.

**Cell Construction

ON = Outside negative plates.

OP = Outside positive plates.

NOTE: All positive plates wrapped top to bottom with Dexter Glass Co. 0.076mm glass mat.

1.1.2 Positive Plates

are: All four plate variations used AC2GW grids whose specifications

- o Thickness 1.83 mm
- o Alloy 6% Sb-lead
- o Weight 97.1 gm nominal

Quality Control data taken during plate manufacture were:

- o Plate Code FP-P1
 - Grid Thickness 1.92 mm
 - Grid Weight 101.7 gm
- o Dry Plate Data
 - Dry density 4.54 - 4.67 gm/cc
 - Dry active material weight 193.7 - 195.3 gms
- o Plate Code FP-P2
 - Grid Thickness 1.92 mm
 - Grid Weight 101.7 gm
- o Dry Plate Data
 - Dry density 4.25 - 4.28 gm/cc
 - Dry active material weight 157.9 - 166.9 gm
- o Plate Code FP-P3
 - Grid Thickness 1.92 mm
 - Grid Weight 101.7 gm
- o Dry Plate Data
 - Dry density 3.94 - 4.05 gm/cc
 - Dry active material 149.5 - 153.8 gm
- o Plate Code FP-P4
 - Grid Thickness 1.92 mm
 - Grid Weight 101.7 gm

- o Dry Plate Data

Dry density 4.00 - 4.03 gm/cc

Dry active material 155.2 - 179.8 gms

1.1.3 Negative Plates

FP-1 Factorial Experiment negative plate nomenclature is FP-N1.
The FP-N1 uses the AC4GW grid whose specifications follow:

- o Thickness 1.47 mm
- o Alloy 0.19% Ca Lead
- o Weight 75 gm nominal

Quality Control data taken during plate manufacture were:

- o Plate Code FP-N1

Grid Thickness 1.43 mm

Grid Weight 73.5 gm

- o Dry Plate Data

Dry density 4.86 gm/cc

Dry active material 158.8 - 160.5 gm

1.1.4 Separators

Quality Control Data as Received:

- o Microporous Hard Rubber

Length	171.0 mm	Std. Dev. 0.369
Width	165.1 mm	Std. Dev. -0-
Thickness	1.4 mm	Std. Dev. 0.01

- o Microporous polyethylene

Length	171.7 mm	Std. Dev. 0.52
Width	162.4 mm	Std. Dev. 0.52
Thickness	1.5 mm	Std. Dev. 0.02

1.1.5 Battery Assembly

Thirty-two battery specifications were prepared. The Experimental Battery Specifications (EBS) are 4 digit numbers used throughout the report, followed by a 3 digit battery serial number.

Representative cells were assembled at the EXIDE Company to check assembly procedures and component fit.

Ninety-six batteries were built, three per each specification. A total of two-hundred eighty-eight 23-plate cells, they were hand stacked and burned. They were built in two groups; one of 72 batteries and one of 24.

The first group of 72 batteries were assembled with FP-P1, FP-P2 and FP-P3 positive plates while the second group of 24 batteries was built with FP-P4 positive plates.

The positive to negative ratios of the dry active material weights, by specification, are shown below:

Batt. Spec. Nos.		Total Pos. Gms	Total Neg. Gms	Ratio P/N
1.285 Acid	1.315 Acid			
5716	5758	5958	5536	1.08
5717	5759	6499	5074	1.28
5718	5760	5958	5536	1.08
5719	5761	6499	5074	1.28
5720	5762	4940	5536	0.89
5721	5763	5389	5074	1.06
5722	5764	4940	5536	0.89
5723	5765	5389	5074	1.06
5724	5766	4940	5536	0.89
5725	5767	5389	5074	1.06
5726	5768	4940	5536	0.89
5727	5769	5389	5074	1.06
5728	5770	4940	5536	0.89
5729	5771	5389	5074	1.06
5730	5772	4940	5536	0.89
5731	5773	5389	5074	1.06

1.1.6 Testing - Characteristics

At the EXIDE Management & Technology Company, before testing, intermediate cell leads were attached to all the batteries so individual cell voltages could be recorded.

The characteristics testing regime was as follows:

<u>Cycle</u>	<u>Disch. Rate Amps</u>	<u>Disch. Rate Hrs.</u>	<u>Starting Temp °C</u>
1	40	5	25
2	60	3	25
3	75	2	25
4	140	1	25
5	10	20	25
6	240	0.5	25
7	40	5	0
8	60	3	0
9	75	2	0
10	140	1	0
11	240	0.5	0
12	40	5	0
13	60	3	40
14	75	2	40
15	140	1	40
16	240	0.5	40

Recharging was done in two steps - a high-rate mode and a low-rate mode. The high-rate mode was controlled at 40 amperes to 90 percent of the discharge capacity. The low-rate mode was held at 5 amps until a total of 115 percent of the discharge capacity is reached.

Twenty-four hours was allotted for recharging (during characteristics testing only) but a shorter time can be used if all conditions are met.

1.1.7 Characteristics Testing

Upon completion of the electrochemical conversion known as formation, 64 batteries (lots 1 & 3) were subjected to a series of constant current discharges at each of three starting temperatures.

1. Rates of 40, 60, 75, 140 and 240 amperes were used.
2. Temperature at start of the discharges were 25, 0, and 40°C.

A summary in tabular form is shown in Tables 1 & 2. Each data point is the average of two batteries and indicate the Whr/Kg obtained to the specified final voltage. In several cases the data is omitted due to equipment malfunctions or an inability to print out the data from the magnetic tapes.

1.1.8 Life Cycle Testing

Thirty two batteries (lot 2) were placed directly onto automatic life cycle test, following formation, in an attempt to get cycle life data as soon as possible.

The 64 batteries which were subjected to the characteristics tests were placed on automatic life cycle test upon completion of the characteristics regimes.

The life test equipment is designed to handle eight 3-cell batteries per circuit or loop hence the batteries were segregated by expected capacity and all were run at the same time regime with slightly varying current rates. The test regime was:

1. Discharge 2.4 hours or until battery reached 5.10 V. Current rates 54 to 60 amps.
2. Open circuit rest 1.4 hours.
3. Hi rate charge 5.9 hours - current rates 15.4 to 17.1 amps.
4. Low rate charge 7.0 hours - current rates 8.6 to 10.6 amps.
5. Open circuit rest 1.4 hours.

The batteries received from 115 to 123% recharge on each cycle.

1.1.9 Internal Inspection at End of Life

When all batteries had been removed from life cycle testing each was disassembled and every component examined to determine its condition. The salient points of an internal inspection are:-

- o Elements
 1. Short circuits due to accumulation of lead particles dislodged from the plate surfaces.
- o Negative plates
 1. Shrinkage or expansion of the active material.
 2. Zones or areas of sulfated material.
- o Positive plates
 1. Texture of the active material.
 2. Strength of the grid metal.
- o Separators
 1. Pin holes or perforations.

1.1.10 Results

- o Characterization Tests

As could be predicted the rate of discharge is the most significant factor in the power output obtained from the lead acid storage

battery system. At high rates of discharge currents (short time intervals) the limiting factor is the rate of diffusion of the electrolyte both between the plates and within the pores of the plate active materials.

The temperature of the batteries at the start of discharge has a significant effect on the power output of the lead acid system since it is actually a chemical reaction dependent on the rate of reaction and the mobility or rate of diffusion of the electrolyte.

Additives to the positive paste formulations did decrease the dry density of the active materials within the range of 7 to 13% resulting in a more porous structure within the plate. The reduction in dry density also resulted in a total reduction of battery weight within the range of 2 to 3%.

Increases in capacity at the C/3 rate were evident within the range of 6 to 11% on batteries whose only variable was the positive paste additive.

Throughout all of the characteristics tests the use of microporous polyethylene separators produced battery voltages slightly higher than similar batteries separated with microporous rubber separators.

The concentration of electrolyte in the battery has an effect when the temperature interaction is examined.

o Life Cycle Testing

See Tables 3, 4 and 5 for total life cycles of each battery in Lots 1, 2 and 3.

An analysis of variance, using total cycles as the criteria (characteristics plus life cycles where applicable) on the FP-1 factorial experiment showed the following factors to be significant at the 95% confidence level.

Positive paste formulation
Electrolyte concentration
Separator type
Paste - separator interaction

There appeared to be no benefit derived from the use of the elements with outside positive plates as compared to the batteries whose elements were constructed with outside negative plates.

Although the use of the additive in the positive active material improved the initial capacities during the characteristics tests the material structure did not hold the material in place during prolonged life cycling.

The use of the higher concentration of electrolyte (1.315 specific gravity) has a slight favorable effect during initial testing. However, it appeared to have a detrimental effect on battery life by causing

more severe sulfation of the negative plates. This sulfation was, we believe, aggravated by the tight element fit in the cell compartment which restricted the circulation of electrolyte.

Batteries containing microporous polyethylene separators, 1.285 specific gravity electrolyte and positive paste formulation without additive demonstrated the best total number of discharge cycles.

o Internal Inspection

It is common practice to use a fiber glass retaining mat against the positive plate surface to restrict the shedding of the positive plate active material during the overcharge portion of the charge cycle. The choice of an ultra-thin mat (0.076mm) did not serve this purpose in the experiment. Internal inspection revealed that the glass mat had disintegrated and appeared to restrict the flow of electrolyte by its accumulation in wads or lumps near the top or bottom of most elements.

The terminology "moss" is used to describe the accumulation of particles of positive active material which becomes dislodged, converts to lead sulfate particles, and these particles are entrapped or settle on the negative plates and/or straps. Below is a tabulation of the number of batteries, by positive paste formulation and acid concentration which had moss accumulations.

Pos. Paste Formulation	1.285 Sp. Gr.			1.315 Sp. Gr.		
	No Moss	Moss Non-Shorting	Shorted Moss	No Moss	Moss Non-Shorting	Shorted Moss
FP-P1	7	4	1	8	4	-0-
FP-P2	6	6	-0-	6	4	2
FP-P3	7	4	1	5	4	3
FP-P4	3	6	3	5	6	1

Another criteria of examination at the end of a battery's useful life, is the condition or texture of the positive active material. This is an empirical value and is compared to the texture of the positive material of a newly electro-formed plate. The following tabulation shows the positive plate material condition by electrolyte concentration and paste formulation.

Pos. Paste Formulation	1.285 Sp. Gr.				1.315 Sp. Gr.			
	Firm	Slightly Soft	Soft	Very Soft	Firm	Slightly Soft	Soft	Very Soft
FP-P1	6	2	3	1	1	7	4	-0-
FP-P2	3	1	8	-0-	2	2	8	-0-
FP-P3	4	1	7	-0-	1	3	7	1
FP-P4	3	2	7	-0-	1	2	8	1

Examination of the physical condition of the separators found them all to be mechanically sound, free of pin holes or perforation with no sign of chemical attack or oxidation from the acid or lead dioxide of the positive plate.

Negative plates of all batteries were inspected to determine their condition regarding material expansion, shrinkage, blisters, gas pockets and amount of sulfated areas within the plates.

All of the negative plates used in the experiment were made at the same time hence we found that all were free of shrinkage and had normal expansion. There was no evidence of gas pockets which are depressions caused by entrapped gas which prevents normal material expansion.

The plates were free of blisters which are caused by non-porous surface areas which trap gas beneath the surface and the resulting pressure blows the surface loose causing blisters.

The degree or amount of inactive areas of lead sulfate found in the plates is shown in the following tabulation. Where the element construction had outside negative plates the condition of the two outside plates is not included in the summary.

Negative Plate Sulfation
Percent of Total Plate Area

VS.

Number of Batteries

By Total Battery Count

	1.285 Sp. Gr.				1.315 Sp. Gr.			
	0-25%	26-50%	51-75%	76-100%	0-25%	26-50%	51-75%	76-100%
FP-P1	8	2	2	2	-0-	4	7	-0-
FP-P2	7	4	-0-	1	4	6	1	1
FP-P3	6	5	1	-0-	6	3	1	2
FP-P4	4	2	4	2	4	6	2	-0-

1.1.11 Conclusions

o Batteries containing Daramic separators operated at a higher discharge voltage hence provided higher watt hours per kilogram of total battery weight.

o The use of 1.315 specific gravity sulfuric acid does not give sufficient additional capacity to overcome the weight penalty of approximately 0.22 kg per battery.

o In order to increase the circulation of electrolyte, it will be necessary to increase the separator rib to provide more space between the plates. This can only be accomplished by removing pairs of electrodes

and it will be necessary to increase the individual plate areas to compensate for this loss.

o Improvement in cycle life must be obtained by increasing the thickness of the positive plate and again compensating for this by removal of pairs of electrodes and increasing the individual plate areas. The constrictions of the present containers will make this difficult.

o The use of radial design grids should be used to decrease internal voltage drop hence increase the battery terminal voltage during discharge.

TABLE 1
Characteristics Discharges
1.285 Sp. Gr. Electrolyte

		25°C					0°C					40°C				
		40A	60A	75A	140A	240A	40A	60A	75A	140A	240A	40A	60A	75A	140A	240A
EBS No.	Pos.															
5716	FP-P1	33.8	30.0	28.1	23.6	19.6	28.9	25.6	22.4	20.7	10.5	35.8	32.9	31.6	24.3*	16.9
5717	FP-P1	32.7	29.3	28.3	23.4	19.7	28.5	25.3	21.8	19.9	10.2	35.5*	31.9	31.0	24.1*	16.5
5718	FP-P1	37.7	34.0	32.4	27.6	23.5	23.5	32.4	28.5	21.5	12.9	40.8	38.6	37.3	28.6*	22.4
5719	FP-P1	35.1	31.9	30.1	25.1	21.4	31.1	27.2	23.7	21.8	12.6	37.9	34.7	33.4	28.8*	18.6
5720	FP-P2	36.5	31.9	29.9	24.4	20.2	30.7	27.1	23.9	19.5	11.8	38.4	35.8	33.8	26.5*	18.7
5721	FP-P2	37.3*	32.4	30.8	25.3	20.8	31.5	28.0	24.1	20.6	12.0	38.7	35.5	33.7	27.3*	18.5
5722	FP-P2	38.7	35.0	32.4	26.8	23.2	32.9	29.2	25.7	21.3	13.3	43.5*	39.9	37.9	29.6*	22.3
5723	FP-P2	38.9	36.1	33.8	27.8	24.0	33.2	29.3	25.3	20.6	13.2	43.4	41.1	39.0	31.0*	22.8
5724	FP-P3	35.5	32.7	30.6	25.0	20.7	31.2	28.1	25.3	23.0*	12.4	40.5*	38.3	35.2	28.3*	20.2
5725	FP-P3	36.0	33.7	31.5	26.1	21.3	32.4	29.2	25.3	21.0	12.8	40.5*	36.7	34.9	19.3*	19.1
5726	FP-P3	38.7	36.1	33.1	27.0	22.9	33.5	30.2	26.1	21.9*	13.7	44.1*	40.7	38.6	30.9*	23.5
5727	FP-P3	40.1	38.3	35.5	29.1	24.8	34.0	30.2	25.3	19.6	14.5*	-	42.5*	39.8*	32.1*	23.1*
5728	FP-P4	34.7	31.8	29.2	24.2	20.1	30.6	27.7	23.6	21.3	11.7	37.5	34.0*	32.7	-	18.0
5729	FP-P4	35.4	33.4	30.6	25.5	21.1	32.3	29.2	24.1	21.6	11.8	39.6	36.3*	34.7	-	19.4
5730	FP-P4	38.4	35.6	32.2	26.6	22.3	32.2	28.9	24.9	20.7	12.7	41.6	39.6*	38.0	-	22.8
5731	FP-P4	38.0	36.9	33.3	28.0	23.3	33.4	29.9	24.7	20.5	12.5	42.4	41.3*	38.7	-	23.1

* Only one data point available

- No data available

TABLE 2

Characteristics Discharges
1.315 Sp. Gr. Electrolyte

		Whr/Kg														
		25°C					0°C					40°C				
EBS No.	Pos.	40A	60A	75A	140A	240A	40A	60A	75A	140A	240A	40A	60A	75A	140A	240A
5758	FP-P1	34.9	31.3	29.8	24.7	19.3	28.8	26.1	22.3	18.2	12.6	39.7*	34.1	33.6	26.9*	18.6
5759	PF-P1	34.1	31.9	30.5	24.9	19.4	28.6	25.8	21.8	17.5	11.8	37.3	31.2*	31.5*	27.7*	17.4
5710	FP-P1	38.6	35.8	33.7	28.2	24.0	31.1	26.9	21.9	16.7	13.4	43.4*	38.6	31.9*	31.9*	22.3
5761	FP-P1	38.0	35.8	33.9	28.1	24.0	30.4	26.7	21.4	17.3	13.5	41.9	39.1	38.4	31.8*	22.6
5762	FP-P2	37.2	34.2	31.4	25.7	21.1	31.3	27.7	24.4	19.9	12.3	41.5*	37.5	36.6	29.5*	20.6
5763	FP-P2	36.7	34.1	32.2	25.9	21.4	31.3	27.7	23.7	18.7	12.0	40.6	37.3	36.6	-	20.4
5764	FP-P2	-	38.3	35.5	29.2	24.9	33.1	29.3	23.6	18.6	13.5	47.0*	42.8	40.8	32.1*	24.6
5765	FP-P2	41.5*	39.6	35.1	38.8	24.7	31.8	27.6	19.7	17.5	12.7	45.0	42.5	40.9	33.1*	23.4
5766	FP-P3	38.3	35.1	32.3	27.0	22.4	33.6	28.7	25.4	20.5	12.8	42.3*	39.1	37.6	31.2*	21.8
5767	FP-P3	36.4	35.8*	31.4	24.5	21.2	35.5	27.4	23.7	19.1	12.0	42.6*	37.8*	36.0	28.5*	20.3
5768	FP-P3	41.0	40.4*	35.2	29.3	24.8	35.4*	28.6*	24.2	19.0	13.1	44.9	43.0	41.0	33.4	23.9
5769	FP-P3	39.8	40.0*	34.9	28.7	24.3	32.9	27.6	22.4	17.6	12.1	44.9*	42.2	40.2	33.4*	23.6
5770	FP-P4	37.5	34.9	32.4	26.9	22.1	32.0	28.9	23.7	19.6	10.9	40.2	37.3	36.2	-	20.0
5771	FP-P4	38.8	35.4	32.9	27.1	22.5	31.1	28.0	21.9	17.8	11.4	42.0	38.2	37.4	-	21.4
5772	FP-P4	40.3	37.1	34.3	28.2	24.1	31.5	27.4	18.8	13.9	8.6	43.1	41.0	39.5	-	23.9
5773	FP-P4	39.0	38.0	34.9	28.4	24.0	28.8	25.1	18.6	14.7	10.0	43.5	40.8	39.4	-	23.1

* Only one data point available

- No data available

TABLE 3

FP-1 Lot 1 Life Cycles

EBS/SER NO.		Total Life Cycles	Pos Plate	Outside Plate	Seq	Sp.Gr.	
5716	001	137	FP-P1	Neg	R	1.285	
5717	007	"	"	Pos	R	"	
5718	014	"	"	Neg	P	"	
5719	019	143	"	Pos	P	"	
5720	025	137	FP-P2	Neg	R	"	
5721	031	"	"	Pos	R	"	
5722	037	"	"	Neg	P	"	
5723	043	"	"	Pos	P	"	
5724	049	"	FP-P3	Neg	R	"	
5725	055	"	"	Pos	R	"	
5726	061	"	"	Neg	P	"	
5727	069	"	"	Pos	P	"	
5728	074	72	FP-P4	Neg	R	"	
5729	079	"	"	Pos	R	"	
5730	087	"	"	Neg	P	"	
5731	091	"	"	Pos	P	"	
5758	004	143	FP-P1	Neg	R	1.315	
5759	010	143	"	Pos	R	"	
5760	016	137	"	Neg	P	"	
5761	022	"	"	Pos	P	"	
5762	028	"	FP-P2	Neg	R	"	
5763	034	"	"	Pos	R	"	
5764	040	"	"	Neg	P	"	
5765	046	"	"	Pos	P	"	
5766	052	"	FP-P3	Neg	R	"	
5767	058	"	"	Pos	R	"	
5768	064	"	"	Neg	P	"	
5769	070	"	"	Pos	P	"	
5770	077	72	FP-P4	Neg	R	"	
5771	082	"	"	Pos	R	"	
5772	088	"	"	Neg	P	"	
5773	094	"	"	Pos	P	"	

TABLE 4

FP-1 Lot 2 Life Cycles

EBS/SER NO.		Total Life Cycles	Pos Plate	Outside Plate	Sen	Sp. Gr.
5716	002	92	FP-P1	Neg	R	1.285
5717	008	92	"	Pos	R	"
5718	015	161	"	Neg	P	"
5719	020	161	"	Pos	P	"
5720	026	92	FP-P2	Neg	R	"
5721	032	"	"	Pos	R	"
5722	038	"	"	Neg	P	"
5723	044	"	"	Pos	P	"
5724	050	"	FP-P3	Neg	R	"
5725	056	"	"	Pos	R	"
5726	062	"	"	Neg	P	"
5727	068	"	"	Pos	P	"
5728	075	"	FP-P4	Neg	R	"
5729	080	"	"	Pos	R	"
5730	085	"	"	Neg	P	"
5731	093	"	"	Pos	P	"
5758	005	92	FP-P1	Neg	R	1.315
5759	011	92	"	Pos	R	"
5760	017	161	"	Neg	P	"
5761	023	161	"	Pos	P	"
5762	029	92	FP-P2	Neg	R	"
5763	035	"	"	Pos	R	"
5764	041	"	"	Neg	P	"
5765	047	"	"	Pos	P	"
5766	053	"	FP-P3	Neg	R	"
5767	059	"	"	Pos	R	"
5768	065	"	"	Neg	P	"
5769	071	"	"	Pos	P	"
5770	078	"	FP-P4	Neg	R	"
5771	083	"	"	Pos	R	"
5772	089	"	"	Neg	P	"
5773	096	"	"	Pos	P	"

TABLE 5

FP-1 Lot 3 Life Cycles

EBS/SER NO.	Total Life Cycles	Pos Plate	Outside Plate	Seq	So.Gr
5716 003	72	FP-P1	Neg	R	1.285
5717 009	"	"	Pos	R	"
5718 013	"	"	Neg	P	"
5719 021	"	"	Pos	P	"
5720 027	"	FP-P2	Neg	R	"
5721 033	"	"	Pos	R	"
5722 039	"	"	Neg	P	"
5723 045	"	"	Pos	P	"
5724 051	"	FP-P3	Neg	R	"
5725 057	"	"	Pos	R	"
5726 063	"	"	Neg	P	"
5727 067	"	"	Pos	P	"
5728 073	"	FP-P4	Neg	R	"
5729 081	"	"	Pos	R	"
5730 086	"	"	Neg	P	"
5731 092	"	"	Pos	P	"
5758 006	72	FP-P1	Neg	R	1.315
5759 012	"	"	Pos	R	"
5760 018	"	"	Neg	P	"
5761 024	"	"	Pos	P	"
5762 030	"	FP-P2	Neg	R	"
5763 036	"	"	Pos	R	"
5764 042	"	"	Neg	P	"
5765 048	"	"	Pos	P	"
5766 054	"	FP-P3	Neg	R	"
5767 060	"	"	Pos	R	"
5768 066	"	"	Neg	P	"
5769 072	"	"	Pos	P	"
5770 076	"	FP-P4	Neg	R	"
5771 084	"	"	Pos	R	"
5772 090	"	"	Neg	P	"
5773 095	"	"	Pos	P	"

1.2 FP-2 Phase

Based on the analysis of the FP-1 test data, the FP-2 battery design is as follows:

- o Standard positive paste - the additive to the positive active material of thin plates improved the initial capacity during characteristics tests but did not retain the active material during life cycles.
- o Microporous polyethylene separators with .25 mm glass matt.
- o 1.285 specific gravity electrolyte

It was found in automotive size grids that grids of radial design were more efficient current collectors.

Radial grids are designed at Exide by computer by the convergence method using Kirchhoff's Law. Convergence is achieved by iteration and relaxation.

The radial design reduces internal resistance thereby increasing voltage. This is most noticeable at high discharge rates such as during acceleration in an electric vehicle.

The internal resistance of a grid is influenced by the following:

- o Grid thickness
- o The height to width ratio
- o Lug location

Two radial grids were designed, the positive 1 EVR and the negative 2 EVR and grid molds were purchased.

1 EVR grids (6% Sb-Pb alloy) and 2 EVR grids (Ca-Pb alloy) were cast to prove the molds. See photo 1.

The grids were pasted and batteries were built with 3 variations for submittal to ANL.

ANL requested the submittal of batteries of the same configuration in order to reduce the testing load.

1.2.1 Work to be Performed for Next Annual Report

Analyze the Battelle grid design and the Exide grid design.

Select the best grid design for the next series of batteries.

Cast 1 EVR and 2 EVR grids to be pasted and built into batteries.

2 EVR RADIAL NEGATIVE

Photo 1

Test batteries for characteristics and life cycles.

1.3 Battelle Columbus Sub Contract 31-109-38-4207-ESB-2

A subcontract to Battelle Columbus Laboratories for a grid design study was approved by ANL on 4 May 1978.

Battelle issued a Phase A report. Copies of this report are available. See p. 56 of Reference (1).

1.3.1 Work Performed Since Last Annual Report

Battelle continued their investigation and completed their Phase B Report on Electric Vehicle Battery Development Studies. A copy of the report is contained in Appendix I of this report.

Based on their studies, they designed a radial grid and fabricated a grid mold.

Exide sent a hand casting stand to Battelle to which the mold was fitted.

Battelle produced 100 grids (photo 2) for Exide where 60 were hand pasted as positive plates and 25 were pasted as negative plates.

Nine of the positive plates and 18 Exide negative plates were sent to Battelle. The results of their study is given in their Phase B Report.

The remaining positives and negatives will be built into cells and tested at Exide.

Some of Battelle's preliminary conclusions based on their studies outlined in the Phase A & B reports follow:

- o Voltage drop results in a pasted Exide orthogonal grid pair were within 50% of calculated values.
- o The calculated voltage drop through the positive of an Exide radial grid pair is at least 0.1 volt lower than that through an orthogonal grid pair of like dimensions.
- o A radial grid cast at Battelle and pasted at Exide had a voltage drop 22% less than an Exide positive orthogonal grid on a pseudo-normalized dimension/weight basis.

POSITIVE RADIAL GRID
BATTELLE Designed and Cast

Photo 2

1.4 TP-1 History

Deep cycle service has proven the superiority of tubular positive plates. Standard tubing configurations are 8mm square or round. Power requirements of the ISOA program dictate a rectangular tube shape rather than square or round. Through innovative filling techniques and corrosion resistant alloys for the grid, we expect to develop a positive plate capable of meeting the peak load requirements while maintaining the deep cycle capabilities of this design.

Thirty-two battery configurations were designed for the TP-1 experiment. They are:

- o Four positive plates
- o Two separators
- o Two electrolyte specific gravities
- o Two acid volumes above the plates.

Two types of braided glass tubing were manufactured by our supplier. A "standard" braid as is used in industrial battery application and a lighter braid made with fewer strands of glass than the standard. In order to improve the diffusion on electrolyte to the active material.

The "standard" tubes were shaped and set with phenolic resin and given two post-shaping applications of phenolic resin. The lighter tubes were only shaped and set with no additional phenolic applications. See Photo No. 3 "CLADEx Tubing".

A production injection grid mold was designed and grids were cast in 9 percent SbPb alloy at Exide's Sumter, S.C. factory. See Photo No. 4 - "TP-1 Positive Spine, Bottom Bar and Plate".

Bottom bars were molded in four colors to identify the four types of positive plates. See Photo No. 4.

The above components and Pb_3O_4 were sent to Exide's facility in Trenton, N.J. Two methods of filling the positive plates with Pb_3O_4 were tried; one was successful. About 1,250 of each of the positive plates were filled. The plate part numbers and their characteristics are shown below:

<u>Pt. No.</u>	<u>Tube</u>	<u>A.M. Fill Wt. Gms.</u>	<u>Bottom Bar Color</u>
85617	Standard	210-220	Black
85195	Light	210-220	Natural (White)
85618	Standard	240-250	Beige
85616	Light	240-250	Red

4mm X 14mm
LIGHT WEIGHT
CLADEX
TUBING

4mm X 14mm
STANDARD
CLADEX
TUBING

8mm SQUARE
CLADEX
TUBING

Photo 3

TP-1 POSITIVE SPINE

TP-1 BOTTOM BAR

TP-1 POSITIVE PLATE

Two 1.0mm (.040") thick separators were selected; one was ribbed microporous rubber and the other ribbed microporous polyethylene envelopes. See Photo No. 5 "TP-1 Rubber Ribbed Separator".

The envelopes were made by thermo-welding a sheet approximately 343mm long by 168mm wide to 171mm by 168mm. See Photo No. 6 "TP-1 Plastic Ribbed Envelope and Ribbed Sheet".

The two electrolyte gravities were 1.285 and 1.315.

In one set of cells, the acid volume above the plates is standard. In the other set, acid volume is higher than standard. This was achieved by reducing the height of the sediment ribs in the bottom of the container from about 16mm to 6.3mm. See Photo No. 7 "TP-1 Containers Standard and Low Sediment Ribs".

The TP-1 battery has 3 cells each of which consists of 21 plates; 10 positives and 11 negatives.

All of the plates that went into the TP-1 batteries were weighted in groups of 10 positives and 11 negatives and the weights recorded.

The plates and separators (or envelopes) were assembled into elements. The positive and negative plates were welded into their respective groups in the cast-on-strap (COS) machine. As the elements were removed from COS machine, they were put into containers and their EBS numbers were stamped on the negative strap. As this was done, the weights of the groups and their assigned EBS and serial numbers were recorded. The battery containers were also labeled with the EBS and serial number.

The elements were then resistance welded through a hole in the intercell partition of the container. In the industry, this is called through-the-partition construction and is abbreviated TTP. After welding, each weld was given a millivolt drop test at 200 amperes to check weld quality. The resistance values averaged less than 2 micro ohms.

The lists of the positive and negative group weights, EBS numbers and serial numbers and millivolt drop are shown in Tables 6 through 9.

Four batteries were built per each EBS for a total of 128 batteries. They were assigned Lot numbers 4 through 7.

TP-1 RUBBER RIBBED SEPARATOR

Photo 5

Photo .6

TP-1 PLASTIC RIBBED ENVELOPE

TP-1 PLASTIC RIBBED SHEET
BEFORE HEAT SEALING INTO
AN ENVELOPE

Photo 7

TABLE 6

TP-1 POSITIVE & NEGATIVE GROUP WTS & MILLIVOLT DROP TEST RESULTS

EBS No.	Ser. No.	Plate Part No.	Pos. Group Weights			Neg. Group Weights			Welds Millivolts Drop Test at 200 A				
			Pos.	Cells Gms. Cen.	Neg.	Pos.	Cells Gms. Cen.	Neg.					
5809	097	85617		3586	3580	3572		2632	2675	2669		0.9	0.8
"	098	"		3584	3612	3631		2618	2639	2669		1.0	1.1
"	099	"		3573	3600	3601		2701	2637	2655		1.1	1.4
"	100	"		3606	3565	3587		2652	2659	2670		1.1	1.0
5810	101	"		3669	3613	3554		2585	2576	2551		1.4	1.2
"	102	"		3527	3597	3593		2566	2544	2544		1.4	1.3
"	103	"		3567	3669	3679		2546	2546	2574		1.2	0.9
"	104	"		3621	3692	3607		2567	2594	2570		1.1	0.9
5811	105	"		3614	3545	3603		2593	2549	2591		1.0	1.2
"	106	"		3577	3554	3565		2591	2535	2573		0.9	1.0
"	107	"		3581	3613	3581		2589	2588	2595		0.9	0.7
"	108	"		3574	3641	3704		2591	2539	2605		1.0	1.2
5812	109	"		3585	3548	3598		2540	2576	2582		1.0	1.3
"	110	"		3578	3588	3647		2567	2536	2576		0.9	1.1
"	111	"		3574	3656	3518		2561	2590	2584		0.9	1.1
"	112	"		3558	3562	3553		2553	2590	2586		0.9	1.0
5813	113	85195		3644	3760	3741		2607	2684	2636		2.6	1.1
"	114	"		3701	3695	3737		2646	2664	2647		1.2	1.3
"	115	"		3745	3735	3728		2641	2628	2640		0.8	1.0
"	116	"		3629	3760	3747		2648	2639	2650		1.4	1.0
5814	117	"		3706	3724	3736		2592	2516	2540		0.9	1.1
"	118	"		3779	3771	3703		2539	2510	2526		0.9	1.1
"	119	"		3747	3745	3680		2589	2535	2575		1.0	1.1
"	120	"		3690	3709	3703		2539	2537	2529		1.0	1.1
5815	121	"		3725	3699	3727		2653	2698	2662		0.8	1.1
"	122	"		3721	3699	3726		2649	2656	2650		1.6	1.3
"	123	"		3711	3665	3719		2653	2613	2614			
"	124	"		3737	3669	3733		2616	2632	2636		1.1	0.9
5816	125	"		3600	3793	3659		2579	2532	2529		0.9	1.1
"	126	"		3733	3744	3702		2537	2550	2551		1.6	5.3
"	127	"		3700	3712	3644		2566	2521	2535		1.0	1.3
"	128	"		3717	3724	3702		2537	2542	2538		1.1	0.9
Avg. Wt. of 10 Positive Assemblies (Spines, Tubes & Bott. Bar) =												1,340 gm	
Avg. Wt. of 11 Negative Grids =												792 gm	

TABLE 7

TP-1 POSITIVE & NEGATIVE GROUP WTS & MILLIVOLT DROP TEST RESULTS

EBS No.	Ser. No.	Plate Part No.	Pos. Group Weights			Neg. Group Weights			Welds Millivolts Drop Test at 200 A	
			Pos.	Cells Gms	Neg.	Pos.	Cells Gms	Neg.		
5817	129	85618		3821	3830		2663	2654	2653	0.9 1.1
"	130	"		3930	3854		2673	2657	2670	1.1 0.9
"	131	"		3796	3899		2672	2691	2666	1.0 0.9
"	132	"		3845	3913		2643	2678	2628	1.1 0.9
"	133	"		3833	3891		2540	2554	2538	1.1 1.2
"	134	"		3935	3802		2624	2617	2616	1.3 1.2
"	135	"		3805	3919		2552	2545	2539	1.1 1.2
"	136	"		3939	3782		2523	2520	2589	1.1 1.3
5819	137	"		3836	3817		2639	2660	2629	1.2 1.3
"	138	"		3865	3820		2657	2662	2653	1.6 0.9
"	139	"		3860	3831		2655	2677	2665	1.2 0.9
"	140	"		3790	3842		2665	2668	2634	1.2 1.0
5820	141	"		3902	3780		2593	2612	2594	1.4 0.9
"	142	"		3778	3796		2611	2609	2582	1.3 1.4
"	143	"		3834	3790		2597	2589	2612	1.0 1.3
"	144	"		3853	3841		2602	2619	2613	1.3 1.1
5821	145	85616		3864	3873		2592	2551	2562	0.8 1.1
"	146	"		3892	3913		2534	2546	2533	0.9 1.0
"	147	"		3905	3827		2590	2543	2517	1.1 0.9
"	148	"		3924	3844		2608	2591	2552	1.2 0.9
5822	149	"		3868	3909		2590	2578	2585	1.4 1.2
"	150	"		3899	3941		2590	2580	2605	1.1 1.3
"	151	"		3884	3854		2602	2588	2590	1.7 1.6
"	152	"		3859	3909		2570	2586	2582	1.2 1.1
5823	153	"		3877	3946		2516	2583	2510	1.2 1.1
"	154	"		3870	3855		2553	2583	2575	1.3 0.9
"	155	"		3936	3856		2537	2516	2565	1.0 1.1
"	156	"		3926	3911		2588	2592	2585	1.1 0.9
5824	157	"		3857	3886		2590	2572	2580	1.0 1.9
"	158	"		3885	3888		2608	2578	2566	1.0 2.0
"	159	"		3907	3822		2578	2571	2580	1.2 1.4
"	160	"		3909	3872		2600	2609	2540	1.3 1.4
Avg. Wt. of 10 Positive Assemblies (spines, tubes & bott bars)=			1,340 gm.							
Avg. Wt. of 11 Negative Grids=			792 gm.							

TABLE 8

TP-1 POSITIVE & NEGATIVE GROUP WTS & MILLIVOLT DROP TEST RESULTS

EBS No.	Ser. No.	Plate Part No.	Pos. Group Weights			Neg. Group Weights			Welds Millivolt Drop Test at 200 A					
			Pos.	Cells	Pos.	Cells	Neg.							
5825	161	85617			3609	3586	3536			2604	2585	2581	1.1	1.3
"	162	"			3660	3520	3550			2600	2603	2668	1.3	1.1
"	163	"			3688	3708	3633			2589	2590	2666	1.3	1.1
"	164	"			3	3648	3557			2576	2578	2588	1.1	1.4
5826	165	"			3627	3578	3556			2568	2602	2571	1.3	1.1
"	166	"			3641	3607	3650			2602	2601	2608	1.3	1.1
"	167	"			3624	3556	3535			2598	2577	2578	1.3	1.1
"	168	"			3574	3522	3544			2582	2608	2591	1.4	1.2
5827	169	"			3645	3647	3614			2607	2595	2586	1.1	1.6
"	170	"			3553	3584	3616			2565	2605	2571	1.2	1.5
"	171	"			3574	3551	3630			2591	2595	2582	1.3	1.6
"	172	"			3659	3616	3629			2614	2605	2556	1.1	1.4
5828	173	"			3614	3640	3600			2566	2614	2572	1.3	1.2
"	174	"			3636	3557	3636			2587	2583	2601	1.2	1.6
"	175	"			3617	3640	3608			2606	2566	2575	1.1	0.9
"	176	"			3618	3576	3594			2570	2569	2593	0.8	1.1
5829	177	85195			3795	3670	3710			2588	2593	2585	1.4	1.1
"	178	"			3672	3622	3732			2600	2572	2597	1.1	1.4
"	179	"			3717	3730	3720			2554	2591	2510	1.4	1.1
"	180	"			3609	3641	3654			2570	2606	2615	1.2	1.1
5830	181	"			3687	3749	3692			2609	2593	2569	0.8	0.9
"	182	"			3696	3743	3733			2757	2602	2600	1.3	1.2
"	183	"			3730	3675	3649			2539	2600	2615	0.9	1.1
"	184	"			3740	3739	3706			2717	2617	2615	0.9	1.1
5831	185	"			3736	3743	3658			2606	2583	2621	1.1	1.3
"	186	"			3700	3696	3641			2630	2609	2613	1.3	1.2
"	187	"			3669	3658	3772			2611	2591	2611	1.1	1.6
"	188	"			3619	3716	3630			2609	2614	2615	1.3	1.0
"	189	"			3690	3687	3637			2732	2695	2554	1.5	1.2
5832	190	"			3707	3664	3691			2612	2691	2630	1.0	0.9
"	191	"			3730	3701	3741			2598	2657	2604	0.9	1.2
"	192	"			3641	3695	3670			2722	2712	2531	1.3	1.5
Avg. Wt. of 10 Positive Assemblies (spines, tubes & bott. bar)= 1,340 gm.														
Avg. Wt. of 11 Negative Grids= 792 gm.														

TP-1 POSITIVE & NEGATIVE GROUP WTS & MILLIVOLT DROP TEST RESULTS

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1.4.1 Testing - Characteristics

The characteristics testing regime is as follows:

<u>Cycle</u>	<u>Discharge Rate</u> <u>Amps</u>	<u>Hours</u>	<u>Ambient</u> <u>Temperature °C</u>	<u>Test</u> <u>Standards</u>
1	40	5	25	Initial Performance
2	60	3	25	" "
3	75	2	25	" "
4	140	1	25	" "
5	10	20	25	" "
6	240	.5	25	" "
7	40	5	0	Low Temperature Performance
8	60	3	0	" " "
9	75	2	0	" " "
10	140	1	0	" " "
11	240	.5	0	" " "
12	40	5	40	High " "
13	60	3	40	" " "
14	75	2	40	" " "
15	140	1	40	" " "
16	240	.5	40	" " "

Charging for the first 16 cycles is done in two steps - a high-rate mode and a low-rate mode. The high-rate mode is 40 amperes until 90% of the discharge capacity is returned. The low-rate mode is 5 amperes until a total of 115% of the discharged capacity is reached.

Twenty-four hours is allotted for recharging (during characteristics testing only) but a shorter time may be used if all conditions are met.

The discharge rate for all of the following cycles is 60 amperes (3 hr) at 25°C.

<u>Cycle</u>	<u>Charge Method</u>	<u>Test Standards</u>
17	As in cycles 1-16	Charge Acceptance vs Temperature
18	40A to onset of gassing at 25°C	Charge Acceptance vs Temperature
19	As in cycles 1-16	Charge Acceptance vs Temperature
20	40A to onset of gassing at 0°C	Charge Acceptance vs Temperature
21	As in cycles 1-16	Charge Acceptance vs Temperature

<u>Cycle</u>	<u>Charge Method</u>	<u>Test Standards</u>
22.	140A to onset of gassing at 25°C	Charge Acceptance vs Charge Rate
23	40A to 2.35v/cell maintained for 4 hours.	Special Charging Tests
24	Same as cycle 23	" " "
25	" " " "	" " "
26	" " " "	" " "
27	As in cycles 1-16	" " "
28	" " " "	" " "
29	After a 2 week stand on open circuit fully charged	Charge Retention Test
30	As in cycles 1-16	

1.4.2 Life Test

The life test is a 2.4 (80% of 3 hours) hour constant current discharge at the 3 hour rate followed by a two step recharge. The first step is the high rate (40A) until the voltage reads 2.35 volts per cell followed by the low rate (9A) until approximately 120% of the discharge is returned.

The life testing equipment consists of three systems I, II, and III. Each system contains 8 loops. Loops 1 through 7 will accept 8 batteries each while loop 8 will accept 6 batteries.

1.4.3 Work Performed Since Last Report

Lot 6 was given the life cycle testing without experiencing the characteristics testing. A sixteen hour cycle was started per the following parameters:

	<u>Dischg</u>	<u>Stabilization</u>	<u>Hi Chg</u>	<u>Lo Chg</u>	<u>Stabilization</u>
Hours	2.4	1.85	3.9	6.0	1.85
Voltage Limit	1.7		2.35	None	

Lot 6 was put on system III on 8/31/79 on loops 1 through 4. The discharge and charge rates were as follows:

<u>Loop No.</u>	<u>Sp. Gr.</u>	<u>Discharge</u>	<u>Hi Chg</u>	<u>Low Chg</u>	<u>Total Chg</u>	<u>% Overchg</u>
1	1.285	60A (144AH)	29.8A(116AH)	9A(54AH)	170AH	18
2	1.315	53A(139AH)	28.5A(111AH)	8.7(52AH)	163AH	17
3	1.285	59A(142AH)	29.0A(113AH)	8.4A(50AH)	163AH	15
4	1.315	59A(142AH)	29.0A(113AH)	10.0A(60AH)	173AH	22

On 9/4/79 at cycle 6 the testing regime was changed because the batteries were not accepting 80% of the discharged ampere hours before reaching the 2.35 volts per cell limit. The cycle time was extended to 18 hours. The timing and the rate changes are shown below:

	<u>Dischg</u>	<u>Stabilization</u>	<u>Hi Chg</u>	<u>Lo Chg</u>	<u>Stabilization</u>
Hours	2.4	1.85	5.9	6.0	1.85
Voltage Limit	1.7		2.35	None	

<u>Loop No.</u>	<u>Discharge</u>	<u>Hi Chg</u>	<u>Lo Chg</u>	<u>Total Chg</u>	<u>% Overchg</u>
1	60A(144AH)	19.7A(116AH)	9A(54AH)	170AH	18
2	58A(139AH)	18.8A(111AH)	8.7A(52AH)	163AH	17
3	59A(142AH)	19.3A(113AH)	8.4A(50AH)	163AH	15
4	59A(142AH)	19.3A(113AH)	10.0A(60AH)	173AH	22

On 9/12/79 at cycle 18 the regime was changed again because the batteries were still not accepting 80% of the discharge amperes before reaching 2.35 volts. The timing and rate changes are shown below:

	<u>Dischg</u>	<u>Stabilization</u>	<u>Hi Chg</u>	<u>Lo Chg</u>	<u>Stabilization</u>
Hours	2.4	1.35	5.9	7.0	1.35
Voltage Limit	1.7		2.35		

<u>Loop No.</u>	<u>Discharge</u>	<u>Hi Chg</u>	<u>Lo Chg</u>	<u>Total Chg</u>	<u>% Overchg</u>
1	60A(144AH)	17.1A(101AH)	9.9A(69AH)	170AH	18
2	58A(139AH)	16.5A(97AH)	9.4A(66AH)	163AH	17
3	59A(142AH)	16.8A(99AH)	9.1A(64AH)	163AH	15
4	59A(142AH)	16.8A(99AH)	10.5A(74AH)	173AH	22

On 11/1/79 at cycle 62 the rates were changed due to premature failures; the timing remained the same.

The rate changes are shown below:

<u>Loop No.</u>	<u>Discharge</u>	<u>Hi Chg</u>	<u>Lo Chg</u>	<u>Total Chg</u>	<u>% Overchg</u>
1	50A(120AH)	14.2A(84AH)	8.3A(58AH)	142AH	18
2	50A(120AH)	14.2A(84AH)	8.0A(56AH)	140AH	17
3	50A(120AH)	14.2A(84AH)	7.7A(54AH)	138AH	15
4	50A(120AH)	14.2A(84AH)	8.9A(62AH)	146AH	22

As of 8/31/80 most of Lot 6 has reached 365 life cycles. See Table 10 for the status of each battery.

The specific energy values of Lots 4 and 5 are listed for cycles 1 through 16 in Tables 11, 12 and 13.

At characteristic cycle 2 (60A discharge at 25°C) the best specific energy achieved was 37.7 WH/Kg by battery 5811/105. Batteries 5812/121, 5819/137 and 5831/185 gave 37.0 WH/Kg.

The vital statistics of the above batteries are listed:

<u>EBS/SER NO</u>	<u>TUBES</u>	<u>AM DEN</u>	<u>SEP</u>	<u>SP.GR.</u>	<u>ACID VOLUME ABOVE PLATES</u>
5811/105	Light	210-220g	P-Env	1.315	Low
5815/121	Std	210-220g	P-Env	1.315	Low
5819/137	Light	240-250g	P-Env	1.314	Low
5831/185	Std	210-220g	P-Env	1.315	High

The consistent features of the batteries were polyethylene envelopes and 1.315 specific gravity electrolyte.

Charge acceptance tests followed the initial characteristics tests.

Table 14 lists charge acceptance versus temperature and charge acceptance versus rate of charge.

TABLE 10

TP-1 BATTERY LIFE CYCLE TEST STATUS

LOT 6

<u>EBS/SER NO.</u>	<u>Date Ended</u>	<u>Last Cycle</u>	<u>Cycles as of 8/31/80</u>	<u>Remarks</u>
5809/099	8/8/80	339		Entire Lot Started on 8/31/79
5810/103			365	
5811/107	12/10/79	98		
5812/111	6/10/80	283		
5813/115			365	
5814/119			365	
5815/123	11/8/79	54		
5816/127			365	
5817/131			365	
5818/135			346	
5819/139			365	
5820/143			365	
5821/147			365	
5822/151			346	
5823/156			365	
5824/159			365	
5825/163	6/10/80	283		
5826/167	12/10/79	98		
5827/171	8/31/79	0		
5828/175	12/14/79	103		
5829/179	8/8/80	339		
5830/183	6/10/80	283		
5831/187			365	
5832/191			365	
5833/195	7/9/80	311		
5834/199	7/9/80	292		
5835/203	1/25/80	145		
5836/207	6/10/80	283		
5837/211			365	
5838/215	8/8/80	292		
5839/219			365	
5840/223			365	

TABLE 11
TP-1 CHARACTERISTICS TEST RESULTS
SPECIFIC ENERGY WHR/KG

LOT	EBS	SER No.	25°C						0°C						40°C					
			40A	60A	75A	140A	10A	240A	40A	60A	75A	140A	240A	40A	60A	75A	140A	240A		
4	5809	097	38.7	34.1	31.2	--	47.0	--	31.6	24.6	20.9	15.3	10.2	39.5	36.0	31.8	28.3	22.8		
5	5809	098	39.5	35.0	32.6	28.1	47.8	19.4	26.6	21.0	17.4	11.4	7.2	39.5	33.9	31.9	26.4	21.2		
4	5810	101	36.9	33.2	30.6	--	46.3	--	--	25.5	21.8	16.6	11.0	37.2	34.4	30.4	26.7	21.8		
5	5810	102	37.0	32.5	30.4	25.6	46.4	17.6	25.4	20.4	17.1	11.5	6.8	36.2	31.8	30.2	25.0	19.6		
4	5811	105	42.5	37.7	34.3	--	49.8	--	25.2	17.3	14.2	8.9	5.4	42.1	36.8	30.3	27.7	21.2		
5	5811	106	40.6	34.6	31.6	25.6	48.7	14.8	19.3	14.4	11.2	6.7	4.4	38.9	34.2	31.5	24.0	18.2		
4	5812	109	40.8	35.9	32.7	--	49.4	--	27.7	19.7	15.2	9.6	5.6	38.9	35.3	30.7	26.9	21.2		
5	5812	110	38.8	34.0	31.7	26.6	48.4	17.6	23.3	18.0	14.6	--	5.4	38.5	34.7	32.6	26.4	21.4		
4	5813	113	38.7	34.3	31.7	--	47.4	--	32.0	24.9	21.1	15.6	10.2	40.6	36.6	32.6	28.8	23.8		
5	5813	114	38.7	34.8	32.4	28.3	46.8	20.2	26.9	21.0	17.7	12.0	8.0	39.9	34.3	32.5	27.1	22.4		
4	5814	117	36.2	32.5	30.0	--	45.3	--	32.1	25.7	21.4	16.8	11.4	37.9	34.6	31.0	27.3	22.4		
5	5814	118	36.5	32.8	30.9	26.9	45.7	19.0	27.3	21.5	18.2	12.4	8.2	37.4	33.1	31.5	26.7	21.2		
4	5815	121	41.5	37.0	34.3	--	49.2	--	28.7	20.4	16.0	10.5	6.4	43.0	38.6	32.7	29.4	23.8		
5	5815	122	41.1	35.7	32.7	27.0	49.0	17.2	21.2	16.0	12.6	7.4	5.0	41.6	36.6	33.8	26.1	21.2		
4	5816	125	40.4	36.2	33.0	--	50.3	--	27.9	19.5	15.0	9.4	5.6	40.7	37.2	33.9	29.2	23.0		
5	5816	126	38.5	34.0	31.6	26.8	48.0	17.6	22.8	17.4	14.6	--	5.6	38.7	35.0	32.8	26.7	21.6		
4	5817	129	36.9	32.6	30.1	--	46.2	--	30.5	23.6	19.9	14.8	9.8	38.7	34.9	31.0	27.4	22.4		
5	5817	130	37.6	33.4	31.2	26.6	45.8	18.0	24.7	18.6	15.6	10.2	6.8	38.3	32.5	31.0	25.0	20.2		
4	5818	134	36.0	32.2	30.4	--	49.4	--	26.0	18.1	19.2	13.6	9.0	36.2	31.9	30.5		22.8		
5	5818	136	40.3	36.0	33.0	--	45.2	--	20.1	15.1	17.2	11.8	7.0	39.4	35.8	32.1	28.1	20.6		
4	5819	137	42.0	37.0	33.9	--	50.3	--	26.0	18.1	14.0	9.1	5.4	42.1	37.0	30.3	27.7	21.2		
5	5819	138	40.6	35.3	32.6	26.6	48.7	16.2	20.1	15.1	12.1	7.2	4.8	40.8	36.0	32.8	25.3	20.0		
4	5820	141	39.6	35.3	32.1	--	49.0	--	30.5	22.8	18.4	12.3	7.4	39.8	35.7	31.6	27.7	22.6		
5	5820	142	37.2	32.7	30.6	26.0	46.9	16.2	22.8	17.6	14.8	--	5.6	38.2	34.5	32.0	26.1	20.8		
4	5821	145	36.8	32.4	30.3	--	45.8	--	30.6	22.8	18.8	13.6	8.6	39.9	36.2	31.9	28.0	23.0		
5	5821	146	37.6	32.9	30.3	25.3	45.8	17.8	22.7	17.5	14.8	9.6	6.0	38.7	32.5	31.1	25.1	21.0		
4	5822	149	34.8	31.0	28.6	--	44.8	--	30.2	24.2	20.1	15.1	9.8	37.2	33.6	30.0	26.0	21.2		

TABLE 12
P-1 CHARACTERISTICS TEST RESULTS
SPECIFIC ENERGY WHR/KG

LOT	EBS	SER No.	25°C						0°C						40°C					
			40A	60A	75A	140A	10A	240A	40A	60A	75A	140A	240A	40A	60A	75A	140A	240A		
4	5822	150	35.7	31.8	29.8	25.8	44.8	18.4	26.0	21.0	16.8	10.7	6.8	36.7	32.1	30.6	25.7	20.6		
5	5823	153	39.9	35.5	32.1	--	48.5	--	23.9	15.9	12.5	8.0	5.0	41.0	36.8	32.4	27.5	21.6		
4	5823	154	37.6	32.6	30.2	24.9	46.9	16.0	19.5	14.6	12.0	7.2	4.6	39.5	34.9	31.8	24.9	20.2		
5	5824	157	39.2	34.6	31.9	--	48.3	--	30.5	22.5	18.0	11.7	7.0	40.0	36.6	32.4	28.3	23.2		
4	5824	158	36.4	32.0	29.8	25.1	46.2	18.6	25.5	20.3	16.8	10.6	6.6	37.1	32.4	31.0	25.0	20.8		
5	5825	161	29.7	21.6	12.0	--	40.5	--	--	4.0	3.9	2.8	--	--	--	--	--	--		
4	5825	162	38.8	34.4	31.5	25.9	49.0	16.6	23.3	18.1	14.6	9.4	5.8	38.2	32.5	30.5	23.9	18.8		
5	5826	165	37.2	33.3	30.2	--	47.5	--	33.4	26.2	21.6	16.6	11.0	38.4	35.2	32.0	27.4	22.2		
4	5826	166	38.9	34.4	32.3	27.3	49.0	19.0	27.7	22.3	18.7	12.7	8.0	38.6	33.8	32.0	26.8	21.0		
5	5827	169	41.9	36.4	32.5	--	48.4	--	23.8	17.1	13.5	8.7	5.2	40.9	33.5	27.8	25.2	18.8		
4	5827	170	43.0	36.0	32.3	25.3	50.8	15.2	19.6	14.8	11.6	6.7	4.4	41.1	35.8	31.0	23.2	18.8		
5	5828	173	40.3	35.3	31.6	--	49.4	--	29.2	21.5	16.7	11.1	6.4	40.3	35.7	30.7	27.5	21.2		
4	5828	174	39.8	33.0	30.2	24.2	43.7	15.0	21.1	16.0	13.0	7.7	4.6	38.1	33.9	30.6	23.6	17.8		
5	5829	177	38.1	33.8	31.1	--	47.9	--	30.3	22.6	18.5	12.9	8.4	41.6	37.1	32.2	28.4	22.8		
4	5829	178	39.0	34.8	32.4	27.8	48.6	19.4	26.9	21.3	17.6	12.2	8.0	40.3	34.7	32.7	27.3	21.6		
5	5830	181	37.0	33.1	30.1	--	47.8	--	33.1	26.1	21.7	17.2	11.4	39.3	35.6	31.6	26.9	21.8		
4	5830	182	37.9	34.0	31.7	27.3	48.1	19.0	27.5	21.9	18.7	12.9	8.4	38.1	33.4	31.8	26.7	20.8		
5	5831	185	41.7	37.0	33.5	--	49.6	--	24.7	17.6	13.6	9.0	5.1	43.1	37.5	31.0	27.6	20.6		
4	5831	186	42.5	36.8	33.9	24.7	51.4	17.2	21.1	16.1	13.0	10.0	5.0	42.1	37.2	33.9	26.3	21.2		
5	5832	189	39.8	35.3	32.1	--	50.1	--	31.9	23.9	19.0	13.5	8.0	41.5	37.4	33.3	28.9	20.6		
4	5832	190	38.4	33.2	31.0	26.1	48.2	17.6	24.1	18.8	16.0		6.2	38.7	34.4	31.9	25.4	20.6		
5	5833	193	40.5	--	33.4	--	49.2	--	31.9	25.0	20.7	15.5	10.2	41.6	37.6	33.0	29.4	23.8		
4	5833	194	39.6	34.2	31.8	26.4	48.7	18.4	25.1	19.5	16.3	10.8	7.0	40.2	33.9	31.6	25.9	20.6		
5	5834	197	36.5	32.3	29.6	--	47.3	--	32.1	25.5	21.4	16.8	11.2	37.4	34.3	30.4	26.0	20.8		
4	5834	198	37.3	33.2	30.8	26.7	47.5	18.4	27.6	22.4	18.8	13.0	8.2	37.7	32.6	31.0	25.8	20.2		
5	5835	201	41.4	36.4	33.3	--	49.9	--	25.8	19.0	16.6	12.1	7.2	42.1	36.1	30.8	27.6	21.0		
4	5835	202	41.7	34.8	32.1	25.7	50.3	16.2	20.9	15.8	12.9	7.8	5.0	41.4	36.4	32.1	24.1	19.2		

TABLE 13
TP-1 CHARACTERISTICS TEST RESULTS
SPECIFIC ENERGY WHR/KG

LOT	EBS	SER No.	25°C						0°C					40°C				
			40A	60A	75A	140A	10A	240A	40A	60A	75A	140A	240A	40A	60A	75A	140A	240A
4	5836	205	40.1	35.8	32.7	--	50.7	--	30.9	23.3	18.4	12.4	7.4	40.5	35.8	31.3	27.5	22.2
5	5836	206	39.0	34.1	31.7	26.7	49.3	18.0	24.7	19.3	15.8	9.7	5.4	39.5	35.8	32.7	26.8	20.8
4	5837	209	38.2	34.0	31.0	--	48.0	--	30.9	23.9	20.5	15.4	10.4	40.6	36.2	32.0	27.8	22.8
5	5837	210-212	33.0	25.7	21.7	--	39.2	--	--	--	--	--	--	--	--	35.3*	30.2*	24.2*
4	5838	213	36.5	32.4	29.7	--	45.2	--	32.8	26.3	22.0	17.4	12.0	37.9	34.0	30.9	25.9	21.0
5	5838	214-216	31.2	26.2	22.3	--	36.9	--	--	--	--	--	--	--	--	33.4 ⁺	28.7 ⁺	22.8 ⁺
4	5839	217	41.1	36.2	33.1	--	49.7	--	28.2	20.7	16.2	11.1	6.8	43.5	38.2	32.1	29.0	22.8
5	5839	218	41.4	35.5	32.4	26.4	50.2	16.6	20.5	15.4	12.4	7.5	4.6	41.3	36.2	32.8	25.2	20.6
4	5840	221	39.8	35.2	32.4	--	49.9	--	32.1	24.4	19.5	13.6	8.2	41.5	37.2	33.0	28.8	23.4
5	5840	222	37.8	33.1	30.8	26.3	48.3	19.0	26.3	21.1	17.8	11.3	7.0	39.4	35.7	32.6	26.9	21.2

* Battery Serial Number 212 Replaced S/N 210 at Cycle No. 14

+ " " " 216 " S/N 214 at Cycle No. 14

TABLE 14

LOT 4				LOT 5			
EBS NO	BATT SER NO	CHARGE ACCEPTANCE VS TEMP AT 25°C %	CHARGE ACCEPTANCE VS CHG RATE AT 140A %	BATT SER NO	CHARGE ACCEPTANCE VS TEMP AT 25°C %	CHARGE * ACCEPTANCE VS TEMP AT 0°C %	CHARGE ACCEPTANCE VS CHG RATE AT 140A %
5809	097	70.7	13.7	098	66.5	57.0	18.1
5810	101	69.2	15.3	102	67.3	54.0	13.1
5811	105	55.9	8.5	106	59.7	46.4	9.6
5812	109	56.5	8.5	110	61.1	49.3	12.1
5813	113	68.7	14.1	114	68.4	58.6	15.9
5814	117	69.7	14.4	118	66.5	57.5	14.8
5815	121	58.8	9.8	122	60.9	48.6	11.7
5816	125	55.6	9.6	126	60.8	49.2	12.0
5817	129	71.1	14.4	130	66.1	56.2	14.8
5818	136	58.3	11.0	134	67.0	55.8	13.5
5819	137	58.7	8.1	138	59.5	48.4	11.1
5820	141	61.5	10.3	142	64.8	50.0	12.0
5821	145	68.8	13.5	146	64.8	54.2	14.1
5822	149	67.8	14.0	150	67.6	55.3	13.4
5823	153	54.3	9.7	154	61.6	48.4	12.1
5824	157	61.7	11.6	158	67.6	53.2	13.5
5825	-	-	-	162	65.1	52.7	12.6
5826	165	64.8	14.4	166	65.2	56.2	15.1
5827	169	56.3	6.9	170	60.6	45.7	11.9
5828	173	59.1	8.1	174	57.9	55.7	6.4
5829	177	66.4	12.4	178	68.1	60.8	16.2
5830	181	68.3	14.8	182	65.5	58.6	14.1
5831	185	54.1	10.3	186	59.8	48.8	12.2
5832	189	59.8	10.5	190	61.2	49.9	13.0
5833	193	67.4	12.6	194	64.6	56.6	14.0
5834	197	67.9	14.8	198	65.0	56.5	13.8
5835	201	59.2	9.0	202	61.6	49.4	12.6
5836	205	60.0	9.9	206	62.4	49.3	13.0
5837	209	70.8	12.6	212	67.5	62.8	16.1
5838	213	69.7	15.6	216	68.8	63.1	17.2
5839	217	58.7	9.1	218	62.1	46.6	13.2
5840	221	60.6	11.5	222	62.5	50.6	13.1

* This data not available for Lot 4.

As of 8/31/80 most of Lot 4 has reached 150 life cycles. See Table 15 for the status of each battery.

As of 8/31/80 Lot 5 has reached 55 life cycles.

1.4.4 Preliminary Conclusions

It is too early to draw conclusions at this point; however, it has been shown that the tubular plate construction is capable of substantially more deep cycles than the flat plate of the FP-1 series.

1.4.5 Work Programmed for Next Year

Complete life-cycle testing and analyze the results.
Purchase equipment to produce new TP design.
Build and test new tubular and flat plate designs.

TABLE 15TP-1 BATTERY LIFE CYCLE TEST STATUSLOT 4

<u>EBS/SER NO.</u>	<u>Date Ended</u>	<u>Last Cycle</u>	<u>Cycles as of 8/31/80</u>	<u>Remarks</u>
5809/097			150	Entire Lot Started on 2/7/80
5810/101			150	
5811/105			150	
5812/109	8/8/80	136		
5813/113			142	
5814/117			150	
5815/121			148	
58.6/125			150	
5817/129			150	
5818/136			136	
5819/137			150	
5820/141			150	
5821/145			148	
5822/149			150	
5823/153			150	
5824/157			150	
5825/161				Ended at Char. Cycle 9 12/10/79
5826/165			135	
5827/169	6/2/80	66		
5828/173	8/8/80	136		
5829/177			150	
5830/181			135	
5831/185	6/2/80	66		
5832/189			138	
5833/193			148	
5834/197			150	
5835/201	4/25/80	46		
5836/205			139	
5837/209	4/25/80	46		
5838/213			150	
5839/217			150	
5840/221			150	

1.5 Advanced Lead Acid Battery

1.5.1 Negative

During the past year, it has been successfully demonstrated that the energy density of the lead-acid battery can be significantly improved by using lightweight, copper containing, negative grids. These grids have no deleterious effect on cycle life, and based on the cost of raw materials can be manufactured at prices comparable to standard cast lead grids. In the advanced lead-acid battery designs now proposed, a cast lead negative contributes 9 to 11% of the total battery weight. By substituting lightweight materials such as plastic or copper, a savings of 50-60% of the negative grid weight is achieved. This corresponds to a 5-6% reduction in the overall battery weight with no loss in performance. In a lead-acid battery, the negative grid serves a two-fold purpose. (1) It is conductive and carries electrons to and from the active material involved in the electrochemical reaction. (2) It acts as a rigid matrix to hold the active material and to allow handling during pasting and subsequent assembly. In 100% lead grids, both functions are served by lead, a material which does not have an exceptionally good conductivity and has a high density. Lead grids are, however, easy to fabricate. The rationale taken in developing a lightweight alternative has been to use plastic or copper as the active material matrix and copper as the electronic conductor. A thin coating of lead is finally applied over the copper to make it electrochemically inert, and to impart added rigidity to the overall grid.

On a unit volume basis, plastic weighs less than one-tenth lead, and copper is nearly sixteen times more conductive (cf Table 16). Therefore, a grid which contains plastic or copper as the active material matrix and incorporates copper as the primary conductor can provide a substantial weight reduction over one which is 100% lead. Exposed copper does, however, reduce the hydrogen overvoltage and presents problems during charge, so that a thin (.025 to .050 mm) coating of lead is needed over the copper. In addition, the lead layer provides the grid with increased conductivity and rigidity.

Table 16: Properties of Grid Materials (2,3)

	Density (g/cm ³)	Resistivity (microhm cm)
ABS	1.08	∞
Copper	8.92	1.77
Lead	11.34	22

A simple analysis was performed to determine the relative weights of a standard EV size cast lead grid and a copper, plastic, lead composite with identical geometry (i.e. volume). The standard is 1.47mm thick. The composite thickness is also 1.47mm and it is arbitrarily distributed in the following manner: 1.34mm plastic with .040mm copper and .025mm lead coated on each side. If the weight of the lead grid is arbitrarily assigned a value X and its resistivity is assigned a value Y, the composite has a weight 0.225X and a resistivity 0.75Y. Therefore, the composite weighs less than one-fourth of the cast lead control and yet is more conductive. The

results of this preliminary analysis convinced us that this type of design could substantially reduce the weight of the negative electrode with no loss of performance. In the past year, two different types of composite lightweight negative grid constructions were investigated based on the rationale developed above. Both investigations resulted in successful manufacture of the grids, the construction of batteries, and the generation of encouraging test data.

1.5.1.1 Lightweight Negative Grid - Type A (Automotive Size)

This type of lightweight negative grid consists of three materials of construction - ABS plastic which serves as the active material matrix, copper plated onto the plastic which acts as the primary current carrier, and lead plated onto the copper to render it electrochemically inert. Initial work involving this approach concentrated on developing an automotive size grid (14.5 cm x 12.3 cm x 0.14 cm) which was considerably smaller than the one proposed for the EV battery (15.8 cm x 15.4 cm x 0.15 cm). An automotive grid mold was readily available for molding the grids, and we decided to use it in order to quickly make a few plastic grids and arrive at some preliminary conclusions regarding their behavior in a lead-acid battery.

The ABS plastic grids (wt - 5 gms) had a thin layer (0.6g) of electroless copper applied to them by conventional techniques; namely, a chromic acid etch, followed by stannous chloride sensitization, and palladium chloride catalyzation, and then they were placed into the electroless plating bath. The amount of copper deposited by the electroless process (0.6 g/grid) was not sufficient to provide adequate conductivity, so more (2.5 g/grid) was applied by conventional electroplating techniques from a copper sulfate plating bath. The electroless deposit therefore only served as a substrate to plate copper on an otherwise non-conductive plastic. Lead plating from a lead fluoboric bath followed (5 g/grid), generally after attaching the lead lug to be used later in paralleling the plates into the negative group. Plating thicknesses ranged from 0.050 to 0.075 mm for copper and 0.075 to 0.125 mm for lead. Composite negative grids with lead lugs attached weighed 20 - 25 gms compared to 47 gms for the cast lead control. Figure 1 is a photograph of the plastic grid, the plated grid with attached lug, and the control.

A standard paste was made and applied to the lightweight negative grids using conventional hand pasting techniques. Seven plate cells were constructed with outside positives and placed in automotive size containers. A milliohm meter was used to check the resistance of the composite against that of a cast lead control. One set of milliohm meter probes was placed on the grid lug and the other set on the bottom of the grid frame diagonally opposite to the lug. Both the resistance of the lightweight composite and the control was between 3 and 4 milliohms indicating that comparable performance in the battery would be obtained.

In Figure 2, discharge curves for cells with the Type A grid and cells with cast lead controls are shown. The current density at the 15 ampere rate on the automotive size plates corresponds to a 75 ampere discharge for the conventional EV-106 battery. No significant differences were observed in either closed circuit voltage or the active material utilization at any of

ABS Plastic Grid Wgt. 5 gm.

ABS Plastic Grid
Plated with Lug Attached Wgt. 26 gm.

Cast Lead Grid Wgt. 47 gm.

LIGHTWEIGHT COMPOSITE NEGATIVE GRID -
TYPE A (AUTOMOTIVE PLATE SIZE)

FIGURE 1

DISCHARGE BEHAVIOR OF LIGHTWEIGHT NEGATIVE GRIDS - TYPE A (AUTOMOTIVE SIZE)

FIGURE 2

the rates tested.

A major problem in this first attempt at constructing a lightweight, plastic matrix for the negative active material was connecting a lead lug to the matrix. Two methods were tried: (1) The plastic lugs were copper plated, dipped in solder flux, dipped in molten tin, and then in molten lead. Although the group was built using conventional burning techniques, this method does not appear suitable for production. (2) Another method was to mechanically attach lead straps and then solder through the molded hole in the lug of the plastic grid. A photograph of this lug configuration is shown in Figure 1. This method also has several drawbacks and only appears suitable for laboratory cell assembly.

A 6-cell automotive size battery (105-9) with seven plate elements containing lightweight negatives - Type A was designed and constructed. The cells were made negative limiting and contained 65 Ahrs of formed active material in the negative group. The battery was placed on extended life testing to determine if the copper plated plastic negative deteriorates with cycling. Over the first twenty-five cycles, load voltages and cell capacities were normal. However, subsequent cycling indicated a gradual but continuous erosion in performance. After initially holding steady at 30 Ahr, cell capacity dropped over 25% down to 22 Ahr. Reference readings and a post-mortem of one cell in the six cell battery clearly showed that the drop in capacity could not be attributed to a deterioration of the negative. Even though the initial ratio of positive active to negative active material was 1.8, the cells became positive limiting. Reference readings showed the negative was -0.23 vs Cd and the positive was 1.86v vs Cd at the end of discharge. The cell post mortem also revealed massive shedding of the pasted positive automotive plate while the negative active material remained intact. Its average weight loss was approximately 6%, small enough to be attributed to handling and disassembly.

A three plate negative group from battery 105-9 was rebuilt into cell N1-3, one of two cells in battery N1. The other, cell N1-6 was a control with cast lead negative grids. Both cells contained four thin tubular positive plates (ISOA-TP1 design) cut to automotive plate size dimensions. The ratio of formed positive to negative active material weight was 2.7/1.0 to insure that the cells were negative limiting. They also contained the same amount of negative and positive active material.

The negative group in cell N1-3 was cycled at 100% depth of discharge for 505 cycles. Sixty cycles were obtained as part of battery 105-9, and the remainder as part of battery N1. The cells' behavior in battery N1 as a function of cycle number at a constant 10 ampere discharge is shown in Figure 3. The test was voluntarily terminated and cell N1-3 was post-mortemed. We observed that the positive tubular plates were quite soft with significant loss of active material. The negative plates had some red discoloration on their surfaces indicating that some copper did dissolve in the electrolyte and replated back on the negative active material. We carefully removed the negative active material from one plate, and found the copper coating still covered between 60 and 70% of the plastic grid. Despite the loss of conductivity from initial values, the performance of the lead-copper coated plastic negatives in cell N1-3 equaled that of the control after 505 deep discharge

Cycle Performance of Cell N1-3
(Lightweight Negative Grids - Type A)

Figure 3

cycles. Based on this data, there is high confidence that the copper-lead coated plastic negative offers a technically feasible way to make a lightweight negative electrode whose performance and life equals that of a cast lead control.

1.5.1.2 Lightweight Negative Grid - Type A (EV Size)

Subsequent work on the Type A grid involved (1) a radial design, (2) scaleup from automotive to EV size, and (3) a solution to the lug problem. Figures 4 and 5 detail the features of the advanced negative EV grid which incorporates these Type A design concepts (Drawing Nos 6024008 and 6024009). In contrast to the standard orthogonal grid geometry, the advanced grid contains current carrying ribs extending radially from the lug. It contains 18 diagonal members which are used to carry the current and 18 horizontal cross members used as a matrix to support the negative active material. The pastable volume of the grid is the same as a standard GW lead cast orthogonal grid. However, it differs in that the total path length of the current carrying members has been increased by 63% whereas the total length of the horizontal members has been reduced by 22%. The spacing between the horizontal rows is a variable optimized so that the maximum pellet area in any given row equals that of any other row.

To eliminate the problem of the lug and permit the use of conventional burning techniques to assemble the negative plates into a group, the advanced lead acid negative grid specification has provided for a lead lug insert around which the plastic grid is molded. The lug insert weighs about 5 grams and a detailed drawing is presented in Figure 5. Nearly 500 of these lugs were hand cast from 6B5 antimony-lead alloy for subsequent insertion into the injection molding operation. The base mold for the lead lug insert was made by Lanson Machine Company, Morrisville, Pennsylvania.

The plastic grid mold was machined by Scholle Corporation, Chicago, Illinois, and the initial effort was limited to 500 grids for sampling purposes. A three plate mold system was used to make the plastic grid matrix with lead lug insert. The polymer extruded was platable ABS (Borg Warner Cycolac EPB 3570) and a series of critical operating procedures had to be determined and specified before success was achieved. These involved correct sizing and balancing of the gate and vent systems, and control of the operating temperatures and pressures. A particularly troublesome area was plastic flow around the delicate lower wire section of the insert, where encapsulation of the lead wires occurred. This resulted because a less expensive machining approach was initially used to provide an open frame pocket instead of a closed reinforced pocket which mated with the contour at the bottom of the lead insert. After several trials, five-hundred grids were successfully molded to specification, and the mold was certified as being suitable for large scale production. A photograph of the finished insert and the molded grid is shown in Figure 6.

After receiving the plastic grids from Scholle, they were sent to General Super Plating Company, Syracuse, New York. They agreed to plate 500 grids according to our specifications. The plating operation consisted of three steps:

DATE	BY	REVISION	AUTH	DO	CL
4/4	B	REVISED		23

DESIGN/RELEASE APPROVALS		DRAWN BY	R.D.	DATE	5/30/79	ESB INCORPORATED TECHNOLOGY CENTER YARDEY, PENNSYLVANIA
APPROVED BY	DATE	ENGINEER		SCALE	2:1 AND 8:1		
		MATERIAL	ALLOY 6B5			LEAD INSERT FOR	
			DO NOT SCALE DRAWING			GRID - RADIAL RIB	
			TOLERANCE				
		FRACTION	DECIMAL	ANGLES		DRAWING NO.	
		± 1/64	.XX ± .010 .XXX ± .005	± 1/4°		6024009	
						E	

Advanced Negative Grid - Lead Lug Insert

FIGURE 5

1. Electroless plate - 0.6 gm of copper was electroless plated on the ABS plastic bringing the overall grid weight to 13.6 gms.
2. Electroplate Copper - an additional 8 - 9 gms of copper was electroplated onto the grid to increase its conductivity to the level obtained with cast lead grids.
3. Electroplate lead - an additional 15 - 18 gms of lead was electroplated over the copper to render it inert, and to reduce hydrogen evolution during charge.

The copper plating increased the grid thickness from 1.47mm to 1.59mm, while the lead resulted in a final grid thickness of 1.77mm. This is somewhat higher than was called for in our original specification (.05mm thick copper and .05mm thick lead), and future work will emphasize a reduction in the lead plating. The final grid weight was 40 gms, nearly one-half of the cast lead control. The weight was broken down as follows:

Lead - Lug (5) + Plating (17) = 22 gms

Copper - Electroless (0.5) + Electroplate (8.5) = 9 gms

ABS Plastic = 8.6 gms

At present, over one hundred plated lightweight negative grids with lead lug insert have been received from General Super Plating. Approximately 4% failed to meet weight and conductivity criteria. The rest are within specifications and could be placed in cells for further evaluation. A photograph of the finished advanced EV battery negative grid - Type A is shown in Figure 7.

In order to initially evaluate the performance of these Type A grids, eleven were assembled into a negative group in cell TP23. Other work on the project has demonstrated that tubular positive plates, TP-1 design, exhibit the longest life of the positive electrode configurations tested, so we decided to couple them with the Type A grids. The tubular plate parameters follow:

Table 17: Positive Electrode Construction Coupled with Negatives

Containing Lightweight Advanced Grids

No. of Tubes per Plate: 11

Grid Weight: lead 122 gms, tubes 16 gms, bottom bar 2 gms,
total weight 140 gms.

Active Spine Length: 15.3 cm

Volume of Spine (twin): 0.675 cm^3

Inside Tubing Dimensions: Avg. Width (cm) - 1.40 cm

Tube Wall: 0.35 mm

ADVANCED EV BATTERY -
NEGATIVE GRID (PLATED) - TYPE A
CONSTRUCTION

FIGURE 7

The pertinent details of cell construction for TP23 can be found in Table 18.

Table 18: Construction of Cell TP23

(Type A Negative Grid, EV Size)

A. Negative Electrode

1. Negative Plate

a)	Grid Type	Type A - EV Size, Electroplated Copper and Lead on ABS Plastic with Lead Lug Insert
b)	Grid Weight (g)	38.4
c)	Paste/Plate (g)	180
d)	DAM/Plate (g)	167
e)	FAM/Plate (g)	159
f)	Theoretical Ahrs.	41

2. Negative Group

a)	Number of Plates	11
b)	Formed Weight (including strap) g	2342

B. Positive Electrode

1. Positive Plate Tubular, cf Table 17

2. Positive Group

a)	Number of Plates	10
b)	Formed Weight (including strap) g	4070
c)	Theoretical Ahrs	574

C. Electrolyte

1.	Sp. Gr. Charged (g/cc)	1.300
2.	Volume/Cell (cc)	2000
3.	Weight (g)	2600
4.	Ahr. Theoretical	278

D. Separators - Ribbed Daramic Envelopes, 0.762 mm Rib,
0.254 mm Backweb, 4.9 g/separator

E. Cell Weight (calculated - Kg) 9.55

Characterization testing of TP23 has been completed and the results are shown below. The initial temperature at discharge was $27 \pm 1^\circ\text{C}$ for all cycles.

Cycle	Current (Amps)	Minutes	Avg. Voltage	Ahr. to 1.6 Volts	Whr. to 1.6 Volts	Initial Sp. Gr.	Positive AM Use	Whr Kg
5	60	182	1.92	182	349	1.300	31.7	36.5
6	75	135	1.90	169	321	1.306	29.4	33.6
7	120	77	1.86	154	386	1.300	26.8	30.0
8	35	346	1.95	202	394	1.310	35.2	41.2
9	25	506	1.96	210	412	1.300	36.4	43.1
11	240 (1)	27.5	1.78	110	196	1.310	19.2	20.5
12	500 (1)	10.4	1.50	86.7	130	1.300	15.1	13.6

1000 amps (2), full charge, 1.37 volts, 1370 watts, 143 watts/Kg

1000 amps, 30% discharged, 1.26 volts, 1260 watts, 132 watts/Kg

1000 amps, 60% discharged, 1.01 volts, 1010 watts, 106 watts/Kg

Notes:

- (1) The cutoff voltage at 240 amps discharge was 1.5V.
The cutoff voltage at 500 amps discharge was 1.0V.
- (2) The discharge current is maintained for 15 secs, and the average voltage determined.

Following the characterization tests, the cell was placed on extended life cycling where it has now accumulated 75 cycles with no loss in capacity.

1.5.1.3 Lightweight Negative Grid - Type B (EV Size)

An alternative to the Type A lightweight negative grid already discussed involves the use of electroformed copper. A joint effort between the Exide Management and Technology Company and the Inco Research and Development Center (IRDC) has resulted in the design and construction of an EV size grid made as follows a) a 0.10mm thick substrate of electroformed copper was deposited in an orthogonal grid design b) the copper was completely covered with 0.05mm thick lead plated onto the copper to render it inert and c) 0.10mm thick lead was plated in the lug area to provide strength and rigidity in a region normally subjected to considerable forces and moments during pasting, handling, and assembly.

The major advantages that the Type B negative grid construction has over the Type A construction are:

- 1) The electroless copper deposition process is no longer necessary, and the multidip operation associated with it is eliminated.
- 2) Plastic is not required to form an active material support matrix; enough rigidity is provided by the electroforming process. The plastic comprises a significant portion (70 to 110 cc) of the available volume in the cell compartment and eliminating it provides that much more space for electrolyte and active material.
- 3) For a given weight of copper, the electroforming operation results in a grid with a conductivity somewhat higher than is obtained by electroless deposition followed by electroplating.

The primary disadvantage of the Type B grid at the present time is the cost of experimental quantities. Obviously, large scale production could substantially lower this figure. It should be pointed out that based on its raw material content, the grid costs less than \$0.06 (18 gms copper at \$1.00/lb = \$0.04, 19 gms lead at \$0.40/lb = \$0.02). Nevertheless some doubt remains as to whether electroforming of copper could ever be cost competitive with lead casting and considerable effort is being spent at IRDC to develop an alternate means for making a thin copper substrate. At present, stamping looks promising, and sample grids should be made in the near future.

A total of 550 electroformed grids were made for us by IRDC to test in advanced lead-acid EV batteries. The first fifty were slightly thinner and contained less copper than the rest. Significant grid parameters are:

		Grid Numbers	
		1-50	51-551
Copper			
Wt	(g)	9	18
Thickness	(cm)	0.05	0.100
Lead			
Wt	(g)	19	19
Thickness	(cm)	0.05	0.05
Total Grid Wt (g)		28	37
Total Grid Thickness (cm)		0.15	0.20

Note: The lug in all grids contained 0.10cm lead plate

Although the thinner electroformed grid had more than adequate conductivity, we decided to specify the heavier grid because of its greater rigidity and ease of handling. Figure 8 (Dwg. 6024007) shows a photo-reduction of the blueprint for the Type B lightweight electroformed negative grid, and Figure 9 is a photograph of a plated sample. The grid geometry is orthogonal. The inherent conductance of copper and the amount present (18g) resulted in a grid which was significantly more conductive than the cast lead controls so

FIGURE 8

W

ADVANCED EV BATTERY - NEGATIVE GRID -
TYPE B CONSTRUCTION

FIGURE 9

that there was no need to employ a radial rib design to accomodate high rate discharges. A study was made to evaluate the relative conductivity of various advanced grids containing plastic and/or copper and those made from cast lead. A milliohmimeter was used to measure resistance; one set of probes was placed on the grid lug and the other set on the bottom of the grid frame diagonally opposite the lug (the voltage monitoring probes were placed inside of the current carrying probes). The results are presented in Table 19.

Table 19: The Resistance of Lead Acid Grids

Grid Designation	Thickness (cm)	Weight (g)	Composition	Lug Position	Resistance (mΩ)
GW (orthogonal)	1.47	80	6% Sb - Pb	Offset	3.77
GW (orthogonal)	1.47	76	0.1% Ca - Pb	Offset	3.61
GW (orthogonal)	1.47	73	0.1% Ca - Pb	In-line	3.58
2EVR (radial)	1.47	84	6% Sb - Pb	In-line	3.23
2EVR (radial)	1.47	76	0.1% Ca - Pb	In-line	3.00
2GW (orthogonal)	1.83	90	6% Sb - Pb	Offset	3.75
2GW (orthogonal)	1.83	90	6% Sb - Pb	In-line	3.50
1EVR (radial)	1.83	92	6% Sb - Pb	Offset	3.07
1EVR (radial)	1.83	91	6% Sb - Pb	In-line	3.18
1GW (orthogonal)	2.08	105	6% Sb - Pb	Offset	3.07
Type A (radial)	1.77	40	Cu+Pb+ABS	In-line	2.05
Type B (orthogonal)	0.15	28	.05cmCu+.05cmPb	Offset	2.00
Type B (orthogonal)	0.20	37	.10cmCu+.05cmPb	Offset	1.05

The finalized Type B design resulted in a grid three times as conductive as cast lead standards while weighing less than half.

An evaluation of the Type B design and conclusions regarding grid performance were primarily based on the cycling behavior of one 6V battery, and two cells.

Battery 1507-8: a three cell battery, 31 plate element, outside positives, negative grid contains 0.05 cm Cu, flat plate positives

Cell AEX-6: 29 plate element, outside positives, negative grid contains 0.10 cm Cu, flat plate positives

Cell TP24: 21 plate element, outside negatives, negative grid contains 0.10 cm Cu, tubular positives

Battery 1507-8 contained 45 lightweight electroformed grids each weighing 28 gms and pasted with 118 grams of negative active material. A typical cured pasted plate is shown in Figure 10, and a formed plate in Figure 11. Other details of construction can be found in Table 20. The overall battery weight was 6% or 2 Kg less than a control with cast lead negative grids.

CURED PASTED PLATE - NEGATIVE GRID
TYPE B CONSTRUCTION

FIGURE 10

FORMED PASTED PLATE - NEGATIVE
GRID TYPE B CONSTRUCTION

FIGURE 11

Table 20: Construction Details of Battery 1507-8

(Type B Negative Grid)

A. Negative Electrode

1. Negative Plate

- a) Grid Type - Electroformed copper substrate 0.05 cm thick, 0.05 cm lead plating
- b) Grid Weight (g) - 28
- c) Paste/plate (g) - 118
- d) DAM/plate (g) - 114
- e) FAM/plate (g) - 110
- f) Theoretical Ahrs. - 28.5
- g) Cured Thickness (mm) - 1.20

2. Negative Group

- a) Number of Plates - 15
- b) Theoretical Ahrs - 428

B. Positive Electrode

1. Positive Plate

- a) Lead Grid Type - 2 GW, 1.83 mm thick, 6% Sb - Pb
- b) Grid Weight (g) - 93
- c) Paste per Plate (g) - 172
- d) DAM/plate (g) - 159
- e) FAM/plate (g) - 161
- f) Theoretical Ahrs - 36.1
- g) Cured Thickness (mm) - 2.16

2. Positive Group

- a) Number of Plates - 16
- b) Theoretical Ahrs - 577

C. Electrolyte

- 1. Sp. Gr. charged - 1.300
- 2. Volume/Cell (cc) - 2100
- 3. Theoretical Ahrs/Cell - 292

D. Separators - Ribbed Daramic Envelopes, 0.762 mm - Rib, 0.254 mm backweb.

E. Total Battery Wt. (Kg) - 29.4

Although the negative plates containing the lightweight electro-formed grids required careful handling after pasting since they were less rigid than normal, the negative groups could be burned using conventional techniques and the battery was assembled without mishap. Battery performance was characterized at selected discharge rates and the results are:

Current (Amps)	Minutes	Avg Voltage	Ahr to 4.8V	Whr to 4.8V	Initial SpGr	Positive AM Use	Whr Kg
40	316	5.89	211	1241	1.300	36.6	42.2
60	200	5.86	200	1172	1.300	34.7	39.9
75	148	5.81	185	1075	1.300	32.1	36.6
125	80	5.71	167	954	1.300	28.9	32.4

Following the characterization tests, 1507-8 was placed on extended life cycling. The battery was nominally discharged to 80% of the 3-hour rate, and charged to 133% of actual capacity. A plot of capacity versus cycle number is shown in Figure 12. Little deterioration in performance was noted during the first 120 cycles. Afterwards, capacity drop off and erratic behavior began to occur. The electrolyte in all cells was cloudy at the top of charge indicating that significant shedding of the positive plates occurred and the possibility of moss shorting was likely. Cadmium reference readings showed that the positive electrode was limiting in all cells; the negative reference readings remained constant indicating that the negative plates were holding up well. By cycle 200, the ampere-hour capacity of 1507-8 dropped below 80% of its maximum value, and the energy density at the 3-hr rate was 33 whr/Kg (53 amps for 3 hrs). It should be noted, however, that at this point in the test the battery outlasted all controls built with conventional cast lead negative grids.

Battery 1507-8 was post-mortemed on 8/5/80 after 270 deep discharge cycles. Capacity at 50 amps had dropped to 115 Ahrs - less than 70% of original. Mossing was evident in all cells, the electrolyte was very cloudy at the top of charge, and considerable sediment was present at the bottom of the cell compartments. Three positive plates in cell 1 exhibited moss shorts in the area of the lug, none in cell 2, and one in cell 3. The battery was taken apart at the top of charge, the plates were carefully rinsed in water, and then vacuum dried. Afterwards, the plate weights were recorded, and in selected instances the active material removed and the grid weights determined. The results shown in Table 21 clearly pinpoint the major mode of battery failure - shedding of the positive active material. The negatives held up remarkably well with no significant loss of active material.

Figure 12: Discharge of 1507-8 (Lightweight Electroformed Copper Negative)

TABLE 21: Post-Mortem of 1507-8

	Cell 1	Cell 2	Cell 3
Positive			
Formed Active Material			
Initial Wt (g)	161	161	161
Final Wt (g)	104	108	90
% Loss	-35	-33	-44
Grid			
Initial Wt (g)	95	95	95
Final Wt (g)	90	96	94
% Loss	-5	0	-1
Negative			
Formed Active Material			
Initial Wt (g)	110	110	110
Final Wt (g)	106	105	107
% Loss	-4	-5	-3
Grid			
Initial Wt (g)	28	28	28
Final Wt (g)	28	28	28
% Loss	0	0	0

Visual examination of the negative plate surface showed no indication of copper dissolution from the grid and subsequent replating. Based on the performance of 1507-8 we feel confident that no technical barrier exists in using lead plated electroformed copper grids as specified in the Type B design for the negative electrode in lead-acid batteries. They are more conductive than conventional cast lead grids, promote a more uniform current distribution at the electrode, offer a weight savings exceeding 50%, and have no harmful effect on battery life.

Cell AEX6 contained 15 lightweight electroformed grids each weighing 37 gms and pasted with 125 gms of negative active material. Other details of construction can be found in Table 22.

TABLE 22: Construction of Cell AEX 6 (Type B Negative Grid)

A. Negative Electrode

1. Negative Plate

- a) Grid Type - Electroformed copper substrate
0.10 cm thick, 0.05 cm lead plating
- b) Grid Wt (g) - 37
- c) Paste Plate (g) - 125
- d) DAM/Plate (g) - 117
- e) FAM/Plate (g) - 110
- f) Theoretical Ahrs - 28.5

TABLE 22 (Continued)

3. Negative Group

- a) Number of Plates - 14
- b) Formed Weight (including strap) g - 2234
- c) Theoretical Ahrs - 39.9

B. Positive Electrode

Oxide and positive plate parameters same as specified for 1507-8 (cf Table 20).

1. Positive Group

- a) Number of Plates - 15
- b) Formed Weight (including strap) - 3900
- c) Theoretical Ahrs - 544

C. Electrolyte

- 1. Sp. Gr. charged (g/cc) - 1.285
- 2. Volume/cell (cc) - 2160
- 3. Weight (g) - 2776
- 4. Ahr Theoretical - 284

D. Separators - Ribbed Daramic Envelopes, 0.762 mm Rib, 0.254 mm Backweb, 4.9 g/separator

E. Cell Weight (Kg) - 9.40

Cell performance was characterized at selected discharge rates and the results follow. The initial discharge temperature was $27 \pm 1^\circ\text{C}$, and the specific gravity was $1.290 \pm .005$.

Current (Amps)	Minutes	Avg Voltage	Ahr to 1.6V	Whr to 1.6V	Positive AM Use	Whr Kg
22.5	1350	1.97	225	443	41.4	47.1
36.0	360	1.97	215	423	39.5	45.0
62	180	1.95	186	363	34.2	38.6
140	60	1.88	140	264	25.7	28.1
240 (1)	30	1.82	120	218	22.1	23.2
500 (1)	10.7	1.61	90	143	16.5	15.2

1000 amps (2) full charge, 1.55 volts, 1550 watts, 165 watts/Kg

Notes: (1) The cutoff voltage at 240 amps discharge was 1.5V
The cutoff voltage at 500 amps discharge was 1.0V

(2) The discharge current is maintained for 15 secs, and the average voltage determined.

Following the characterization tests, the cell was placed on extended life cycling where it has now accumulated 120 cycles with no significant loss in capacity. The depth of discharge is 100%. A 33% overcharge was maintained in cycles 1-45, and was reduced to 25% in subsequent cycles. This was done to maximize cycle life by inhibiting corrosion of the positive grid and shedding of the active material. A plot of capacity versus cycle number is shown in Figure 13. The drop in delivered capacity which occurred between cycles 40 and 50 is directly attributable to the change in the charge regime. Although a reduction in overcharge did initially drop capacity by 10%, it has since remained level.

Cell TP24 contained 11 lightweight electroformed grids each weighing 37 gms and pasted with 180 gms of negative active material. The 0.20 cm thick electroformed grid was rigid enough to handle this relatively large amount of paste without any problem. Pasting, handling, and burning were accomplished with no grid member or lug distortion. Except for the negative grid, TP24 was built identically to TP23 (cf Table 17 to obtain details of the tubular positive grid, and Table 18 to obtain negative and positive electrode parameters). TP24 contained 2090 cc of acid and weighed 9.65 Kg, the ratio of positive to negative formed active material was 1.47.

Characterization testing of TP24 has been completed and the results are shown below.

Cycle	Current (Amps)	Minutes	Avg Voltage	Ahr to 1.6V	Whr to 1.6V	Initial Sp.Gr.	Positive AM Use	Whr Kg
3	60	182	1.92	182	353	1.300	31.7	36.6
10	75	133	1.91	166	318	1.290	28.9	33.0
9	120	72	1.88	144	271	1.290	25.1	28.1
12	35	34.8	1.96	203	398	1.300	35.4	41.2
13	25	504	1.97	210	414	1.300	36.4	42.9
8	240	28.3	1.79	113	203	1.290	19.7	21.0
5	500	10.4	1.56	86.7	135	1.300	15.1	14.0

1000 amps, full charge, 1.39 volts, 1390 watts, 144 watts/Kg
 1000 amps, 30% discharged, 1.29 volts, 1290 watts, 134 watts/Kg
 1000 amps, 60% discharged, 1.09 volts, 1090 watts, 112 watts/Kg

A comparison of this data and that of TP23 discussed earlier indicates little difference in the performance characteristics of the two cells. Only at high current drains does the cell containing the lightweight electroformed grids (Type B construction) show a significant improvement over the cell with the plated plastic negatives (Type A construction). The increased energy output is due primarily to a higher average cell voltage generated by the more conductive electroformed copper grids. Following the characterization tests, the cell was placed on extended life cycling where it has now accumulated 70 cycles with no loss in capacity.

Figure 13: Discharge of AEX-6 (Lightweight Electroformed Copper Negatives)

1.5.2 Positive

The positive electrode is a critical component affecting the energy density of the lead acid battery. Typically it comprises 40% of the total battery weight (the positive grid 15% and the positive active material 25%). During the past year, two different types of positive electrodes were investigated - tubular, and pasted flat plate. Unfortunately, our study has shown that each type of electrode possesses some unique advantages which are not shared by the other.

	Tubular	Flat Plate
Advantages	1) Outstanding cycle life, 3x flat plate	1) lower cost 2) thin plates, good active material use, greater than 38% @ 3hr rate 3) ease of assembly
Disadvantages	1) Expensive, greater than flat plate 2) thicker plates, almost 2x flat plate, poor active material use, 33-35% @ 3hr rate 3) assembly more complicated	1) Poor cycle life

The flat plate positive electrode is superior in all respects but one - cycle life. The question therefore remains in EV battery design, is one willing to accept the minuses associated with tubular construction in order to utilize this outstanding plus?

We have attempted to resolve this dilemma and come up with a battery which exhibits the best of both worlds. The positive electrode study aimed to 1) improve the utilization of the positive active material in tubes while maintaining cycle life and 2) increase cycle life of the positive active material in flat plates with no loss in utilization. Only minor successes were achieved towards these goals.

1.5.2.1 Tubular Electrode

In a tubular electrode, the positive active material is encapsulated in a phenolic impregnated woven glass fiber tube, and shedding is thereby restrained.

In contrast to flat plates which are pasted with a mixture of oxide, sulfuric acid, and water, tubular positive plates are filled with dry oxide powder only. The powder is introduced in the space between the tube wall and the centrally located lead spine. The process is considerably aided by vibration or shaking which is absolutely needed to achieve the required fill density. An optimum fill density exists above which utilization of the active material is poor, yielding a low energy density, and below which wash-out occurs and plate life is short. The optimum density should ideally result in a tubular electrode which combines long life and good utilization.

The tubular grid used was the same as the one designed for the ISOA-TP1 battery. Typical grid dimensions were presented in Table 17.

A possible solution towards improving the active material utilization is to maximize the surface area of the tubular positive group. This reduces the rate of electrochemical reaction per unit surface area (the current density) without altering the diffusion rate of the electrolyte, and in effect enhances accessibility of the positive active material to sulfate ions needed for discharge. With the plate thickness of the tubular ISOA grid held as a constraint, maximizing the surface area of the positive group meant squeezing as many plates as possible into the EV cell compartment while still remaining positive limiting. Even so, the utilization of the active material in the tubular electrode was nearly 10-15% less than obtained with a pasted flat plate construction. Part of the problem may be that tubular plates are nearly twice as thick as flat plates. The positive active material is not nearly as accessible to the electrolyte even though low fill densities are specified. This is particularly true at high discharge rates. A solution would be to make the tubular electrodes thinner thereby increasing the surface area of the group. Manufacturing them, however, becomes quite difficult and tube dimensions are very difficult to hold. Also, the tube wall becomes a substantial portion of the total electrode thickness and the room remaining for the positive active material is substantially reduced.

1.5.2.2 Flat Pasted Plate Electrode

The flat pasted plate electrode is the simplest and cheapest plate to build and exhibits the best energy density of all those tested. It is made by pasting a grid with a mixture of fine oxides, water, and sulfuric acid. The electrolyte composition is adjusted to a given paste density and to a given viscosity. The pasted plate is then cured in a wet air atmosphere and dried. It is stored until the positive group is ready to be burned. As indicated earlier, this type of electrode can be made thin to enhance acid penetration into the positive active material, and it contains no inert material such as plastic or glass which tend to increase the current density at the electrode surface. These factors make for good utilization. The only disadvantage of the flat pasted plate construction is that it is not conducive to long life.

During the past year, a considerable effort was aimed at increasing the life of the flat plate electrode while maintaining active material use. This included investigations of 1) A proprietary additive to the positive mix whose purpose was to reduce shedding with low paste density 2) Stranmat, a unidirectional glass fiber mat placed against the positive paste to retard shedding 3) carbon addition to the positive paste to increase its electronic conductivity. Positive group plate number, plate thickness, and plate density were also varied in order to maximize the overall battery energy density while maintaining life. Although some successes were achieved, in general we were not able to increase cycle life of the flat pasted plate much beyond 200 cycles while still maintaining the battery energy density at 40 whr/Kg @ the 3-hr discharge rate.

A five battery factorial experiment was run to study the effect of plate thickness, paste density, and additives, on the life and active material use of flat plate positives. Except for plates per group, the negative group was unchanged from one battery to the next. Cell parameters are listed in Table 23.

TABLE 23: Battery Parameters for Flat Plate Electrode Factorial Design Study

		Battery Designation				
		1507-1	1507-3	1507-4	1507-5	1507-6
A. Negative Electrode						
1.	Negative Plate					
a)	Lead Grid Type			GW		
b)	Grid Weight (g)			83		
c)	Paste per Plate (g)			110		
d)	DAM/Plate (g)			114		
e)	FAM/Plate (g)			110		
f)	Theoretical Ahrs.			28.5		
g)	Cured Thickness (mm)			1.47		
2.	Negative Group					
a)	Number of Plates	14	15	15	15	14
b)	Theoretical Ahrs.	399	428	428	428	399
B. Positive Electrode						
1.	Positive Plate					
a)	Lead Grid Type	1GW	2GW	2GW	GW	2GW
b)	Grid Weight (g)	105	95	95	83	95
c)	Paste per Plate (g)	172	172	172	150	172
d)	DAM/Plate (g)	164	162	155	141	154
e)	FAM/Plate (g)	166	164	158	143	157
f)	Theoretical Ahrs.	37.2	36.8	35.4	32.1	35.2
g)	Cured Thickness (mm)	2.21	2.21	2.18	1.70	2.44
2.	Positive Group					
a)	Number of Plates	15	16	16	16	15
b)	Theoretical Ahrs.	558	588	566	514	528
C. Electrolyte						
1.	Sp. Gr. Charged			1.300		
2.	Volume/Cell (cc)	2025	1980	2000	2080	2050
3.	Theoretical Ahrs/Cell	281	275	278	289	285
D. Separators						
Ribbed Daramic Envelopes, 0.762 mm rib, 0.254 mm backweb						
E. Total Battery Wt. (Kg)						
		30.5	31.4	31.6	30.4	30.2

All of the batteries were initially discharged at 60 amperes. Maximum capacities obtained with an initial discharge temperature of 30°C were:

Battery No.	Cycle No.	Time (Mins)	Ahr. Capacity	Whr. Capacity	Pos. Active Mat. Use (%)	Whr/Kg
1507-1	12	205	205	1200	36.7	39.3
1507-3	10	208	208	1220	35.4	38.9
1507-4	6	205	205	1200	36.2	38.0
1507-5	10	194	194	1137	37.9	37.4
1507-6	6	204	204	1195	38.5	39.6

Following characterization testing, they were placed on extended life cycling with automated test equipment. The cycle regime was: High rate charge - 20 amps for 5.9 hours, Low rate charge - 11 amps for 7 hours, Discharge - 65 amps for 2.4 hours or to a 5.1 volt cutoff, whichever came first. The batteries were nominally discharged to 80% depth of the 3-hr rate, and charged to 125% of actual capacity. Seventy-five percent of capacity went in at the high rate with the remaining 50% at the low rate. Plots of capacity vs cycle number are presented for batteries 1507-1, 1507-3, 1507-4, 1507-5 and 1507-6 in Figures 14, 15, 16, 17, 18 respectively.

Based on the maximum performance characteristics of the batteries and their cycle life behavior we can conclude the following:

- (1) At a high positive paste density, the effect on positive active material use of reducing the plate thickness is significant. Battery 1507-5 with plates 1.70 mm thick exhibited 38% use of PAM whereas 1507-3 with plates 2.21 mm thick exhibited 35.4%. However, because of the fixed weight of some of the other battery components, on an overall battery basis the energy density with thinner positives (less active material, less theoretical ampere hours) was worse. We therefore conclude that a plate thickness of 2.2mm and 2 GW grids should be used in any pasted flat plate designs.
- (2) Even the best performing battery, 1507-1, failed to deliver more than 150 cycles at the 3-hr rate. A post mortem revealed that mossing occurred in all cells, the electrolyte was very cloudy at the top of charge, and that considerable sediment was present at the bottom of the cell compartments. Positive plate weights indicated massive shedding - in excess of 30% active material loss occurred. Post-mortem data from this and other flat plate cells forced us to conclude that without improved retainers around the positive plate, the combined energy density and cycle life goals of the EV battery cannot be met using the pasted flat plate construction.

In order to improve the utilization of positive active material, we studied the addition of carbon to the positive paste. Two levels (2% and 5% by wt.) of Shawiningan Black, a conductive, high surface area acetylene black commonly found in dry cells, were added to the positive paste. It was hypothesized that carbon would initially improve the overall electrical conductivity of the positive, and even as the carbon was slowly oxidized over the life of the battery, void structures would be left to enhance electrolyte penetration to the internal structure of the electrode. Two paste compositions were formulated for the positive groups in cells PP17 and PP18.

Figure 14: Cycling Discharge Behavior of 1507-1 (15 plate pos. group, 2.21mm thick)

Figure 15: Cycling Discharge Behavior of 1507-3 (16 plate pos. group, 2.21mm thick)

Figure 16: Cycling Discharge Behavior of 1507-4 (16 plate pos. group, 2.18mm thick)

Figure 17: Cycling Discharge Behavior of 1507-5 (16 plate pos. group, 1.70mm thick)

Figure 18: Cycling Discharge Behavior 1507-6 (15 plate positive group, 2.44mm thick)

Plates per Cell

15 with outside positives

Ahr per Plate

35.4

After 15 cycles, the energy density of the carbon containing electrodes was no better than a control without carbon. The cell with 2% Shawinigan had a 3-hr discharge capacity identical to the control whereas the one with 5% behaved much worse.

	Current (Amps)	Time (mins)	Capacity Ahrs	
PP17	60	191	191	Note: all positive groups contained the same amount of formed active material
PP18	60	163	163	
Control	60	190	190	

Based on this data no further work was done with carbon containing positives.

A battery was built with thin (55 mil - 1.4 mm) split positive plates, i.e. 22 plate positive group, 11 plate negative. We anticipated that the thin split positive would 1) improve circulation to the positive active material and increase its reactivity and 2) improve the cycle life of the battery by providing more uniform mass transfer to and from the electrode. Cell parameters are listed in Table 24.

TABLE 24: Design Parameters for Battery with Split Positive Construction

A. Negative Electrode

1. Negative Plate

- a) Lead Grid Type - 2GW, 2.0 mm thick, 6% Sb alloy
- b) Grid Weight (g) - 79
- c) Paste/Plate (g) - 167
- d) DAM/Plate (g) - 156
- e) FAM/Plate (g) - 149
- f) Theoretical Ahrs. - 38.6
- g) Cured Thickness (mm) - 1.98

2. Negative Group

- a) Number of Plates - 11
- b) Theoretical Ahrs. - 425

B. Positive Electrode

1. Positive Plate

- a) Lead Grid Type - GW, 6% Sb alloy, compressed to 1.4mm
- b) Grid Weight (g) - 75
- c) Paste per Plate (g) - 115
- d) DAM/Plate (g) - 108
- e) FAM/Plate (g) - 110
- f) Theoretical Ahrs. - 24.7
- g) Cured Thickness (mm) - 1.52

TABLE 24 (Continued)

2. Positive Group
 - a) Number of Plates - 22
 - b) Theoretical Ahrs. - 543
- C. Electrolyte
 1. Sp. Gr. Charged - 1.300
 2. Volume/Cell (cc) - 2000
 3. Theoretical Ahrs/Cell - 278
- D. Separators - Ribbed Daramic Envelopes, 0.762 mm Rib, 0.254 mm Backweb, 32 per cell (one included between each split positive).
- E. Total Battery Wt. (Kg) - 30.3

The maximum capacity of the battery was not significantly better than the control. Typically at 60 amps, 190 Ahrs and 1110 whrs were obtained. This corresponds to 37 whr/Kg and a positive active material use of only 35%. Before the test was terminated, Battery 1507-10 accumulated 112 deep discharge cycles. A considerable drop in capacity was evident at this point, and cycle life performance did not exceed that of the control with standard element construction. Representative Ah capacity data follow:

Cycle No.	Current (Amps)	Time (Mins)	Capacity (Ahrs)
30	50	225	187
50	50	210	175
90	50	180	150
100	50	175	146
110	50	166	138
112	50	144	120

A cell post-mortem revealed that significant shedding of positive active material occurred from the thin positive plates.

Two batteries were constructed under control conditions to evaluate the relative performance of 25 versus 29 plate elements. We wanted to determine if there was a significant improvement in the energy density of the 25 plate element cell due to increased electrolyte volume. In both batteries, the negative and positive grids, the negative and positive pastes, and the active material per plate were identical. A detailed summary of the battery designs follows in Table 25.

TABLE 25: 25 Plates vs 29 Plates Element Construction

	25 Plate Element	29 Plate Element
A. Negative Electrode		
1. Negative Plate		
a) Lead Grid Type	GW, 1.47 mm thick, 6% Sb alloy	
b) Grid Weight (g)	80	
c) Paste/Plate (g)	125	
d) DAM/Plate (g)	118	
e) FAM/Plate (g)	116	
f) Theoretical Ahrs.	30.03	
2. Negative Group		
a) Number of Plates	12	14
b) Formed Weight (including strap)	2502	2894
c) Theoretical Ahrs.	360	420.4
B. Positive Electrode		
1. Positive Plate		
a) Lead Grid Type	2GW, 1.83 mm thick, 6% Sb alloy	
b) Grid Weight (g)	88	
c) Paste/Plate (g)	172	
d) DAM/Plate (g)	160	
e) FAM/Plate (g)	162	
f) Theoretical Ahrs.	36.3	
2. Positive Group		
a) Number of Plates	13	15
b) Formed Weight (including strap)	3400	3900
c) Theoretical Ahrs.	472	545
C. Electrolyte		
1. Sp. Gr. Charged (g/cc)	1.300	
2. Volume/Cell (cc)	2180	2025
3. Weight (g)	2834	2632
4. Ahr. Theoretical	303	280
D. Separators - Ribbed Daramic Envelopes, 0.762 mm Rib, 0.254 mm Backweb, 4.9 g/separator.		
E. Container and Cover (g)		
	1071	
F. Total Battery Weight (Kg)		
	27.5	29.5

It is apparent from the construction data that although the 25 plate cell has a net reduction of 12.8% in the positive active material, the overall battery weighs only 6.8% less.

Performance data for both batteries were obtained at the 3-hr. discharge rate, and maximum values at 27°C are tabulated below.

	25 Plate Element	29 Plate Element
Time (min)	180	180
Current (Amps)	60	65
Voltage	5.84	5.83
Ahrs.	180	195
Whrs.	1051	1136
Pos. AM Use (%)	38.1	35.8
Neg. AM Use (%)	50.0	46.4
Acid Use (%)	59.4	69.6
Whr/Kg	38.2	38.5

A 25 plate element did improve the utilization of positive active material from 35.8 to 38.1%. However, since the battery construction incorporates such fixed weight items as the container, cover, straps, and posts, the increase in utilization did not result in a net improvement in the battery's overall energy density. The presence of more electrolyte in the 25 plate element did increase use of the PAM by 6.4%, and the battery did weigh 7.3% less, but this did not override the net energy increase of 8.1% obtained from the 29 plate element. From the total energy, and volumetric energy density point of view, this experiment showed that the 29 plate element is more desirable. The benefits from a 25 plate element, if any, may lie in the area of cycle life. At present, life is a major problem in deep discharging flat pasted plate batteries at the 3-hr. rate. At 1 1/2 cycles per day, the positive in this type of battery normally fails before 150 cycles. Use of the smaller element allows the gap between plates to increase from 0.96 mm to 1.42 mm. Therefore, glass retainers can be more readily employed to constrain the positive active material from shedding and/or softening. We constructed a 25 plate element battery, 1507-11 similar to the one described above except that 1.00 mm "Stranmat" from Hydramatic Company was u-folded around the positive plates. The "Stranmat" consists of unidirectional glass fibers which are oriented vertically. Experience with industrial pasted plate lead acid batteries shows that this material helps to retain the positive active material but still allows good acid transfer from top to bottom of the cell container and good use of the positive active material. Inclusion of the "Stranmat" increased the weight of the 3-cell battery by 0.45 Kg, and reduced the cell electrolyte volume by 130 cc.

Battery 1507-11 was placed on automatic life cycling to test the effects of "Stranmat" on long term battery behavior. It was discharged at 55 amps for 2.4 hours or to 5.1v - whichever came first. Charging occurred in two steps: high rate charge - 18 amperes for 5.9 hours, low rate charge - 10 amperes for 7 hours. The charge into the battery corresponded to 133% of discharge. At selected cycles, the battery was given an equalization charge and discharged at 60 amps to 4.8 volts. As indicated below, the use of "Stranmat" decreased the maximum capacity of a 25 plate element by 7.5%.

Cycle No.	Current (Amps)	Time (Mins)	Initial Temp (°C)	Init SpGr	Positive Active Material Use (%)	Capacity (Whr/Kg)
1507-11 10	60	162	29	1.290	34.3	34.1
Control 10	60	175	29	1.290	37.1	36.8

However, by cycle 85, the performance of the "Stranmat" containing cell exceeded that of the control. This shows that the drop in capacity as a function of cycle number is much less with "Stranmat", and at this point in the test little doubt remained that this retainer increases the life of pasted flat plate positive electrodes undergoing EV type charge and discharge cycling. The question only remained by how much. At present, 1507-11 has been discharged 170 times to 80% depth or greater and will be tested to failure (indicated by the battery's inability to reach 80% of original capacity). Figure 19 illustrates performance as a function of cycle number. If present life trends are extrapolated, the cell will accumulate in excess of 200 cycles which represents at least a 50% improvement over controls without "Stranmat". We anticipate more testing with this retainer since it alone of all the experiments performed with pasted flat plate positive electrodes offers the promise of long life with little loss in battery energy density.

Another approach for increasing the cycle life of the positive in flat plate batteries shown to be impractical for EV discharge rates, was to increase the positive paste density 12%. An otherwise standard 25 plate element cell was constructed and tested and after 5 cycles, at 60 amps, the discharge time did not exceed 130 minutes, i.e. 26.2% use of positive active material, 26 Whr/Kg. Despite the possibility of long cycle life, these capacity values make this battery design unacceptable.

Three cells (PP22, PP23, PP24) were built and placed on test to evaluate the relative performance of 1) standard rectangular grids (GW negative, 2GW positive) 2) radial grids with conventional lug placement (2-EVR negative, 1-EVR positive) and 3) radial grids with inverted lug placement (the lug from the conventional radial grid was removed and placed at the diagonally opposite corner). Each of these grid geometrics is uniquely different and may significantly alter the current distribution at the plate. We investigated the degree to which the grid geometry affected the active material use as a function of current density, and the effect on battery life. Cells PP22, PP23, and PP24 were built identically to AEX6 (cf Table 22) with respect to the following: negative oxide, negative paste, negative paste/plate, negative DAM/plate, number of negative plates per cell, positive oxide, positive paste, positive paste/plate, positive DAM/plate, number of positive plates per cell, the type and number of separators. Additional details of construction were that all cells contained 2060 cc of electrolyte, and

	PP 22	PP 23	PP24
Negative Grid Type	2-EVR - 0.1% Calcium alloy - radial with std lug	GW - 0.1% Calcium alloy-rectangular with std lug	2-EVR - 0.1% Calcium alloy-radial with inverted lug
Negative Grid Wt(g)	76	76	76

Figure 19: Discharge of 1507-11 (Stranmat Retainer)

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	PP22	PP23	PP24
Positive Grid Type	1-EVR-6% Antimony-radial with std lug	2GW-6% Antimony- rectangular with std lug	1-EVR-6% Antimony- radial with inverted lug
Positive Grid Wt(g)	92	93	91

The cells were each discharged at various rates and their relative performance is summarized in Table 26. The following conclusions can be made.

A) At all rates tested, the cell containing radial grids with an inverted lug performed worst. Both average discharge voltage and cell capacity were lower with this configuration. No further work with this type of grid is anticipated.

B) At discharge currents corresponding to the 1-hr. rate or more, no significant difference in the performance of cells built with conventional radial grids or orthogonal grids was noted. Both cell capacity and average discharge voltage were independent of grid geometry at currents below 120 amps.

C) At currents greater than 500 amps, the superior performance of radial grids was evident. The use of these grids resulted in a 4% improvement in average voltage and a 6% improvement in total energy delivered. Power delivered at 1000 amps also increased by 4%. Resistance readings of cells PP22 and PP23 were taken fully charged and fully discharged. The results:

	Resistance (milli-ohms)	
	PP22(Radial)	PP23(Orthogonal)
Charged	0.57	0.73
Discharged	0.72	0.83

show that radial grids significantly lower the resistance of EV cells.

D) In summary, the radial grids with conventional lug placement generate the best overall cell performance. The improvement is directly related to the lower grid resistance which results in significantly higher average discharge voltages at large current drains. There is however no indication that the radial grid geometry improves utilization of the active material and it does not affect the cell's ampere-hour capacity.

TABLE 26

The Performance Characteristics of Various
Grid Geometrics in EV Cells

	PP22	PP23	PP24
	Radial Grid Conventional Lug	Orthogonal Grid	Radial Grid Inverted Lug
1000 Amps for 15 secs at Top of Charge			
Avg. Volts	1.52	1.46	1.40
Power (watts)	1520	1460	1400
500 Amps (99°F initial temp)			
Volts Avg.	1.71	1.64	1.62
Time (min)	11.8	11.6	10.7
Ahr.	98.3	96.7	89.2
Whr.	168.2	158.5	144.4
120 Amps (84°F initial temp)			
Volts Avg.	1.92	1.92	1.90
Time (min)	74	74	68
Ahr.	148	148	136
Whr.	284.2	284.2	258.4
75 Amps (83°F initial temp)			
Volts Avg.	1.95	1.95	1.94
Time (min)	146	147	138
Ahr.	182.5	183.7	172.5
Whr.	355.9	358.2	334.6
60 Amps (82°F initial temp)			
Volts Avg.	1.96	1.96	1.96
Time (min)	191	188	173
Ahr.	191	188	173
Whr.	374.4	368.5	340.1

- Note: 1) At the top of charge, all cells had a specific gravity of 1.315.
- 2) For purposes of calculating energy density, the cell weights are
 9.75 Kg.

1.5.3 Electrolyte

The primary objectives of the advanced lead-acid battery program are to develop a battery which has (a) long life, and (b) high energy density. In the past, our work indicated that the density of the positive paste played a significant role in promoting a high energy plate and good active material use. However, whereas active material use is inversely related to paste density, plate life is directly affected (low paste densities result in good active material use but short plate life due to shedding). We therefore did not consider low density pastes as a viable approach towards achieving the overall advanced battery goals.

In order to avoid or minimize the shedding problems normally associated with low density pastes, we recently began to study the effect of mechanically agitating the electrolyte during charge. Mechanical agitation of the electrolyte is used to replace the electrochemical stirring action produced by the gassing normally associated with overcharge of the lead acid battery. Therefore, overcharge of the battery can be significantly reduced. Overcharge is quite detrimental to life. It increases corrosion of the positive grid, and it promotes shedding of the active material by generating gas bubbles within the internal structure of the positive plate. It is normally needed, however, to completely charge the positive and negative plates since it promotes acid transfer to the active material and helps water diffuse from the positive. The lower the paste density, the more pronounced the effect of shedding produced by the electrochemical effects of overcharge. A further advantage of mechanical agitation is that the ampere-hour and watt-hour efficiencies of the battery should be improved, and this should more than offset the energy consumed by the outside source used to stir the electrolyte. The need for watering is also reduced.

Several questions remain regarding electrolyte circulation during charge and these will be resolved during the course of this study. The most important are:

- (1) How much agitation is required to simulate the gassing effects normally produced during overcharge?
- (2) Does mechanical agitation significantly reduce shedding below that normally seen with overcharge?
- (3) Can mechanical agitation be used to satisfactorily charge a battery with little or no overcharge needed?
- (4) Can low density pastes be used to construct positive plates which will not shed and which will have long life and high active material use in the absence of overcharge?

In the initial phase of this study, we are investigating the use of simple air bubbling through the electrolyte during charge. A manifold exit pipe was placed at the bottom of the cell container through the sediment ribs to insure good air distribution throughout the electrolyte. The cell

under test (TP25) is identical to TP 24 (cf Table 17 for tubular positive electrode design) except that it contains a 19 plate element rather than a 21. Cell TP25 contains 10 lightweight electroformed grids each weighing 37 gms and pasted with 180 gms of negative active material. It contains 2150 cc of acid and weighs 9.15 Kg. The theoretical Ahrs of positive active material are 513. The bubbling rate of air through the electrolyte is approximately 100 cc/min. Over a 13.5 hr charge, 81,000 cc of air have passed through the cell. With a normal 25% overcharge, nearly 18,800 cc of H₂ and 9400 cc of O₂ are evolved for this 180 Ahr rated cell. Therefore, nearly three times the volume of evolved gas is being passed through with mechanical bubbling - hence more than adequate stirring is achieved.

Although TP25 is usually cycled with air bubbling through during charge, on selected cycles the air is turned off and the electrochemical overcharge increased from 3 to 4% up to 25%. Table 27 below summarizes the data obtained on selected cycles.

TABLE 27: The Effect of Electrolyte Circulation During Charge on Cell Performance

Cycle No.	Discharge Current(Amps)	Time (Mins)	Ahrs	Charge Current(Amps)	Time (Mins)	Ahrs	% Over-Charge	PAM Use(%)	Whr Kg
23	50	204	170	13	810	176	3.2	33.1	36.4
24	50	203	169	13	810	176	4.1	32.9	36.2
25	50	203	169	13	810	176	4.1	32.9	36.2
27	50	212	177	13	1086	235	32.9	34.5	37.9
28	50	209	174.5	13	1050	227.5	30.4	34.0	37.2
29	50	209	174	13	1008	218.4	25.5	34.0	37.2

Figure 20 illustrates the voltage-time behavior of TP-25 with and without bubbling during charge (note: at no time is air bubbled during discharge). It is apparent from the data that bubbling permits a reduction in overcharge from 25% down to 4% and yet the discharge capacity drops by less than 3%. The ampere-hour and watt hour efficiencies exhibit a tremendous improvement.

	Avg Chge Voltage	Avg Dschge Voltage	Ahr Dischge	Ahr Chge	Ahr Eff	Whr Eff
Bubbling	2.20	1.95	170	176	96.6	85.6
No Bubbling	2.29	1.96	175	218	80.3	68.7

A simple calculation shows a charging energy saving per cell per cycle equal to 112 Whr. If we assume 54 cells per electric vehicle battery and 250 cycles per year, the potential savings in energy generated by bubbling air during charge is 1500 Kwhr. We are in the process of evaluating the effect of 4% overcharge with bubbling on long term electrode behavior. We are particularly concerned about possible ill effects this low degree of overcharge has on the health of the negative. We also intend to scale up the bubbling apparatus schematically shown in Figure 21 and accommodate multicell units. The control box illustrated in Figure 21 was built in house and does the following:

Figure 20: The Effect of Bubbling Air on Cell Performance

Figure 21: AIR BUBBLING SCHEMATIC FOR ELECTROLYTE CIRCULATION

1) it monitors the cell and when its voltage drops below 1.7 the cell is automatically placed on charge, the solenoid opens the air valve, and a timer is started, 2) when the timer completes its cycle, the cell is placed on discharge, the solenoid relay is deactivated, and the air supply is shut off. The air supply is regulated by the flowmeter valve, and can be readily controlled with no significant fluctuation at 100cc/min.

1.5.4 Advanced Battery - Conclusions and Accomplishments

1. Negative Grid - Type A - Plated Plastic

- A. Deposition of copper on a plastic grid can achieve the same conductivity as a cast lead control while the grid weight is less than half.
- B. Electroless copper deposition is needed to make the plastic grid sufficiently conductive for further copper and lead electroplating.
- C. The copper deposited by electroless techniques is not sufficient to provide adequate conductivity and additional copper must be applied using conventional electroplating techniques.
- D. Lead must be applied to the copper to render it inert and to prevent excessive hydrogen evolution or charge.
- E. In order to guarantee that dissolution of copper does not occur, the cell containing the copper negative must be made positive limiting, i.e. the voltage of the negative electrode vs cd should not rise above +0.5V at the end of discharge.
- F. Cells containing Type A lightweight negative grids have behaved as well as those with cast lead controls under negative limiting conditions. Cell capacity and load voltages match the controls over 500 cycles at full depth of discharge. A post-mortem showed little evidence of grid deterioration.
- G. Type A grids reduce overall battery weight from 5-6% with no loss in delivered energy or cycleability.
- H. The Type A grid was successfully scaled up from automotive to EV size. A new radial rib design was molded in ABS plastic and served as the grid matrix.
- I. Incorporating a lead lug insert into the plastic mold solved the problem of how to connect a series of Type A grids into a negative group using conventional burning techniques.
- J. EV size Type A grids were successfully plated and placed into cells (coupled with both tubular and flat plate positives). Performance comparable to cast lead controls obtained. Life tests still ongoing (70+ cycles).

2. Negative Grid - Type B - Electroformed Copper with Lead Plating

- A. A 0.05 mm thick electroformed copper grid can achieve the same conductance as a cast lead control.
- B. Lead must be applied to the copper to render it electrochemically inert and to prevent hydrogen evolution on charge.
- C. In order to guarantee that dissolution of the copper does not occur, the cell should be made positive limiting, i.e. the voltage of the negative electrode vs Cd should not rise above +0.5 at the end of discharge.
- D. An EV size grid was developed which weighs less than one-half the cast lead controls and is three times as conductive. The overall grid thickness is 0.20mm including the lead plate.
- E. A unique aspect of the grid design is that the frame and ribs have a concave cross section.
- F. The thin grid is rigid, can be pasted to a thickness of up to 1.8mm, burned, and assembled without any frame or lug distortion. No plastic is needed as an active material matrix.
- G. Grids have been tested in EV batteries, have been coupled with both pasted flat plate and tubular positive electrodes.
- H. Battery testing reached 300 cycles. Post-mortem revealed no significant deterioration of either the negative active material or the negative grid.
- I. High rate (500+ ampere) performance of batteries containing Type B grids exceeds that of controls with cast lead negatives.
- J. Type B grids promote excellent utilization of the negative active material and have no deleterious effect on battery cycle life.

3. Positive Electrode - Tubular

- A. Fill densities for thin tubular electrodes must be carefully controlled. Although greater utilization of the positive active material initially is obtained with lower fill densities, life is not as good.
- B. Life in excess of 300 cycles at 80% depth of discharge or greater at the 3-hr rate has been obtained. Positive active material use was 33-35%.
- C. Tubular positive groups containing 9 and 10 plates, TP-1 design, 250 gms of oxide per plate, yielded optimum positive electrode performance. 37 whr/Kg at the 3-hr discharge rate (1.290 SpGr, 26.5°C) has been obtained with batteries containing this positive electrode configuration.

4. Positive Electrode - Pasted Flat Plate

- A. Cells built with flat pasted plate positives give the best performance (load voltage, capacity) of the different electrode types tested. 40 whr/Kg at the 3-hr discharge rate (1.290 SpGr, 26.5°C) has been obtained with batteries containing flat plates.
- B. Unless special retainers were employed to prevent positive material shedding, cycle life for pasted flat plate electrodes did not exceed 150 deep discharges (1 1/2 cycles per day, 3-hr discharge rate, 80% depth).
- C. Major mode of electrode failure - shedding of positive active material.
- D. The following experiments were run but failed to improve life of the flat plate electrode while maintaining active material utilization:
 - 1) carbon addition to the paste
 - 2) Split positive electrode construction - a 22 plate positive group and 11 plate negative, separators are used to gap thin positives and permit better circulation of electrolyte.
- E. Flat plate positives containing radial grids with conventional lug placement generate the best overall cell performance. Their superiority is directly related to the lower grid resistance which results in significantly higher average discharge voltages at large current drains. There is, however, no indication that the radial grid geometry improves utilization of the active material.

5. Electrolyte

- A. A study was initiated on the bubbling of air through the electrolyte during charge. Potential benefits include:
 - 1. less watering
 - 2. lower operating temperatures
 - 3. improved ampere--hour and watt- hour efficiencies
 - 4. longer life because of less shedding of positive active material and lower grid corrosion.
- B. Initial results are encouraging. Equivalent discharge capacity was obtained for 1) conventional charge regime, 25% overcharge no air bubbling and 2) 3% overcharge and air bubbling at 100 cc/minute.

1.5.5 Future Work

1. We will continue testing of Type A and Type B lightweight negative grids in both cells and batteries. Negative groups containing these grids will be coupled with optimized tubular and flat pasted plate positive electrodes in order to maximize energy density and cycle life.
2. The performance of lightweight grids containing 50% less lead plate will be evaluated.
3. A continuing but low priority effort will continue to be a diligent search for methods of increasing active material utilization without decreasing energy density, cycle life, or power density. This will include the use of high surface area oxides for tubular fill.
4. A considerable effort will be made to investigate and develop the use of electrolyte circulation during charge as a means to improve the cycle life of EV batteries. Circulation will be promoted by various techniques such as air bubbling, air lift pumps, etc. and will be coupled with very low overcharging. Engineering studies will be done to insure uniform air distribution from a central compressor to a multi-cell battery.

1.6 Charging of Lead Acid Batteries for Electric Vehicles

1.6.1 Introduction

Selection of the correct charging procedure is essential to obtain maximum life from a lead-acid battery in deep cycle applications such as electric vehicle propulsion. Consistent undercharging leads to gradual capacity decrease which may be irreversible. Excessive overcharge shortens life and/or performance in several ways: high temperature develops which accelerates positive grid corrosion, positive active material may be eroded from a strongly gassing plate with consequent capacity loss or the particles will be reduced to sponge lead (potential shorts) when they settle out on the negative plates. Water maintenance will be required at more frequent intervals for batteries which are charged excessively. Without such maintenance, low electrolyte level and high sulfuric acid concentration will result. Each has a severe effect on performance and life.

A description of charge procedures being used in life testing of batteries built under this contract is followed by a discussion of the constant current - constant voltage - constant current technique for charging lead-acid batteries.

1.6.2 Cycle Life Testing

It is necessary to describe the characteristics of the equipment being used for these tests since these affect the charging schedule. Each life circuit may include up to 8 six-volt batteries. Seven circuits make up one life test system. All batteries on one system must cycle on the same time schedule. The discharge portion of the cycle consists of a discharge at the 3 hr rate for 2.4 hr or until average cell voltage falls below 1.7 V, whichever occurs first. Before a battery lot is placed on life test, initial performance is determined at various rates and temperatures. The 3 hr rate at 25°C for each battery is calculated from these data. The test batteries are then assigned to a life circuit according to performance. In this way all batteries in a circuit are discharged as nearly as possible to 80% depth, based on 3 hr capacity.

Charging is done with constant current in two steps. The time schedule is given below for an 18 hr cycle.

Cycle Timing

	Discharge	Open Circuit	Hi Chg	Lo Chg	Open Circuit
Hours	2.4	1.35	5.9	7.0	1.35
Voltage Limit (V/cell)	1.7		2.35	None	

For purposes of illustration, the discharge and charge rates are tabulated below for a life circuit of eight batteries which had an average 3 hr discharge rate of 59 A. Ampere-hour output on each discharge was 142 Ah

(59 x 2.4). Return of 70% of this quantity (99 Ah) in 5.9 hr requires a high charge rate of 16.8 A (142 x 0.7/5.9). Total charge per cycle was 142 x 1.15 or 163 Ah. Thus, input during the 7 hr low charge or finishing period was 163-99 or 64 Ah at a rate of 9.1 amps.

Discharge & Charge Rates

	Discharge	Charge		Total Charge	% Overcharge
		Hi Rate	Lo Rate		
Amp	59	16.8	9.1		
Amp-Hr	142	99	64	163	15

The high charge rate was set to return 70% of discharged capacity in 5.9 hr. Low charge rate and time were determined by two factors: 1) total Ah input required for 115% recharge and, 2) maximum allowable finishing charge rate. The latter is related to battery size as follows: finishing rate in amperes equals 4-5 A per 100 Ah rated battery capacity at the 5 hr rate. The batteries on test have a 5 hr capacity of about 200 Ah and the finishing rate should be 8-10 A. Since the positive plates tend to shed active material if overcharged at currents above the finishing rate, higher rates of charge are permitted only until battery voltage reaches 2.39 V/cell at 25°C, at which point gassing becomes significant. In a normal cycle, battery voltage will not reach this level before the end of the 5.9 hr high charge period but a 2.35 V/cell limit is imposed as an added precaution.

This procedure has proved to be satisfactory and schedules for all life testing have since been based on 70% return in the first charge step. When the cycling rate was changed to one cycle per day for one group of batteries to determine the effect of cycle frequency on life, only the time on open circuit was increased.

1.6.3 Constant Current - Constant Voltage - Constant Current Charging (IEI)

The principal disadvantage of using 2-step constant current is the relatively long time required to complete a charge. In life testing many experimental batteries it was necessary to set up the equipment in this way to accommodate the numerous component and construction variables.

For electric vehicle operation we recommend the IEI method of restoring a battery to full charge quickly and without danger of either under- or over-charging. For 6 volt BCI group size GC-2 EV batteries, the charger should supply an initial "high" rate of 20 to 30 A which is held constant until battery voltage reaches the gassing or crossover voltage (V_c) which is 2.39 VPC at 25°C. The charger should maintain this voltage while the current tapers to a finishing rate of 6-10 A, depending on battery capacity. At the start of the final constant current period, between 95 and 100% of discharged capacity has been returned. Charging should continue at the fixed current finishing rate until charge termination. A satisfactory method of accomplishing this is to provide means in the charger to start a 3 hour timer at the moment battery voltage reaches 2.39 V/cell, i.e. at the start of current taper. Total charge time will be 8 hours or less at normal temperature. More than 8 hours

may be required if the battery is cold (0°C) since charge acceptance falls rapidly with temperature. Warm batteries (45°C) are likely to receive more than optimum charge if the crossover voltage (V_c) is maintained at the 25°C value of 2.39. Battery temperature should not exceed 50°C. The charger should be able to compensate for variations in battery temperature. The crossover voltage should vary with battery temperature as shown below:

Battery Temp °C	V_c Volts/cell
45	2.28
40	2.31
30	2.33
25	2.39
20	2.415
10	2.47
0	2.525

It is not necessary to vary starting and finishing rates over this temperature range.

At regular intervals the battery should receive an equalizing charge. This consists of a normal charge plus an extended period of charging at the finishing rate recommended by the battery manufacturer. Periodic equalizing is necessary to restore electrolyte specific gravity to the normal full charge level and to minimize variations so that all cells are capable of delivering uniform, maximum capacity. By preventing electrolyte stratification, equalizing avoids deterioration of the active material which otherwise will develop an increasing residual content of lead sulfate, a significant fraction of which may become difficult or impossible to reconvert to sponge lead or lead dioxide. If the length of the equalizing charge is not specified by the manufacturer it can be determined by measuring specific gravity at hourly intervals. The charge is considered completed when three successive readings (corr'd to 25°C) differ by 0.005 or less. Charging beyond this point shortens the interval between water additions and reduces the life of the battery. Records of specific gravity and voltage of individual batteries at the end of equalizing charge are useful since departures from average trends for either characteristic are often the first indication of impending battery failure.

Typical start and finish rates for IEI charging are listed below for several 6V EV batteries. Using these values, the rated capacity of the batteries listed will be returned in an 8 hour period.

Battery Rated Capacity Minutes at 75 A (25°C)	Charge Rates		Estimated Input in % of Rated Capacity		
	Start	Finish	At Start of Taper	At End of Taper	At End of Chg
125	30	8	81	95	106
106	25	7	80	95	106
88	22	6	80	95	108

Even faster recharge is feasible with the IEI method. Figure 22 shows voltage trends of a 36 volt EV battery during a 5 hr charge. This battery is being life cycled as part of company - sponsored development. Rapid recharge is being used to accelerate the test by cycling at a rate of 2.5 per day. The battery is equalized at intervals of 5-7 cycles. After 170 cycles on this schedule, capacity remains well above 80% of rating.

The suitability of the charger and charge schedule should be checked for each new installation or vehicle. This can be done by recording battery voltage over the entire charge to confirm that behavior approximates that are shown in Figure 22. A check of the battery at the end of charge should show that all cells are gassing but that electrolyte temperature does not exceed 50°C.

Charging systems are available which can rapidly recharge lead acid batteries in electric vehicles while minimizing the harmful effects of excessive overcharge. Careful consideration of charger design is worthwhile since optimum charging techniques can extend battery life at least 25% with corresponding reduction in per mile battery amortization cost.

Figure 22: 5 Hour Recharge of 8-Cell EV Battery
with IEI Method

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- (1) Second Annual Report for F/Y '79 dated June 1980 - ANL Contract 31-109-38-4207.
- (2) CRC Handbook of Chemistry and Physics, Robert C. Weast, Editor, CRC Press, Cleveland, Ohio, 1977, pages B-122, C-800.
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APPENDIX I

BATTELLE COLUMBUS LABORATORIES

PHASE B REPORT

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PHASE B REPORT

on

SUBCONTRACT NO. 31-109-38-4207-ESB2
ELECTRIC VEHICLE BATTERY DEVELOPMENT STUDIES

to

EXIDE MANAGEMENT
AND TECHNOLOGY COMPANY

January 13, 1981

by

L. E. Vaaler; P. W. Cover
and E. W. Brooman

BATTELLE
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EXECUTIVE SUMMARY

Background

The Exide Management and Technology Company has been contracted by the Department of Energy to develop "improved state of the art" (ISOA) and "advanced" lead-acid batteries for electric vehicle applications. As part of the effort on ISOA batteries, Battelle's Columbus Division was subcontracted to use mathematical modelling techniques to improve the design of grids. More specifically the objective was to improve the performance of positive plates, through the design of the grid, by equalizing the current density distribution over the plates, and reducing the internal resistance losses. In a Phase A study, the mathematical model developed at Battelle was modified to make it more applicable to battery electrodes. The model was then used to establish a grid design which might offer improved performance. In the Phase B study, the results of which are reported herein, the objective was to experimentally demonstrate the improved performance of the new grid design, and to further refine the mathematical model.

Accomplishments

The applicability of the mathematical model developed in the Phase A study was demonstrated in a series of experiments with conventional, orthogonal grids. One positive electrode was modified to incorporate potential probes at selected grid nodes. In a three-electrode cell, at various high rates of discharge (corresponding to the maximum and intermediate power requirements of an electric vehicle battery as defined by the performance specifications) the potential distribution over the positive plate was measured. The result obtained agreed to within 25 percent of the values calculated from the original model.

Having demonstrated the applicability of the model, experiments were performed with Battelle's non-orthogonal grid, and the model was further modified to allow radial grid designs to be handled.

Using computer-assisted design and machining techniques, the non-orthogonal grid was cut into book molds for incorporation into a hand-casting stand. Grids were then hand cast for evaluation. Preliminary experiments with mold filling with the tab at the bottom of the mold were not successful. With a more conventional arrangement, namely casting with the tab on the side, acceptable grids were obtained, and forwarded to Exide for hand-pasting and forming. Several positives were returned to Battelle in the dry-charged condition for evaluation. Experiments, similar to those conducted for the conventional grids, were performed with these plates incorporating the non-orthogonal grid design. The results demonstrated that, compared with the conventional positives, the voltage drops between similar probe positions on a positive/negative plate pair were at least 34 percent, and as much as 48 percent lower. Thus the non-orthogonal design shows promise as being able to contribute to improved performance.

The model was used to compare conventional and radial grid designs supplied by Exide. For the same alloy mass and overall grid dimensions, it was shown that the voltage drop between positive/negative plate pairs would be at least 0.1 volt lower for the radial grid design.

Conclusions

In summary, radial and/or non-orthogonal grid designs offer the prospect of improved performance for electric vehicle applications because of improved potential and current density distributions, and lower internal resistance losses, for a fixed mass and given set of overall plate dimensions. Conversely, for a given performance criterion, a radial and/or non-orthogonal grid could be designed having less mass and smaller dimensions.

PHASE B REPORT

on

SUBCONTRACT NO. 31-109-38-4207-ESB2
ELECTRIC VEHICLE BATTERY DEVELOPMENT STUDIES

to

EXIDE MANAGEMENT
AND TECHNOLOGY COMPANY

by

L. E. Vaaler, P. W. Cover
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BATTELLE
Columbus Division

January 13, 1981

INTRODUCTION

In March, 1978, ESB Technology Company, now Exide Management and Technology Company (hereafter referred to as Exide) executed Contract No. 31-109-38-4207 with Argonne National Laboratory for research on improved state of the art (ISOA) and advanced lead-acid batteries for electric vehicle applications. During the initial stages of the contract, emphasis was to be placed upon specifying, designing, fabricating and delivering the ISOA battery system. Exide proposed that a parallel effort be employed to develop an ISOA battery, and identified the so-called "flat-plate" (FP) approach, and the "tubular plate" (TP) approach. For the FP battery, research was to be conducted on:

- (a) Positive grid design and configuration
- (b) Utilization of the positive active material
- (c) Diffusion of electrolyte within each cell
- (d) Effect of electrolyte concentration on performance and life
- (e) Reduction of negative grid and plate weights.

Similarly, for the TP battery, research was to be conducted on the following

- (1) Reduction of positive grid structure weight
- (2) Grid to active material contact
- (3) New tubular retainers
- (4) More efficient active materials
- (5) Reduction of negative grid and plate weights.

From the above overview of the general research effort described at the Second Annual Battery and Electrochemical Technology Conference, held on June 5, 1978, it is apparent that a considerable portion of the proposed effort was concerned with improving positive and negative grid and plate performance. Exide, therefore, chose Battelle's Columbus Laboratories (now part of Battelle, Columbus Division and hereafter referred to as Battelle) as a qualified subcontractor to work on specific problems associated with grid design and optimization. Subcontract No. 31-109-38-4207-ESB2 was executed on May 15, 1978, and the program effort began in June, 1978.

Phase A of the subcontract was directed towards improving FP grid design and performance, and was divided into two tasks. Task 1 was concerned with modeling conventional grid designs and predicting the behavior of an intuitive design supplied by Exide, and an intuitive design generated by Battelle. Task 2 had as its objective the design of an improved grid from first principles, given the appropriate boundary conditions. As will become apparent from the following discussions of the research effort expended on this phase of the program, the development of three-dimensional models has permitted the preliminary evaluation of varying such parameters as electrolyte specific gravity/conductivity and paste conductivity and thickness. Thus, results could be presented for plates as well as grid elements. Also, because of the flexibility of the models, several intuitive designs could be studied, in addition to the a priori calculations.

In Phase B, the subject of this report, the effort also involved two tasks, and was directed towards verifying the improved performance predictions of the non-orthogonal grid developed in Phase A, and refining the radial grid mathematical model to improve its applicability to grid

design. The former activity involved designing a grid, trading off fabricability (castability) against preferred design; cutting the grid molds; casting trials; hand pasting the grids; and finally, determining the potential distribution over these pasted grids for comparison with predicted behavior; and orthogonal (conventional) grid designs. Further details of both the Phase A and Phase B studies are given in the next section of this report. A comprehensive description of the Phase A study, and its accomplishments are given in Reference (1).

TECHNICAL BACKGROUND

Phase A Outline

As mentioned earlier, the Phase A study was divided into two major activities. The first activity was concerned with developing the Battelle mathematical model⁽²⁾ to better describe the behavior of grids of conventional, orthogonal design of the type shown in Figure 1. The second activity had as an objective the adaptation of the model to the evaluation and design of non-orthogonal grids, such as the "radial" type shown in Figure 2. Through the use of the mathematical model, experimentation and intuition, non-orthogonal designs were those chosen to minimize variations in potential and current density distribution over the surface of a positive plate in service. It is well known that the positive plate limits the performance of a lead-acid battery in this context.

The development of the orthogonal model was relatively straightforward. In its final form the model could accommodate changing the position of the tab; could handle non-identical positive and negative grid designs; could take into account overpasting and variable paste electrical conductivity; and was not limited to the restriction of assuming a constant current density distribution over the grid (plate) surface.

The development of a universal mathematical model, and grid design from first principles (only the mass of lead alloy fixed, and

FIGURE 1. EXAMPLE OF A CONVENTIONAL BATTERY GRID SHOWING A RECTANGULAR ARRAY OF GRID MEMBERS

FIGURE 2. SILHOUETTE OF AN EXIDE
EXPERIMENTAL (RADIAL)
GRID DESIGN

overall dimensions) met with less success. However, significant progress was made towards developing a model for non-orthogonal grids with linear design elements (similar to that shown in Figure 2). A problem with such radial designs is maintaining a useful pellet size. As the radiating elements spread out as "spokes" from the tab, extra grid elements must be added to maintain sufficiently small openings, and these elements are not connected directly to the tab by a radial element. The elements, generally following the equipotential lines, must be designed with sufficient conductance to feed the current to the added radial elements.

The success of a radial design will be measured by the amount the lead volume is reduced as compared to an orthogonal design of equivalent performance. The objective in designing a radial grid is to provide grid elements of maximum conductivity in the direction that current will flow (minimum voltage loss) and to minimize the size of the grid elements in directions in which current flow is negligible.

Phase A Study Results

The three-dimensional model, as developed, was used to evaluate a number of modifications to the orthogonal design shown in Figure 1, including TTP (through-the-partition) tab locations, and discontinuities in various numbers of grid bars at the top center of the positive plates in an effort to change the pattern of current flow during high-rate discharges, which might be encountered in electric vehicle applications. The criteria of performance from the computer model used to evaluate modifications are related to cell voltage drop (at the tabs) and the variation in current density over a plate. The lower these values, the better the performance to be expected. More uniform current density distribution can be associated with better active material utilization, and by implication longer cycle life. Lower voltage drops (resistive losses) may be associated with improved energy and power densities, when considered in conjunction with better active material utilization.

The results for the orthogonal designs indicated that the best performance would be obtained by increasing the grid conductivity in the vicinity of the tab at the expense of conductivity in areas more remote from the tab. A conceptual design was generated (Figure 3) in which the voltage drop was minimized and the current density more equalized. In this conceptual design the tabs are located in the centers of the sides of the plates, opposite each other, and the grid members located near the tabs are heavier. Note that in this design there are more grid members oriented in the direction of current flow (horizontal for this design) than in the transverse direction. This approach is exactly opposite to conventional grid design (e.g., Figure 1, where current flow is in vertical direction). The conceptual design approximates a TTP plate turned on its side (rotated 90°).

The model calculations were used to construct equipotential lines on the conventional orthogonal design positive plate design (Figure 4). With this approach, a non-orthogonal (radial) design was derived with heavier grid members positioned perpendicularly to the equipotential lines to facilitate current flow and collection. Lighter grid members are positioned along equipotential lines because current flow in this direction is absent in theory. The resulting radial grid design is shown in Figure 5, and should be either lighter than an orthogonal grid of similar performance, or should provide improved performance for the same grid mass. A model to verify this prediction was not developed in Phase A. However, various approaches were tried to develop models which could handle any grid design, and proportion grid alloy distribution according to current flow requirements. Based on these preliminary results it was recommended that additional development work be carried out in a Phase B effort.

Phase B Outline

While some important accomplishments resulted from the Phase A study, there were certain aspects of the radial and grid alloy distribution

Thickness: 0.213 cm (0.084 in)

Right Border: 0.3 cm at tab
0.2 cm at C, D

Other Borders: 0.2 cm

Horizontal Elements:

BCDE: 0.070 cm (0.027 in)

ABEF: 0.035 cm (0.014 in)

Vertical Elements:

BCDE: 0.073 cm (0.029 in)

ABEF: 0.036 cm (0.014 in)

FIGURE 3. PROPOSED POSITIVE GRID DESIGN TO
MINIMIZE VOLTAGE AND CURRENT DENSITY
DIFFERENCES--PHASE A STUDY

FIGURE 4. GRAPHICAL METHOD FOR DESIGN OF
NON-ORTHOGONAL GRID--PHASE A STUDY

FIGURE 5. POSITIVE PLATE; TTP, EXTRA TALL:
DISTRIBUTION OF METAL IN PHASE A
STUDY DESIGN

Thickest Line = 0.070 cm wide
Medium Line = 0.035 cm wide
Thinnest Line = minimum width

optimization models which needed improvement. Also, as a result of a review meeting which took place in 1979 at Argonne National Laboratory, it was considered desirable to be able to experimentally verify the performance characteristics of optimized orthogonal designs and/or the conceptual, non-orthogonal design for comparison with the behavior of conventional Exide ACG1W or ACG2W plates. Thus, the Phase B study was divided also into two tasks, one conceptual in nature, the other experimental, as described below.

Task 1: Experiments to Verify Design Predictions

The objective of this task was to conduct experiments to verify the design predications resulting from the modeling exercises performed during the Phase A study.

Two separate activities were to be undertaken under this task. The first activity was to determine the potential distribution over conventional, orthogonal grids/pasted plates. Approaches had to be investigated for measuring the voltage distribution of a positive electrode while under load in a three-electrode laboratory cell. The results obtained were to be compared with those results for potential distribution predicted by the model. The performance of this laboratory cell was to serve as a basis of comparison for the performance of the conceptual non-orthogonal (radial) design.

The second activity planned was to use Battelle's CAD/CAM* facilities and experience to design and cut the molds for use in a hand-casting stand. Radial grids would then be cast using a grid alloy and mold-coat dressing supplied by Exide. These grids would be shipped to Exide (at Yardley) for hand pasting and curing. The plates would then be returned to Battelle for the determination of potential distribution under load, again in a three-electrode cell, for comparison with the conventional plates with grids of orthogonal design. Originally 25 prototype grids were to be shipped to Exide. Subsequently, the sub-contract was modified, and 100 grids were required so that Exide could perform additional in-house evaluations.

* computer-aided design/computer-aided machining.

Task 2: Development of Universal Grid Model

In a concurrent activity, work was to proceed towards the development of a model (and associated computer program/software) for handling grid designs with "generalized" (asymmetrical, non-linear and/or linear) coordinates using the foundation already laid in the Phase A study. This model, ideally, should be capable of handling any grid geometry, including radial designs; variable tab location; differing paste conductivity; overpasting; changes in electrolyte conductivity; and dissimilar positive and negative grid designs. Upon conclusion of this task, recommendations were to be made for grid designs for consideration for the EP-2 lead-acid, electric vehicle battery.

ORTHOGONAL GRID DESIGN

Determination of Potential Distribution

As a baseline condition, an Exide AC2GW positive plate with an orthogonal grid was selected, and this was positioned between two AC2GW negatives in one cell of an EV106 container. Battery grade acid* was added, and the potential distribution over one face of the positive was determined at high rates of discharge. The manner in which this was accomplished, and the subsequent results are described below.

Figure 6 shows an AC2GW positive grid with the locations of the five potential probes marked and numbered consecutively from 1 through 5. The positioning of these probes was determined from the nodes selected from the computer modeling of this grid in the Phase A study (Tables 8 and 9, Figure 8). The probes were lead wires attached to the grid by a spark welding technique. The weld and lead wire were protected from corrosion by potting in an epoxy compound after applying heat-shrinkable PVC tubing. Figure 7 shows a mock up of a three-electrode

* Scholle Corporation, Northlake, Illinois 60164.

FIGURE 6. AN EXIDE AC2GW POSITIVE GRID SHOWING THE LOCATION OF POTENTIAL PROBES

FIGURE 7. MOCK-UP OF A THREE-ELECTRODE CELL FOR
POTENTIAL DISTRIBUTION MEASUREMENTS

Unpasted grids have been used to verify
feasibility of attaching lead wire probes,
and to show distribution of cell elements.
No separators are used.

cell using grids, and not plates, for illustrative purposes. The tab potential probe is not present in this figure because often a small "crocodile" clip was used for ease of handling. The three electrodes are spaced approximately 1.25 cm (0.5 in) apart from each other using pieces of slit PVC tubing. No separators were used as the objective was to determine only the potential distribution over the surface of the positive. The whole assembly was held together with PVC string. The rationale behind using this assembly was to enable the three-electrode pack to be handled easily, without fear of damaging or dislodging the probes. Figure 8 shows the probes attached to an AC2GW positive plate. Before the lead wires could be welded on, a small amount of active material had to be scraped away over each selected node to provide access to the grid.

The three-electrode cell was conditioned for five charge/discharge cycles using guidelines established for EV106 cells. The procedure was as follows:

- (1) Charge at 2.5 A until cell voltage reaches 2.37 V.
- (2) Reduce current to 0.5 A and continue charging for balance of 10 hours.
- (3) If too much gassing observed taper current to 0.2 A (minimum): record end of charge voltage and number of charge coulombs.
- (4) Discharge at 5.0 A to 80 percent depth of discharge: record end of discharge voltage and number of coulombs discharged.
- (5) Repeat cycle four times.

The fifth discharge was conducted at 10 A (5 A per side of positive electrode) to a 1.00 V cut off while the potentials of the five probes were monitored. The purpose of this experiment was to become familiar with the monitoring technique before the desired experiments at higher current discharges (e.g., 20 to 24 A; and 40 to 50 A, corresponding to maximum electric vehicle power requirements).

FIGURE 8. AN AC2GW POSITIVE PLATE WITH POTENTIAL PROBE (LEAD) WIRES ATTACHED TO SELECTED GRID NODES

Lead wires are covered with heat shrinkable PVC tubing and held in place with an epoxy potting compound.

The results of the preliminary experiment were encouraging, and differences in potential between the common negative electrode and the five potential probes were of the order expected, namely 10's of millivolts. However, it was decided that to be consistent with the model, it would be more appropriate to use the potential probe No. 1 located on the tab as the reference value, and to measure differences between probes 2 through 5 and probe 1. The relative potential distribution over the positive could then be determined. Later, probe position 2 was taken as the reference point, and ratios of potential drops between this position and the tab, and other positions and this position were taken as a measure of variability.

Results of Preliminary Experiments

Calculations with the model indicated that the potential drop in an electrode, and the ratios of voltage drops at various probe positions for the experimental conditions used, were relatively insensitive to the value chosen for the electrolyte conductivity. Hence, the absence of the separator in the experimental cell was not considered important in interpreting the results obtained.

While the preliminary experiments were useful in establishing the experimental procedure, the expected monotonic increase in potential drop from the tab to the probes was not observed as the discharge current was increased from 10 to 24 to 50 amperes. Also, the absolute value of these potential drops (~ 100 to 135 mV) was about twice the calculated range (~ 35 to 65 mV). Nevertheless, the largest potential drop was observed between probe positions 1 and 5 (see Figure 6) and the smallest drop was measured between positions 1 and 2, consistent with the model. The tabulation given below, taken from the preliminary experiments, indicates that during the initial stages of a high-rate (50 A) discharge (25 A per side of positive electrode) the potential measured does not change very much (Table 1).

TABLE 1. RESULTS OF PRELIMINARY EXPERIMENT TO DETERMINE
POTENTIAL DISTRIBUTION OVER POSITIVE PLATE:
50 A DISCHARGE

	Position of Probe			
	2	3	4	5
Initial Potential, mV	94.50	113.40	128.90	135.60
Potential after 8 min., mV	95.00	108.20	127.50	138.00
Initial Ratio*	1.00	1.20	1.36	1.43
Calculated Ratio	1.00	1.27	1.58	1.76

* Compared to probe position 2.

In checking the experimental apparatus in an effort to explain why such relatively high potential drops had been observed, a high resistance contact was found in the probe connection to the tab, and in one position on the grid. After correcting this situation, subsequent experiments gave results which showed the expected monotonic increase and linearity with applied discharge current. These results are given in the next section.

Potential Distributions as a Function of Discharge Current

After modifying the experimental apparatus, two further series of experiments were performed to compare the potential distributions at various current densities with the model predictions.

The results of the first set of experiments are summarized in Table 2, and graphically depicted in Figure 9. Because it had been shown that the potential drops did not vary much with duration of applied current, the approach taken was to sequentially apply 10, 24, and 50 amperes, approximately, and record the voltages at potential probe positions 2 through 5. Again, the data are presented as both absolute values of the potential at each location, and as a ratio compared with the potential measured at probe position 2. For comparative purposes, the calculated values from the model of these ratios is also given in Table 2. The measured values agree to within an average of 4.7 percent, when the conductance of the electrolyte/separator between each plate is assumed to be 0.500 ohm^{-1} per pellet area. In the preliminary experiments the value of this conductance was assumed to be 0.207 ohm^{-1} for the model calculations.

The measured potential drops increase in a monotonic manner as anticipated, however, the calculated values are only approximately 70 percent of the experimentally measured values. The differences can readily be accounted for by changing the conductivity values assumed for the lead alloy and paste. Allowance was not made for any differences

TABLE 2. POTENTIAL DROPS AND POTENTIAL DROP RATIOS
OVER AN AC2GW POSITIVE PLATE AT VARIOUS
RATES OF DISCHARGE

Discharge Time, Minutes	Discharge Current, Amperes	Position of Probe on Positive Plate							
		2		3		4		5	
		mV	Ratio*	mV	Ratio	mV	Ratio	mV	Ratio
0.0	10	--	--	--	--	--	--	--	--
0.5	10	10.91	1.00	13.49	1.24	16.91	1.55	18.34	1.68
1.0	22	--	--	--	--	--	--	--	--
1.5	22	24.69	1.00	30.58	1.24	37.81	1.53	40.79	1.65
2.0	50	--	--	--	--	--	--	--	--
2.5	50	55.60	1.00	69.07	1.24	84.35	1.52	90.45	1.63
3.0	10	--	--	--	--	--	--	--	--
3.5	10	10.82	1.00	13.41	1.24	16.65	1.54	18.10	1.67
4.0	24	--	--	--	--	--	--	--	--
4.5	24	27.00	1.00	33.47	1.24	41.01	1.52	44.20	1.64
5.0	50	--	--	--	--	--	--	--	--
5.5	50	56.06	1.00	69.51	1.24	84.62	1.51	91.05	1.62
6.0	10	--	--	--	--	--	--	--	--
6.5	10	10.99	1.00	13.63	1.24	16.88	1.54	18.41	1.68
7.0	24	--	--	--	--	--	--	--	--
7.5	24	26.93	1.00	33.48	1.24	40.93	1.52	44.20	1.64
8.0	50	--	--	--	--	--	--	--	--
8.5	50	56.22	1.00	69.83	1.24	84.95	1.51	91.34	1.62
9.0	10	--	--	--	--	--	--	--	--
10.5	10	10.96	1.00	13.62	1.24	16.89	1.54	18.41	1.68
11.0	24	--	--	--	--	--	--	--	--
12.5	24	27.04	1.00	33.56	1.24	40.94	1.51	44.19	1.63
13.0	50	--	--	--	--	--	--	--	--
13.5	50	56.27	1.00	70.00	1.24	84.86	1.51	90.86	1.61
14.5	50	56.37	1.00	70.08	1.24	85.30	1.51	91.06	1.63
Calculated**		--	1.00	--	1.27	--	1.58	--	1.76

* Ratios are those compared to potential drop at position 2.

** Assumes a conductance of 0.500 ohm^{-1} between plates for each pellet area.

FIGURE 9. POTENTIAL DIFFERENCES ON AN AC2GW POSITIVE PLATE DURING DISCHARGE

Elapsed time 3 to 6 minutes.
Majority of individual data points
(see Table 2) not included to
facilitate presentation of data.

which might occur in electrical conductivity of charged, partially discharged, and discharged electrodes. The conductivity of a fully charged electrode is anticipated to be greater than for a partially discharged electrode.

The difference in potential drop between probe positions 4 and 5 (lower quadrant, see Figure 6) is less than between positions 2 and 4 (upper quadrant), which indicates the expected non-uniform current distribution. A greater proportion of the total current passes to the negative electrode at the 50 ampere discharge rate than at the 10 ampere rate. This indicates that there is no excessive build-up of polarization losses near the tab for the situation described.

A second positive plate was instrumented with potential probes, as before, then conditioned prior to some additional experiments to check the reproducibility of the data previously obtained. This conditioned plate, in a three-electrode cell configuration, was discharged at various currents ranging from 10 to 50 amperes, as was done previously. The experimental data are summarized in Table 3. These measurements also showed the expected monotonic increase with probe position, and good linearity between discharge current and potential drop (Figure 10). Almost identical results were obtained for the third and fourth discharge cycle for considerable discharge times (depths of discharge). The variability amounted to approximately 2 percent for individual probe positions according to the data in Table 3. The results were similar to those obtained in prior experiments (e.g., Table 2) and the reproducibility between positive electrodes based on these data is approximately 10 percent, as indicated in Table 4.

NON-ORTHOGONAL GRID DESIGN

Modifications to Original Design

The non-orthogonal (radial-type) design which resulted from the Phase A study is shown in Figure 5. As mentioned earlier this design was a compromise between that obtained from a consideration of

TABLE 3. POTENTIAL DROPS IN AN AC2GW POSITIVE PLATE
AS A FUNCTION OF DISCHARGE CURRENT FOR
THIRD AND FOURTH CYCLES

Discharge Condition			Potential Drop in mV as a Function of.			
Time, Minutes	Capacity Removed, Coulombs	Current, Amperes	Position of Probe on Plate ^(a)			
			2	3	4	5
<u>Cycle 3</u>						
11.3	6,800	10	9.8	12.1	15.3	16.8
		20	19.9	24.6	30.8	33.8
		25	25.0	31.0	38.7	47.4
		30	30.2	37.4	46.7	51.2
14.3	12,200	50	50.1	62.0	77.5	84.8
44.3	24,000	10	9.5	11.9	14.5	15.7
		20	19.6	24.4	29.8	32.2
		25	24.4	30.4	37.2	40.2
		30	29.4	36.6	44.8	48.5
48.3	27,800	50	49.1	61.1	75.0	81.4
<u>Cycle 4</u>						
(44 ^(b))	24,000	10	9.6	11.9	15.0	16.4
		20	19.5	24.2	30.2	33
		25	24.7	30.6	38.2	41.7
		30	29.9	37.1	26.3	50.6
(49)	26,900	50	49.7	61.7	77.1	84.5

(a) Potentials compared with potential measured at tab (probe position 1).

(b) Brought to same depth of discharge as for 44.3 minutes, Cycle 3.

FIGURE 10. COMPARISON OF EXPERIMENTAL POTENTIAL DISTRIBUTION WITH THAT CALCULATED FROM ORTHOGONAL MODEL

TABLE 4. COMPARISON OF POTENTIAL DISTRIBUTION DATA
FOR DIFFERENT POSITIVE ELECTRODES

Probe Position	Discharge Current, A	Potential Measured, mV		Difference, %
		1st Series (a)	2nd Series (b)	
2	10	10.96	9.8	10.6
	50	56.27	50.1	11.0
3	10	13.62	12.1	11.2
	50	70.0	62.0	11.4
4	10	16.89	15.3	9.4
	50	84.86	77.5	8.7
5	10	18.41	16.8	8.8
	50	90.86	84.8	<u>6.7</u>
average:				9.7

(a) See Table 2 for details.

(b) See Table 3 for details.

the distribution of equipotential lines/current flow, and that based on an equalization of maximum paste pellet sizes (0.7 x 1.5 cm). No consideration was given to the ability to cast this design in the Phase A study.

At the beginning of the Phase B study, a preliminary design for a 15.6 x 17.1 cm (6.125 x 6.75 inch) "extra tall" grid, 0.18 cm (0.072 inch) thick, was finalized and submitted for review by Exide, after Battelle staff experienced in casting techniques had had an opportunity to contribute their suggestions. Figure 11 depicts schematically this preliminary radial-type design. The portion of this design to be machined in each half of the grid mold blanks are shown in Figures 12 and 13, while Figure 14 shows the recommended cross-sections to obtain the desired grid mass and dimensions. The heavier grid members are obtained by machining half the cross-section into each book mold half. The minimum weight members are obtained by machining the appropriate design in only one half of the mold. The cross-sectional area of the minimum weight members, namely 0.00318 cm^2 (0.00125 sq inch) was estimated from the blueprint of an AC2GW grid supplied by Exide. It is known that such grid bars can be cast. The medium weight members have twice this cross-sectional area, that is 0.0064 cm^2 (0.0025 sq inch) while the heaviest weight members have a cross-sectional area of 0.0127 cm^2 (0.0050 sq inch). The top border was 0.3 cm (0.118 inch) wide, and the other border (frame sections) were 0.2 cm (0.078 inch) wide. The estimated weight of this grid design was 95 gm (0.21 lb) although Exide indicated that this extra tall positive grid could weigh as much as 105 gm (0.23 lb). Approximately 37 percent of the lead alloy mass is concentrated in 22 percent of the grid area near the tab (see Figure 11).

Mold Design and Cutting

The general design features of the grid have been described. The grid designs were cut into the book mold halves such that the tab was at the bottom of the mold. To accommodate this bottom casting a sprue and runner were cut into the mold, to one side of the grid pattern, and feeding into the tab cavity.

FIGURE 11. MODIFIED DESIGN OF EXTRA TALL, TTP,
POSITIVE PLATE SHOWING NON-ORTHOGONAL
(RADIAL-TYPE) ARRANGEMENT OF GRID MEMBERS

— These grid members are thicker to carry
the current to the tab.

FIGURE 12. SCHEMATIC OF GRID MEMBER DESIGN TO
BE CUT INTO ONE HALF OF GRID MOLD

- = heaviest weight (largest cross-section)
- = medium weight (intermediate cross-section)
- = lightest weight (minimum cross-section)

FIGURE 13. SCHEMATIC OF GRID MEMBER DESIGN TO
BE CUT INTO OTHER HALF OF GRID MOLD

- = heaviest weight (largest cross-section)
- = medium weight (intermediate cross-section)
- = lightest weight (minimum cross-section)

FIGURE 14. CROSS-SECTION PROFILES OF GRID MEMBERS
IN MODIFIED GRID DESIGN

(Dimensions in inches: 1 inch $\equiv$ 2.54 cm)

It was anticipated that with this design it might be easier to completely fill the non-orthogonal mold cavity, compared with a conventional feed of lead alloy, and gravity filling. Some preliminary experiments were performed to evaluate this assumption. The grid designs for the two mold halves were programmed into Battelle's CAD/CAM facility, and the program checked by machining the design into blocks of clear plastic (methyl methacrylate). The program worked satisfactorily, thus the plastic blocks were used for casting experiments using colored water to simulate the flow of grid lead alloy in order to determine if complete filling would occur from the bottom up.

Figure 15 is a photograph of these two mold halves which were brought face to face and clamped for the simulated casting experiments, after machining the necessary feeders to the tab. Holes were also provided for air release along the top frame member (Figure 16). Colored water was introduced into the tab by gravity feed, with some blocking of the frame on each side of the tab to slow filling of the vertical border frame members. In spite of this blocking, Figure 17 shows that filling of these borders was fast enough to trap air in some of the grid members.

The plastic mold was disassembled, cleaned, dried, and the mating surfaces coated with a silicone mold release agent to provide a hydrophobic surface. Such a surface was thought to better represent the non-wetting of a metal mold by molten lead. Figure 18 shows the reassembled mold filled through several fill ports along the bottom frame member, but not the tab. Trapping of air was minimized, but not eliminated, for example along the bottom border.

Additional experiments, including varying the rate of flow in several of the fill ports; and completely blocking the bottom corners of the frame, failed to totally eliminate the trapping of air when colored water was used. However, substitution of mercury for water completely prevented air entrapment, even when it was introduced into the mold through only one fill port. Figure 19 is a photograph of the mercury-filled mold. The few air spaces at the top are due to

FIGURE 15. PHOTOGRAPH OF THE GRID DESIGNS CUT INTO THE TWO PLASTIC BLOCKS FOR THE SIMULATED CASTING EXPERIMENTS

FIGURE 16. TWO HALVES OF PLASTIC PROTOTYPE MOLD ASSEMBLED TOGETHER PRIOR TO FILLING EXPERIMENTS

FIGURE 17. RESULT OF FILLING EXPERIMENT USING
COLORED WATER AS "CASTING" FLUID:
NO MOLD RELEASE AGENT

FIGURE 18. RESULT OF FILLING EXPERIMENT USING
COLORED WATER AS "CASTING" FLUID:
TREATED WITH SILICONE RELEASE AGENT

FIGURE 19. RESULT OF FILLING EXPERIMENT
USING MERCURY AS "CASTING" FLUID

the fact that the top of the mold blocks were too close to the grid cavity (top border frame) so that the height of mercury in the outside reservoir could not be adjusted to an adequate height without excessive spilling. This situation will not occur in the metal molds for the lead alloy grid casting experiments.

When filling the plastic mold with mercury, it was observed that, because of its high specific gravity, the level of mercury rose uniformly during filling. The even progression of metal through the mold cavity eliminated air trapping. It was believed that lead would behave in a similar manner in filling steel molds, provided there was proper control of casting, and mold temperatures.

The hand casting stand was supplied by Exide. Before use it was refurbished. The old grid molds were removed, and the platens resurfaced. The heating elements were replaced. Gray cast iron slabs were cast, cut to size, surface milled, and finished ready for the CAD/CAM machining. The grid designs were then cut into these mold halves proper, and the two halves mounted on the platens ready for the casting experiments. The mold coat was supplied by Exide.

Preliminary Casting Trials

The hand-casting stand was assembled in Battelle's foundry next to a furnace used to melt the lead alloy. This apparatus is shown in Figure 20. Prior to each casting trial, the grid mold was brought up to temperature, and coated with the mold dressing using an aspirator. The lead pot, which held 110 kg (50 lbs) of the 6-percent antimony alloy, (Heat No. 1768), was also brought up to temperature. The ranges of conditions used are summarized below.

Pot temperature. . . .	500 $\pm$ 20 C	(930 $\pm$ 30 F)
Mold temperature . . .	220 $\pm$ 15 C	(425 $\pm$ 25 F)
Time in mold	30 to 60 seconds.

FIGURE 20. PHOTOGRAPH OF THE HAND-CASTING
APPARATUS USED FOR CASTING TRIALS

The alloy was poured into the mold by hand from a ladle after skimming off the dross. Mold filling via the tab at the bottom had to be accomplished by gravity feeding. A relatively large volume of alloy, compared with the grid, was associated with the sprue and runners, etc.

The first attempts at casting the non-orthogonal grid were a failure insofar as one half or less of the bottom portion of the mold was filled. Additional feeders were then machined into the mold halves at the top, and leading to the upper frame member, replacing some of the air vent channels. When these feeders were used to supply additional molten alloy, approximately the top quarter of the grid mold was filled, in addition to the one half or so filled from the bottom. Entrapped gas or premature solidification of the alloy were thought to be responsible in part for the failure to obtain a satisfactory casting.

Figure 21 shows one of the better grids, as judged by the completeness of filling of the mold cavities. To obtain this degree of filling, additional feeders were introduced along the bottom frame member. The frame members were adequately filled, but the thinnest grid members (compare Figure 12) froze at a thickness of about 0.10 cm (~ 0.04 inch) when about 8 to 13 cm (~ 3 to 5 inches) long. Since the surface tension of the antimony alloy is probably similar to that of pure lead, it should require only a 1.5 cm (0.5 inch) head to fill these smallest cross-section grid members. Therefore, it is possible that rapid solidification, due to rapid heat transfer to the mold, prevents the mold being filled completely with the liquid alloy.

At a review meeting at Battelle in April, 1980, the difficulties encountered with casting were discussed, and recommendations made for obtaining more satisfactory castings. The principal causes for failure in the original trials were thought to be (1) bottom filling, a procedure not normally adopted, (2) insufficient allowance for mold coat thickness when grid designs were cut, and (3) insufficient venting. The consequence of (2) above is that the effective cross-sectional area of the grid members is reduced, thus making filling more difficult.

FIGURE 21. CAST GRID POURED FROM BOTTOM AND TOP
DURING PRELIMINARY CASTING TRIALS

Improved Mold Design

As a result of the meeting at Battelle, it was decided that the mold design would be modified as follows:

- (1) the design would be cut symmetrically into both mold halves, and arranged in a conventional manner so that the lug is located at the side and not the bottom,
- (2) the cross-sectional area of the grid bars would be increased to permit a greater allowance for the mold coat, and
- (3) additional air vents (and mold coat scratching) would be employed to facilitate mold cavity filling.

If, after these modifications had been made, imperfect castings were still being obtained, then the angles of the sides of the bars cut into the mold (see Figure 14) would be increased.

The cut molds were resurfaced, the CAD/CAM facility reprogrammed, and the design changes (1) to (3) above were incorporated into the "improved" design machined into the mold blocks. When completed the mold more closely resembled a conventional book mold.

Casting of Grids

The mold blocks were reassembled into the hand casting stand. Mold coat (fresh solution supplied by Exide) was applied with an air gun, as opposed to an aspirator, in order to obtain a more uniform coating in all the mold cavities. The mold was brought up to temperature, and the lead alloy melted for the casting trials with the improved mold design. The preliminary castings were reasonably sound (Figure 22) thus work proceeded on producing the 100 grids for Exide. The following casting

FIGURE 22. PHOTOGRAPH DEPICTING THE REMOVAL
OF A CAST GRID FROM THE MOLD IN
THE HAND CASTING STAND

parameters were used:

Pot temperature. . . .510 $\pm$ 11 C (950 $\pm$ 20 F)

Mold temperature . . .205 $\pm$ 16 C (400 $\pm$ 30 F)

Time in mold 60 to 100 seconds.

Grids were usually obtained with 0 to 10 imperfections. In this context an imperfection refers to a partially filled grid member (bar) inside the frame. Such imperfections were not consistently located at the same positions on the grid. Only those grids with five or less imperfections were kept, the others were returned to the pot and remelted. Occasionally, perfect grids were obtained. An example is shown in Figure 23, after the flash had been trimmed off.

Approximately 150 grids were retained. Of this number, 75 grids with the fewest number of imperfections were shipped to Exide for hand pasting. Subsequently a further 25 grids, with less than five imperfections per grid, were forwarded to Exide. The remainder were retained at Battelle.

Pasting of Grids

As described above, seventy-five grids with three or less casting imperfections, such as incomplete filling of some internal grid members (bars), were forwarded to Exide for hand pasting and curing. A further 25 cast grids, with approximately three to five imperfections, were also forwarded to Exide for any supplementary experiments such as the determination of hardness or strength. Nine pasted positives, incorporating the non-orthogonal grids, were returned to Battelle for the potential distribution determinations described in the next section. Details of the paste composition or pasting procedure were not disclosed. Inspection of the positives showed complete filling, no missing pellets, and essentially no overpasting, as may be seen in Figure 24.

FIGURE 23. EXAMPLE OF A SIDE CAST, PROTOTYPE,
NON-ORTHOGONAL GRID AFTER TRIMMING

FIGURE 24. PHOTOGRAPH OF A HAND-PASTED NON-ORTHOGONAL
GRID USED FOR POTENTIAL DISTRIBUTION MEASUREMENTS

Determination of Potential Distribution

The potential distribution over the pasted, non-orthogonal positive grids was determined in a similar manner to that described earlier for the Exide AC2GW positives. Figure 25 shows the location of the potential probes. These locations were selected in order to (1) approximate the positions 1 through 5 on the AC2GW grid, as shown in Figure 6, and (2) lie on selected equipotential lines identified in the modeling study. Probes numbered 1 through 5 correspond with the probes of the same number on the conventional grid. Potential probes 6 through 9 are located at grid nodes on the equipotential lines. The probes were constructed and attached to the non-orthogonal pasted grid in a similar manner to that shown in Figure 8.

A three-electrode cell, using two pasted negatives supplied by Exide, was constructed, and inserted into the end cell of an EV106 container. This cell was filled with fresh battery-grade acid*, then the electrodes were conditioned using a modified regime to that described earlier because of time constraints. The conditioning procedure was as follows:

- (1) Charge at 0.4 A with a cell voltage cut-off of 2.37 V.
- (2) Reduce current if necessary while cell voltage is ≤ 2.37 V; record number of charge coulombs.
- (3) Discharge at 5.0 A to 80 percent (max.) depth of discharge; record end of discharge voltage and coulombs discharged.
- (4) Repeat cycle three times.
- (5) Charge at 2.5 A to 2.37 V cut-off.
- (6) Let current fall, record charge coulombs.
- (7) Repeat step (3).
- (8) Repeat steps (5) through (7).

* Scholle Corporation, Northlake, Illinois 60164.

FIGURE 25. THE BATTELLE NON-ORTHOGONAL GRID SHOWING THE LOCATION OF POTENTIAL PROBES

Potential Distributions as a Function of Discharge Current

The results of the discharge experiments are shown graphically in Figure 26, and summarized in Table 5. There is a decrease in slope from 27.5 to 47 amperes and these lines do not go through the origin as do lines plotted through data points obtained at 11 and 27.5 amperes discharge current. This change in slope was shown not to be due to inaccurate current measurement with the different power supply used. It might be explained by higher polarization on the bottom of the electrode, but this seems unlikely.

The results for probe positions 3 and 6 are very similar as would be expected, since they are close to an equipotential line in the original model (Figure 27) from which the model for casting was derived. However, it was expected that the potential drop value measured for position 2 would fall between those for probe positions 3 and 9, whereas it is much higher and close to the value for position 4 (see Figure 26). Inspection of the positive plate did not reveal any mistake in positioning of the probes, thus this observed behavior cannot be explained at this time.

It is possible to make some comparisons of these non-orthogonal data with those for the orthogonal grid, shown in Figure 10. Probe positions 1, 2, 3, 4 and 5 are located in approximately the same positions on the two grids. If position 2 values are disregarded because these appear to give anomalous results for the non-orthogonal plate, then position 3, 4 and 5 values may be compared. The slopes of the lines for these positions are shown in Table 6. Slopes for the non-orthogonal (radial) plate were calculated for discharge currents up to 27.5 amperes so that the apparent decreasing slopes at higher discharge rates (Figure 26) are not involved. Table 6 shows that the voltage drop through the non-orthogonal grid is only about 50 to 70 percent of that through the conventional AC2GW orthogonal plate.

FIGURE 26. POTENTIAL DIFFERENCES ON A NON-ORTHOGONAL (BATTELLE) POSITIVE PLATE DURING DISCHARGE

TABLE 5. SUMMARY OF EXPERIMENTAL DATA (POTENTIAL DROPS)
FOR THE NON-ORTHOGONAL (BATTELLE) POSITIVE PASTED GRID

Discharge Current, Amperes	Test Series Number	Potential Drop in mV as a Function of Position of Probe on Plate ^(a)					
		2	3	4	5	6	9
11	1	11.3	7.6	11.9	14.2	8.1	3.4
	2	11.5	7.7	11.9	13.7	8.0	3.5
	3	11.5	7.7	11.9	13.6	8.1	3.5
	average	11.4	7.7	11.9	13.8	8.1	3.5
27.5	1	29.7	19.9	31.0	36.3	20.9	9.1
	2	27.8	18.7	28.8	33.4	19.6	8.5
	3	27.8	18.8	28.8	33.2	19.7	8.6
	average	28.4	19.1	29.5	34.3	20.1	8.7
47	1	45.4	29.4	41.9	43.9	25.9	11.3
	2	37.3	25.3	38.9	44.9	26.5	11.6
	3	37.6	25.5	38.8	44.6	26.6	11.7
	average	40.1	26.7	39.9	44.5	26.3	11.5

(a) Potentials compared with potential measured at the tab
(probe position 1).

FIGURE 27. POSITIVE PLATE; TTP, EXTRA TALL (6.75 in):
POTENTIAL DISTRIBUTION (EQUIPOTENTIALS)
FROM COMPUTER PRINT-OUT

TABLE 6. SLOPES OF DISCHARGE CURVES FOR
ORTHOGONAL AND EXPERIMENTAL
RADIAL GRID

Probe Position on Grid	Type of Grid Design	Slope ^(a) mv/amps	Percent of Orthogonal Slope
3	Orthogonal ^(b)	1.32	--
3	Non-Orthogonal ^(c)	0.69	52
4	Orthogonal	1.76	--
4	Non-Orthogonal	1.25	71
5	Orthogonal	1.62	--
5	Non-Orthogonal	1.07	66

(a) Effective resistance at high current drains.

(b) Conventional Exide AC2GW design.

(c) Battelle radial-type design.

The orthogonal AC2GW grid weighed approximately 90 grams and had a 0.183 cm (0.072 inch) wide frame. The non-orthogonal grid is heavier, weighing about 125 grams so it was thought that part of the slope reduction (voltage improvement) might be attributable to the larger lead volume. However, it should be remembered that the non-orthogonal grids were of the "extra-tall" configuration. The difference in geometric area between the two grids is 3.8 percent. The ACGW dry-charged positive plates weighed 307 g, while the non-orthogonal grids weighed 318 g. Thus the difference in weight is 3.6 percent. On a specific weight/area basis, therefore, the two positive plates are essentially equivalent. Because of this, we believe the difference in performance is real and we believe that a lighter non-orthogonal grid would give equivalent results to those for a heavier conventional grid when casting conditions are established to enable them to be made.

MATHEMATICAL MODEL DEVELOPMENT

Requirements of a Radial Grid Design

In the orthogonal grid design commonly used in commercial lead batteries the current through the metallic grid elements travels vertically or horizontally. Current through the paste may follow a more direct path between potentials on the grid surface. A more efficient design is to:

- (1) Utilize a more conductive grid element near the tab, where the elements carry the highest current, and
- (2) Direct the elements in the direction of maximum current flow, which is the direction of the potential gradient.

Potential gradient maps for various orthogonal grid designs were plotted from calculated data and shown in the Phase A report. These indicated potential gradients that followed a somewhat diagonal path through the grid as a whole. Thus, in the ideal grid the conducting elements should be positioned to follow the potential gradient which is perpendicular to the equipotential lines. Other elements to form adequate pellet areas and provide mechanical strength to the structure should follow the equipotential lines and should be of minimum cross-section as they carry no current.

In the non-orthogonal (radial) grid designs to be considered in Battelle's model these ideals are not reached. However, the grid design considered consists of grid members arranged in straight lines which radiate from the tab (e.g., see Figure 2). The linear grid members follow the potential gradients to a better degree than conventional orthogonal elements. Also, tapering is introduced to provide higher conductivity nearer the tab than away from it, as is done on many commercial and experimental grid designs. Finally, another requirement of a radial grid model is that allowance should be made for the fact that the (pellet) area associated with each node is not constant, even when additional grid members are introduced to try and equalize pellet areas below or at the maximum permissible size.

Development of a Model for a Radial Grid

Initial progress in developing a program to solve the potential and current distribution of a radial grid was discussed in the Phase A report (Page 65, et seq.). An experimental radial grid (Figure 2) approximately 12.5 x 14.2 cm (4.9 x 5.6 inch) in size, and consisting of linear elements, was provided by Exide. For purposes of developing the computer program, a simplified grid design containing only 29 nodes was used, as shown in Figure 28.

The matter of indexing the nodes in radial designs is more complicated than for an orthogonal grid. Also, the area associated with each node is not constant. The matrix of coefficients for the Kirchoff equations is symmetrically banded as for the orthogonal grid, therefore, the subroutine for banded matrices could be used to minimize computer storage requirements, but the proper indexing of coefficients is somewhat involved.

The schematic of the smaller grid structure is shown in Figure 28. The nodes are sequentially numbered from 1 to 29. The tab, which would be attached to node 1 is not shown. The grid is surrounded by a fictitious array of elements and nodes that simplify some of the programming. The conductances of these elements are zero and their location is that of the real border. A double subscripted (I,J) system is used to index both fictitious and real nodes. Figure 28 also shows the areas associated with nodes 13 and 14. These are delineated by points lying at the "center of gravity" of the four areas surrounding each node.

In the program the nodes on the borders are read in. Locations of interior nodes are calculated by determining equations for the straight-line grid members and calculating their intersections. The banded structure of a full matrix is shown in Figure 29. The center diagonal contains coefficients of the equation for the node around which Kirchoff's equation is written. The adjacent diagonals are conductances of horizontal elements. The diagonals farther away are conductances for diagonal or

FIGURE 28. SCHEMATIC OF SCALED-DOWN EXIDE
EXPERIMENTAL (RADIAL) GRID

Note: Real nodes numbered sequentially,
M = 1 to 29. Compare this sim-
plified design with that shown
in Figure 2.

FIGURE 29. MATRIX OF COEFFICIENTS FOR 29 KIRCHOFF EQUATIONS FOR THE SCALED-DOWN EXIDE EXPERIMENTAL RADIAL GRID

vertical grid elements. These may be indexed both by M, the node number, and by a double subscript (I,J), with the maximum value of $I=N(J)$, including fictitious nodes, varying from row to row. The two numbers in the off-center diagonals in the matrix are the (I,J) indexes for each of the conductances.

The model is small enough to print out the rectangular matrix obtained by converting the banded portion of a full matrix. This is believed to be of the correct form for use with the IMSL routine LEQTIF for a banded matrix.

The program was first developed for an unpasted grid prior to adding conductances to the elements due to the paste surrounding them. A persistent error in this program was eventually traced to an incorrect algorithm.

Areas for each node were calculated by assuming a perimeter joining the center of gravity of the pellet areas surrounding each node. The conductance added to each element and due to the paste was calculated by first determining the volume of paste associated with half of the pellet area on each side of the grid element, then:

$$XCPAS(I,J) = (\sigma)(TH+OVP)(AREA)/(XLGTH(I,J)**2)$$

where:

XCPAS(I,J) = conductance due to paste to be added to
horizontal grid element at I,J
 σ = specific conductance of paste
TH = grid thickness (at border)
OVP = overpaste thickness
AREA = sum of 1/2 area of adjacent pellet areas
XLGTH(I,J) = length of element at I,J.

While this program was being developed, Exide had designed and cast a larger radial (EVR*) grid measuring about 15.6 x 16.0 cm (6.13 x 6.31 inches) which is the same size as the orthogonal ACGW grids previously

* 1EVR = positive; 2EVR = negative plate.

investigated. However, several features of the design of this larger radial grid required a modification of the design or of the computer program to make the latter useable.

First, the coordinate system on the EVR blueprints started at the bottom left corner of the grid. Most vertical elements radiated from a tab located near the upper right corner with most of these elements intersecting either the bottom or left border (frame) of the grid. Two elements also radiated to the right border. Second, the radial elements did not always join horizontal elements.

The EVR design was made compatible with the existing computer program through a simple change in coordinate system; a slight shift in the positions of several radial members to intersect with horizontal members at the vertical border; and the elimination of two radial members intersecting the vertical border nearest to the tab. The result is shown in Figure 30. Elimination of two radial grids intersecting the left border in this figure at vertical positions 5 and 13 was compensated for by putting the equivalent mass of these elements into the vertical border between $J=2$ and $J=14$. This modification is believed to be a reasonable compromise to adapt the computer program, since current carrying requirements in this area of the electrode are small, particularly in the horizontal direction. Thus, the accuracy of results should be little affected by combining vertical components of conductance.

The 2EVR (negative) grid contains 23 horizontal grid members (bars) not including top and bottom borders. The 1EVR (positive) grid however, contains 30 horizontal grid members, not including the borders. The mathematical model should be negligibly influenced by converting the 1EVR design to 23 horizontal grid members containing the same total mass as the 30 members in the 1EVR grid, therefore, this conversion was made.

Changes in the design of the grids was much less time consuming than changing the computer program to accommodate Exide's revised design, and it was possible to do this in the above instance. However, some of the radial grid members and borders in the EVR grid designs were tapered and it was considered necessary to modify the program to account for this design element rather than modifying the design to take account of this tapering.

FIGURE 30. MODIFIED EXIDE 2EVR (NEGATIVE) GRID
SUITABLE FOR MODELING STUDIES

The computer program for the radial model was then run successfully, converging to values within 0.1% of the total potential at each node after only four iterations. The grids in this stage of development of the model each contain 496 nodes. Even using the banded rather than full matrix for solution of Kirchoff's equations, the matrix is relatively sparse when 496 equations are solved simultaneously. Figure 31 is a photograph of this matrix on 36 computer-print-out sheets. Of the 24,304 entries in this matrix only 2432 or 10 percent are non-zero. The sub-program and computer capable of solving this matrix were available, and thus used without further consideration. Other methods of solving these equations are probably available or could be developed to utilize less memory.

Comparison of Results with
Those of an Orthogonal Grid

The EVR radial grids contained less lead and were thinner than the ACGW grids previously investigated. Thus, the advantage of the radial grid could not be determined by direct comparison of results with those of the ACGW grids. It was necessary to conceptually design an orthogonal grid for direct comparison. This was done with the following constraints:

- (1) The positive and negative orthogonal grids are to weigh the same as the positive and negative radial grids.
- (2) Horizontal members in the orthogonal design are to be the same in number, position, and cross-section as in the radial grids.
- (3) Borders on the orthogonal grid are to be of the same volume as corresponding borders on the radial grid. However, the borders on the orthogonal model are not tapered.

FIGURE 31. SYMMETRICAL BANDED MATRIX FOR
496-NODE RADIAL GRID MODEL

Since a conceptual grid cannot be weighed, it is desirable to have a convenient way to calculate its total volume (and weight). This is easy to do with an untapered orthogonal grid but more difficult with the radial grid design. Since the lengths and average cross-sections of all grid elements are calculated in the radial grid program, it is easy to add an algorithm to calculate the volume of each element and add them up. However, this procedure should give a high value because no correction is made for the overlap at intersections. Nevertheless, the method was used to compare the calculated weight with the actual weight of 70.5 grams (without the tab) for a 2EVR grid. The calculated volume was 7.176 cm^3 (0.4379 in^3). Assuming a density of 10.95 g/cc (17.94 g/in^3) the calculated weight is 78.6 grams (without tab). Thus a negative correction of about 10% to this value will give the actual weight.

The calculated volume of the 1EVR grid was 8.702 cm^3 (0.5310 in^3) giving a weight after the 10% correction and addition, of the tab of 91.3 grams. Orthogonal grids were designed with volumes of 8.702 cm^3 (0.5310 in^3) (positive) and 7.176 cm^3 (0.4379 in^3) (negative) not correcting for overlaps, within the constraints listed above, utilizing 10 vertical members, including the borders (frame).

Calculations of potential drops and current distribution were made for the orthogonal and EVR radial grids using the following inputs:

Current (both sides) 48 amperes
 Lead conductivity $4063 \text{ ohm}^{-1} \text{ cm}^{-1}$ ($10320 \text{ ohm}^{-1} \text{ in}^{-1}$)
 Positive paste conductivity $135 \text{ ohm}^{-1} \text{ cm}^{-1}$ ($343 \text{ ohm}^{-1} \text{ in}^{-1}$)
 Negative paste conductivity $5496 \text{ ohm}^{-1} \text{ cm}^{-1}$ ($13960 \text{ ohm}^{-1} \text{ in}^{-1}$)
 Overpaste (over border thickness) . 0.013 cm (0.005 in).

The dispersion of the current density was calculated as the root-mean-square of deviations from the average for each node and made dimensionless by dividing by the average current density:

$$\text{RTMSQ} = \frac{\sqrt{(\sum(\Delta \text{CD}(\text{M}))^2 * \text{ARM}(\text{M})) / \sum \text{ARM}(\text{M})}}{\text{CDAVE}}$$

where:

$\Delta CD(M)$ = deviation of current density at node M
from average (CDAVE)

$ARM(M)$ = area associated with node M.

Table 6, Cases 1 and 2 show results of these calculations, and for a lead conductivity of $4063 \text{ ohm}^{-1} \text{ cm}^{-1}$ ($10320 \text{ ohm}^{-1} \text{ in}^{-1}$). The voltage of the radial grid is 0.1 volt lower than that for the orthogonal grid. The dispersion of the current density is also substantially less.

Equipotential plots for both electrodes and plots of lines of equal current density have been made in Figures 32 through 37. Tabs were in the TTP position, the positive to the right and the negative to the left. The plots for orthogonal grids reflect these positions but note that the plots for radial grids always show the tab to the left for both positive and negative.

The voltage drop through the positive radial grid is approximately 0.1 volt less than through the positive orthogonal grid and thus responsible for the overall voltage reduction. The voltage drop reduction is of the order of 20 percent. Voltage drops through the radial and orthogonal negatives are essentially the same, although lines of current are directed more vertically in the radial grid. The current density variation with the radial grid pair is substantially less than with the orthogonal grid pair, reflecting the decreased dispersion value.

If the conductivity of the lead is assumed to be the same as the paste, then the model simulates an electrode made up 100% of paste. If the orthogonal and radial models closely represent the physical situation, the same results should be obtained by substituting the conductivity of the paste for lead in either model. Thus, this substitution provides a method of testing the equivalency of the models. The conductivity of the positive paste, $135 \text{ ohm}^{-1} \text{ cm}^{-1}$ ($343 \text{ ohm}^{-1} \text{ in}^{-1}$), was substituted for that of lead, which is $4063 \text{ ohm}^{-1} \text{ cm}^{-1}$. This should greatly decrease the conductance in the positive plate, but have much less effect on the negative plate that contains paste of high conductivity. Results are shown in Table 7, Cases 3 and 4 and in Figures 38 through 43.

TABLE 7. COMPARISON OF CALCULATED VOLTAGES AND
CURRENT DISTRIBUTIONS FOR RADIAL AND
ORTHOGONAL COMPUTER GRID MODELS

Model	Case No.	Lead Conductivity,		Tab-to-tab Volts	RTMSQ(Δ CD) CDAVE
		$\text{ohm}^{-1}\text{cm}^{-1}$	$\text{ohm}^{-1}\text{in}^{-1}$		
Radial	1	4063	10320	0.841	0.16471
Orthogonal	2	4063	10320	0.938	0.2567
Radial	3	135	343	2.037	0.46146
Orthogonal	4	135	343	1.794	0.7176

FIGURE 32. EQUIPOTENTIAL LINES ON RADIAL
POSITIVE GRID (1EVR)

FIGURE 33. EQUIPOTENTIAL LINES ON RADIAL
NEGATIVE GRID (2EVR)

FIGURE 34. LINES OF EQUAL CURRENT DENSITY
FOR RADIAL GRID PAIR

(Units are amps/in²)

FIGURE 35. EQUIPOTENTIAL LINES ON
POSITIVE ORTHOGONAL GRID

FIGURE 36. EQUIPOTENTIAL LINES ON
NEGATIVE ORTHOGONAL GRID

FIGURE 37. LINES OF EQUAL CURRENT DENSITY
FOR ORTHOGONAL GRID PAIR

(Units are amps/in²)

FIGURE 38. EQUIPOTENTIAL LINES ON
RADIAL POSITIVE (1EVR) GRID

(Conductivity of lead
assumed = $343 \text{ ohm}^{-1} \text{ in}^{-1}$)

TAB

FIGURE 39. EQUIPOTENTIAL LINES ON
RADIAL NEGATIVE GRID (2EVR)

(Conductivity of lead
assumed = $343 \text{ ohm}^{-1} \text{ in}^{-1}$)

FIGURE 40. LINES OF EQUAL CURRENT DENSITY
FOR RADIAL GRID PAIR

(Conductivity of lead
assumed = $343 \text{ ohm}^{-1} \text{ in}^{-1}$;
units are amps/in^2)

FIGURE 41. EQUIPOTENTIAL LINES ON
POSITIVE ORTHOGONAL GRID

(Conductivity of lead
assumed = $343 \text{ ohm}^{-1} \text{ in}^{-1}$)

TAB

FIGURE 42. EQUIPOTENTIAL LINES ON
NEGATIVE ORTHOGONAL GRID

(Conductivity of lead
assumed = $343 \text{ ohm}^{-1} \text{ in}^{-1}$)

FIGURE 43. LINES OF EQUAL CURRENT DENSITY
FOR ORTHOGONAL GRID PAIRS

(Conductivity of lead assumed =
343 ohm⁻¹ in⁻¹; units are amps/in²)

The results for the radial model are over 0.2 volt higher than for the orthogonal model and the dispersion of current density for the radial model is substantially less. The plots again show that this difference is in the positive grid. Potential plots on the negative radial and orthogonal grids are quite similar and the current density plots are much more alike than would be surmised from the dispersion values.

The comparison test is an extreme one in that the very minimum conductance is assumed for the positive. In the orthogonal model the positive node is matched exactly with a negative node with the same coordinates and associated area. In the radial program the node on one electrode is not directly opposite one on the other electrode and is matched to the closest one. This potential is shifted slightly, and more so as the conductivity of the electrode decreases. This may be responsible for the lack of agreement between models with a positive of poor conductance.

Also an array of conductance elements is an approximate representation of a conductive continuum such as the paste. The array representation is less accurate as the coarseness of the grid is increased and absolute voltage differences increase as the conductance decreases. The radial model has grid elements both smaller and larger than the uniform size in the orthogonal model, and the effect of this is difficult to predict.

A sensitivity analysis in which the positive paste conductance is varied would be useful in establishing the range of agreement of the models, but time did not permit this exercise. In the analysis of the grids with lead conductivity at $4063 \text{ ohm}^{-1} \text{ cm}^{-1}$ ($10320 \text{ ohm}^{-1} \text{ in}^{-1}$), the voltage of the radial positive was lower than the orthogonal positive rather than higher as in the model comparison test. Therefore, this lowering may be a little conservative and is certainly not optimistic.

Development of a Universal Model

In a truly universal model for grid and plate development, the nodes and interconnecting grid elements may be randomly distributed, in addition to the parameters already addressed by the Battelle Model, namely: (1) random position of tab around frame (border) and different positions on negatives and positives, (2) different arrangements of grid elements for positives and negatives, (3) variable grid element thickness such as tapered elements, and (4) overpasting. Such a program would handle orthogonal, radial with linear elements and radial with non-linear elements but linear segments.

Some preliminary consideration has been given to how such a model could be programmed, and the universal model concept appears feasible. Nodes may be numbered in an arbitrary sequence, as are the interconnecting elements. The coordinates of these nodes become input to the program. However, as with the orthogonal program, development of a full matrix of equations satisfying Kirchoff's law at each node will result in a matrix too large for many computers. The use of banded matrices or other approaches should avoid this difficulty.

SUMMARY AND CONCLUSIONS

The following summary may be drawn as a result of the original Phase A study and the Phase B study reported herein:

- (1) Useful mathematical models for the performance of grid-pairs have been developed for orthogonal grids and for radial grids composed of linear elements.
- (2) Experimental results for the potential distribution (voltage drops) in a pasted orthogonal (ACGW) grid pair were within 25 percent of values calculated from the model.
- (3) The calculated voltage drop between the positive and negative plates of an EVR radial grid pair is at least 0.1 volt lower than that through an orthogonal grid pair of the same weight and overall dimensions.
- (4) An experimental non-orthogonal (radial) grid with some non-linear elements, designed and cast at Battelle, and pasted at Exide, had voltage drops of 34 to 48 percent less than a positive orthogonal (ACGW) grid on a pseudo-normalized dimension/weight basis.
(Pasted weight was 3.6% larger for the Battelle radial grid with some non-linear elements, but the plate area was 3.8% greater.)

In conclusion, radial grid designs offer the prospect of improved performance for electric vehicle applications because of improved potential and current density distribution for a fixed mass, and given set of overall plate dimensions. Conversely, for a given performance criterion, such as a given voltage drop under load at a fixed rate of discharge, a radial grid can be designed having less mass and smaller dimensions.

RECOMMENDATIONS

As a result of both the Phase A and the Phase B studies, Battelle's Columbus Laboratories makes the following recommendations:

- (1) There should be further experimental development of a lighter grid with experimental determination of performance.
- (2) The development of a universal mathematical model to handle all types of grid design (both linear and non-linear elements) should be concluded.
- (3) A sensitivity analysis should be performed to indicate the useful conductance range of the grids/plates derived from the mathematical models.
- (4) The Exide/Battelle experimental pasted grids should be incorporated into test cells for full-scale battery experiments to determine performance to weight relationships.

Finally, a mathematical model will only be successful if accurate data exist for all the input parameters. Values have been assumed for paste conductivity, alloy conductivity, and electrolyte conductivity, for example. While a sensitivity analysis will indicate the effect of state of charge or discharge within gross boundaries, it would be helpful to have experimentally determined values of some of these parameters, and some knowledge of how such values are influenced by temperature of operation.

REFERENCES

- (1) Vaaler, L. E., Thomas, R. E., and Brooman, E. W., Phase A Report on "Electric Vehicle Battery Development Studies", included in Second Annual Report (June, 1980) on Contract No. 31-109-38-4207 to Argonne National Laboratory, p 56.
- (2) Vaaler, L. E. and Brooman, E. W., "Mathematical Model for the Design of Grids for Electric Vehicle Batteries", SAE Paper No. 780221 (1978).

APPENDIX A

COMPUTER PROGRAM FOR THE NON-ORTHOGONAL GRID MODEL

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APPENDIX A

COMPUTER PROGRAM FOR THE NON-ORTHOGONAL GRID MODEL

Legend

A(M,L)	Elements of the symmetric banded matrix.
AMP	Amperes of current distributed to the two sides of an electrode.
AR(I,J)	Area associated with node I,J.
ARM(M)	Area associated with node M.
CE	Conductance between electrodes per unit electrode area.
D	Distance from a node on one electrode to nodes on the other electrode.
DM	Distance to closest node.
IDD(J)	Value of I for node on each horizontal element where no further tapering of the horizontal element occurs.
IN(I,J)	Value of I on negative node closest to positive node I,J.
ITAB4, ITAB2, ITAB3	Nodes on top border of electrode to which the tab is connected.
JDD(I)	Value of J for node on vertical element where no further tapering of the vertical element occurs.
JN(I,J)	Value of J on negative node closest to positive node I,J.
LL	Number of columns in the symmetrical banded matrix.
MM	Number of rows in the symmetrical banded matrix; number of nodes on each electrode.
MN(M)	Node, on negative closest to node M on positive electrode.

N(J)	Number of nodes on each horizontal element, J.
NSUM(J)	Total number of nodes after J horizontal elements have been counted.
NT(J)	Equals zero if the right border node consists only of a horizontal element and the vertical border; Equals 1 if a vertical radial element also intersects this node.
OVP, OVPN, OVPP	Thickness of overpaste over border thickness.
PCN	Conductivity of negative paste.
PCP	Conductivity of positive paste.
SLOPE	Slope of radial elements.
SPC	Conductivity of grid elements.
TAB(M)	Conductance of tab element connected to each node. This is zero except for M = ITAB1, ITAB2, ITAB3.
THN	Thickness of negative border.
THP	Thickness of positive border.
VOL	Total calculated grid volume.
WIDTH	Electrode width.
X(I,J)	X-coordinate of nodes with origin on left and reading to right.
XC(I,J)	Average cross section of horizontal grid segment I,J.
XCON(I,J)	Conductance of horizontal segment I,J, with associated paste.
XC1(J)	Cross section of horizontal grid element J at node 2,J (left border).
XC2(J)	Cross section of horizontal grid element J at node IDD(J), J.
DXLGT(I,J)	Length of grid segment I,J on horizontal grid element J.
XM(I,J)	Coordinate of center of gravity of area AR(I,J).

XN	X coordinates of electrode with origin on right and reading positivity to the left.
X1	Coordinate of radial member at top border.
X2	Coordinate of radial member at bottom on right border.
YC(I,J)	Average cross section of radial grid segment I,J.
YCEPT(I)	Intercept of radial grid element with vertical coordinate through I = 2.
YCON(I,J)	Conductance of radial segment I,J, with associated paste.
YC1(I)	Conductance of radial element I at node I,2 (top border).
YC2(I)	Conductance of radial element I at node I, JDD(I).
YHORZ(J)	Y coordinate of horizontal grid element J.
YLGTH(I,J)	Length of radial grid segment I,J.
YM	Y coordinate of center of gravity of area AR(I,J).
YN(I,J)	Y coordinate associated with XN(I,J). Actually the same at Y(I,J).
YVOL(I,J)	Volume of radial grid segment I,J.
Y1(I)	Coordinate of radial element I at top border, Y10.
Y2(I)	Coordinate of radial element I at bottom or right border.

For convenience in program development and use, the A matrix is developed in a first program and stored on tape along with associated variables. In the second program these are read out and used for solution of the matrix. Additional variables read in or developed in the second

program are:

CD(M)	Current density at node M.
CDAVE	Average current density.
CDDIF(M)	CDAVE - CD(M)
CRIT	Largest difference in potential of the same node for successive iterations. Has been set at 0.001 or 0.1% of tab-to-tab potential.
IMAX	Maximum number of iteration to be run if convergence according to CRIT is not obtained with fewer iterations.
PNPN(M)	Potential difference between positive electrode node and nearest negative node, using area associated with positive node.
PNPP(M)	Potential difference between negative node and nearest positive node, using area associated with negative node.
VOLT	Tab-to-tab voltage due to IR drop.
LEQT1B	IMSL subroutine for solving a symmetrical banded matrix.

```

1      PROGRAM LEV(INPUT,OUTPUT,DEBUG=OUTPUT, TAPE50)
      C      ESB EXPTL GRID, CALC OF A MATRIX
      C      496-NODE RADIAL GRIDS,1EVR,2EVR
      DIMENSION X1(27),Y1(27),X2(27),Y2(27),YHORZ(27),SLOPE(27),
5      1YCEPT(27),X1(27,27),Y1(27,27),NT(27),N(27),X0(27),Y0(27),
      2XM(27,27),YM(27,27),AR(27,27),XN(27,27),YN(27,27),OM(27,27),
      3IN(27,27),JN(27,27),YCON(27,27),A(496,496), XCON(27,27),
      4      TAB(496),MN(496),ARM(496), NSUN(27),
      5YC(27,27), XLGTH(27,27),YLGTH(27,27),
10     6JDD(27),IDD(27),XC1(27),XC2(27),YC1(27),YC2(27),XC(27,27)
      7, XVOL(27,27), YVOL(27,27)
      CB      ARKAYS
      READ 1, M1,M1, ITAB1, ITAB2, ITAB3,TAB1,TAB2,TAB3,WIDTH,
      1 THP, THN, SPC, AMP,CE,PCP,PCN,OVPP,OVPN
15     1 FORMAT(5I4, 7F8.0/ 8F8.0 )
      PRINT 141
141    FORMAT(52H M1 N1 ITAB TAB1 TAB2 TAB3 WIDTH )
      PRINT 100
      PRINT 1, M1,N1, ITAB1, ITAB2, ITAB3,TAB1,TAB2,TAB3,WIDTH
20     1 PRINT 100
      PRINT 140
140    FORMAT(95H THP THN SPC AMP CE PCP PCN
      1 OVPP OVPN )
      PRINT 139, THP,THN,SPC,AMP,CE,PCP,PCN,OVPP,OVPN
25     139 FORMAT(1X, 11E12.4)
      PRINT 100
      M2= M1+1
      M3=M1+2
      N2=N1+1
      N3= N1+2
30     1 READ 2,( X1(I), I= 3,M1)
      2 FORMAT(10F8.0)
      READ 2,( X2(I), I= 3,M1)
      READ 2,( Y1(I), I= 3,M1)
35     1 READ 2,( Y2(I), I= 3,M1)
      READ 2,(YHORZ(J),J= 2,N2)
      PRINT 142
142    FORMAT(120H X0 X1 Y0 X2 SLOPE Y1 YCEPT Y2
      1 )
40     1 PRINT 100
      DO 3 I= 3,M1
      X0(I)=X2(I)-X1(I)
      Y0(I)=Y2(I)-Y1(I)
      SLOPE(I)=Y0(I)/X0(I)
      YCEPT(I) = -SLOPE(I)*X1(I) +Y1(I)
45     3 PRINT 20,X1(I),X2(I),Y1(I),Y2(I),X0(I),Y0(I),SLOPE(I),YCEPT(I)
      20 FORMAT(1X,8E15.8)
      PRINT 100
      PRINT 143
50     143 FORMAT(20H X(I,J),Y(I,J) )
      PRINT 100
      DO 4 J= 2,N2
      NT(J)= 0

```



```

55      I=2
       7  I = I+1
         X(I,J) = (YHORZ(J)-YCEPT(I))/SLOPE(I)
         Y(I,J) = YHORZ(J)
         TEST=ABS(X(I,J)-WIDTH)
         IF(TEST-.01)8,8,19
60      8  NT(J)=1
         GO TO 10
       19 IF(X(I,J)-WIDTH)5,9,9
       9  X(I,J) = WIDTH
         Y(I,J) = YHORZ(J)
65      GO TO 10
       5  IF(M1-I)6,6,7
       6  I=I+1
         X(I,J) = WIDTH
         Y(I,J) = YHORZ(J)
70      10 N(J) = I+1
         X(1,J)=0.0
         Y(1,J)=YHORZ(J)
         X(2,J)=0.0
         Y(2,J)=YHORZ(J)
75      X(I+1,J) = X(I,J)
         Y(I+1,J) = Y(I,J)
         NA=N(2)
         DO 11 I=1,NA
           X(I,1) = X(I,2)
80      11 Y(I,1) = Y(I,2)
         NA=N(N2)
         DO 12 I=1,NA
           X(I,N3) = X(I,N2)
85      12 Y(I,N3) = Y(I,N2)
         N(1)=N(2)
         N(N3)=N(N2)
         DO 14 J=1,N3
           NA = N(J)
           PRINT 15, (X(I,J),I=1,NA)
90      15 FORMAT(1X,16F8.4)
         100 FORMAT(1X,/)
           PRINT 15, (Y(I,J),I=1,NA)
         14 PRINT 100
           PRINT 100
95      PRINT 144
         144 FORMAT(23H  NT(J), N(J) )
           PRINT 100
           PRINT 17, (NT(J),J=2,N2)
           PRINT 17, (N(J),J=2,N2)
100     PRINT 100
         17 FORMAT(1X,30I4)
           PRINT 145
         145 FORMAT(20H  XN(I,J), YN(I,J) )
           PRINT 100
105     DO 70 J= 1,N3
           NA = N(J)

```

```

DO 35 I=1,NA
  XN(I,J) = ABS(X(I,J)-WIDTH)
  YN(I,J) = Y(I,J)
110 PRINT 33, (XN(I,J),I=1,NA)
  PRINT 33, (YN(I,J),I=1,NA)
  70 PRINT 100
  PRINT 146
115 146 FORMAT(1X,23HDM(I,J),IN(I,J),JN(I,J))
  PRINT 100
  DO 71 J=2,N2
    IF(2-J) 127,128,128
    127 IF(N2-J) 129,129,130
    128 L1=J
    120 L2=J+1
    GO TO 131
    129 L1=J-1
    L2=J
    GO TO 131
    125 130 L1=J-1
    L2=J+1
    131 NA=N(J)-1
    DO 36 I=2,NA
      DM(I,J)=WIDTH
      DO 36 L=L1,L2
      DO 36 K=2,NA
        D = SQRT((X(I,J)-XN(K,L))**2. + (Y(I,J)-YN(K,L))**2.)
        IF(DM(I,J)-D) 36,38,38
      38 DM(I,J) = D
    135 IN(I,J) = K
    JN(I,J) = L
    36 CONTINUE
    PRINT 33, (DM(I,J),I=2,NA)
    PRINT 80, (IN(I,J), I = 2,NA)
    140 PRINT 80, (JN(I,J),I=2,NA)
    80 FORMAT(1X,30I4)
    71 PRINT 100
    PRINT 147
    145 147 FORMAT(20H XM(I,J), YN(I,J) )
    PRINT 100
    DO 24 J=1,N2
      NA = N(J) -1
      DO 30 I=1,NA
        IF(NA-1-I) 41,23,22
    150 22 XM(I,J) = (X(I,J)+X(I+1,J)+X(I+1,J+1)+X(I,J+1))/4.0
        YN(I,J) = (Y(I,J)+Y(I+1,J)+Y(I+1,J+1)+Y(I,J+1))/4.0
        GO TO 30
    23 IF(NT(J+1)) 22,22,21
    21 XM(I,J) = (X(I,J)+X(I+1,J)+X(I,J+1))/3.0
    155 YN(I,J) = (Y(I,J)+Y(I+1,J)+Y(I,J+1))/3.0
    GO TO 30
    41 IF(NT(J+1)) 22,22,42
    42 XM(I,J)=(X(I,J) + X(I+1,J) + X(I-1,J+1) + X(I,J+1))/4.0
    YN(I,J)=(Y(I,J) + Y(I+1,J) + Y(I-1,J+1) + Y(I,J+1))/4.0

```

160

30 CONTINUE

PRINT 31, (XM(I,J),I=1,NA)

PRINT 31, (YM(I,J),I=1,NA)

PRINT 100

31 FORMAT(1X,16E8.3)

165

24 CONTINUE

SUMA = 0.0

DO 25 J=2,N2

NB = N(J)-1

DO 25 I=2,NB

170

IF(NB-1) 26,27,26

26 AR(I,J) = 0.5 * ((YM(I-1,J-1) * (XM(I,J-1) - XM(I-1,J))) + (YM(I,J-1) *

1 (XM(I,J) - XM(I-1,J-1))) + (YM(I,J) * (XM(I-1,J) - XM(I,J-1))) +

2 (YM(I-1,J) * (XM(I-1,J-1) - XM(I,J))))

AR(I,J) = ABS(AR(I,J))

GO TO 29

175

27 IF(NT(J) 126,26,28

28 AR(I,J) = 0.5 * ((YM(I,J-1) * (XM(I+1,J-1) - XM(I-1,J-1))) + (YM(I+1,J-1)

1 * (XM(I,J) - XM(I-1,J-1))) + (YM(I,J) * (XM(I-1,J) - XM(I+1,J-1)))

2 + (YM(I-1,J) * (XM(I-1,J-1) - XM(I,J))) + (YM(I-1,J-1) *

180

3 (XM(I,J-1) - XM(I-1,J))))

AR(I,J) = ABS(AR(I,J))

29 SUMA = SUMA + AR(I,J)

25 CONTINUE

PRINT 148

185

148 FORMAT(10H AR(I,J))

PRINT 100

DO 32 J=2,N2

NB = N(J)-1

190

32 PRINT 33, (AR(I,J),I=2,NB)

33 FORMAT(1X,16F8.4)

PRINT 100

PRINT 149

149 FORMAT(10H SUMA)

PRINT 100

195

PRINT 34, SUMA

34 FORMAT(1X,E15.8)

PRINT 100

PRINT 500

500 FORMAT(14H XLGTH, YLGTH)

200

PRINT 100

DO 13 J=1,N2

NA = N(J) - 2

DO 18 I=1,NA

XLGTH(I,J) = X(I+1,J) - X(I,J)

205

18 YLGTH(I,J) = SQRT((X(I,J+1) - X(I,J))**2. + (Y(I,J+1) - Y(I,J))

1**2.)

NB = N(J) - 1

II = N(J + 1) - 1

XLGTH(I,J) = 0.0

210

YLGTH(I,J) = Y(II,J+1) - Y(NB, J)

PRINT 37, (XLGTH(I,J), I=1, NB)

PRINT 37, (YLGTH(I,J), I = 1,NB)

```

13 PRINT 100
215 37 FORMAT (1X,16F8.4)
    PRINT 100
    ND = 0
    TH = THP
    PC=PCP
    OVP=OVPP
220 83 IF(ND) 84,84,85
    84 ND = ND + 1
    GO TO 86
    85 TH = THN
    PC=PCN
    OVP=OVPN
225 ND = ND + 1
    86 READ 66, (IOD(J),J=2,N2)
    PRINT 54, (IOD(J),J=2,N2)
230 READ 82, (XC1(J),J=2,N2)
    PRINT 56, (XC1(J),J=2,N2)
    READ 82, (XC2(J),J=2,N2)
    PRINT 56, (XC2(J),J=2,N2)
    READ 66, (JOD(I), I=2,M2)
    PRINT 54, (JOD(I), I=2,M2)
235 READ 82, (YC1(I), I=2,M2)
    PRINT 56, (YC1(I), I=2,M2)
    READ 82, (YC2(I), I=2,M2)
    PRINT 56, (YC2(I), I=2,M2)
240 66 FORMAT(20I4)
    82 FORMAT(10E8.3)
    54 FORMAT (33I4)
    56 FORMAT (1X,16E8.3)
    PRINT 100
245 DO 63 J=2,N2
    NA = N(J) - 2
    DO 63 I = 2, NA
    ID = IOD(J) - 1
    IF(I - ID) 64,64,65
250 64 XC(I,J) = ((X(I,J) + X(I+1,J))/ (X(ID+1,J)))*.5*(XC2(J) - XC1(J))
    1 + XC1(J)
    GO TO 63
    65 XC(I,J) = XC2(J)
    63 CONTINUE
255 DO 39 J = 2, N1
    NA = N(J) - 2
    DO 39 I = 2, NA
    JD = JOD(I) - 1
    IF (J - JD) 40, 40, 50
260 40 YC(I,J) = ((Y(I,J) + Y(I,J+1))/ (Y(I,JD+1)))*.5*(YC2(I) - YC1(I)) + YC1(I)
    GO TO 39
    50 YC(I,J) = YC2(I)
    39 CONTINUE
    JD = JOD(M2)
    IH = N(JD) - 1
265 DO 67 J = 2, N1

```

```

      I= N(J) - 1
      II = N(J) - 2
      IF (JD-J) 68,68,69
270 69 YC(I,J) = (Y(I,J) + Y(II,J+1))/Y(IN,JD)*.5*(YC2(M2)-YC1(M2))
      1 + YC1(M2)
      GO TO 67
      68 YC(I,J) = YC2(M2)
      67 CONTINUE
      J = N2
275      NA = N(J) - 1
      DO 74 I = 2, NA
      74 YC(I,J) = 0.00
      PRINT 150
280 150 FORMAT(17H XC(I,J) YC(I,J))
      DO 75 J = 2, N2
      NA = N(J) - 2
      PRINT 76, IXC(I,J), I= 2, NA)
      NA = N(J) - 1
      75 PRINT 76, IYC(I,J), I= 2, NA)
285 76 FORMAT(1X, 22F6.4)
      PRINT 100
      VOL = 0.
      PRINT 159
290 159 FORMAT(22H XVOL(I,J),YVOL(I,J) )
      PRINT 100
      DO 89 J=2,N2
      NB = N(J)-2
      DO 157 I=2,NB
      XVOL(I,J) = XLGTH(I,J)*XC(I,J)
295 157 VOL = VOL + XVOL(I,J)
      NB = N(J)-1
      DO 158 I=2,NB
      YVOL(I,J) = YLGTH(I,J)*YC(I,J)
      158 VOL = VOL + YVOL(I,J)
300      NB=N(J)-2
      PRINT 37, (XVOL(I,J), I=2,NB)
      NB=N(J)-1
      PRINT 37, (YVOL(I,J), I=2,NB)
      89 PRINT 100
305      PRINT 160
      160 FORMAT(15H TOTAL VOLUME )
      PRINT 100
      PRINT 37, VOL
      E=SPC
310      P = PC*(TH + OVP)
      DO 58 J=2,N1
      NA = N(J)-2
      DO 58 I=2,NA
      XCON(I,J) = ((E - PC)*XC(I,J) / XLGTH(I,J))
      1 +P*(Y(I,J)-Y(I,J-1))*(XLGTH(I,J-1)+3.*XLGTH(I,J))+Y(I,J+1)-
      2 Y(I,J))*3.* XLGTH(I,J) + XLGTH(I,J+1))/ (8.*(XLGTH(I,J)**2.))
      XTEST = XCON(I,J) - ((E)*C(I,J) +PC*(XC(I,J)/TH)*OVP)/XLGTH(I,J)
      IF (XTEST) 78, 79, 79

```



```

320 78 XCON(I,J) = (E*XC(I,J) + PC*(XC(I,J)/TH)*OVP) /XLGTH(I,J)
79 YCON(I,J) = ((E - PC)*YC(I,J) /YLGTH(I,J))
1+P*((Y(I,J+1)-Y(I,J))*( XLGTH(I-1,J)+XLGTH(I-1,J+1)+XLGTH(I,J)+
2 XLGTH(I,J+1))/(4.*(YLGTH(I,J)**2.))
YTEST = YCON(I,J) - ((E*YC(I,J) +PC*(YC(I,J)/TH)*OVP)/YLGTH(I,J))
IF (YTEST) 92, 58, 58
325 92 YCON(I,J) = (E*YC(I,J) + PC*(YC(I,J)/TH)*OVP) /YLGTH(I,J)
58 PRINT 77, I,J,TH,OVP,P,PC,X(I,J),Y(I,J),XLGTH(I,J),YLGTH(I,J)
1 , XCON(I,J),YCON(I,J)
77 FORMAT (1X,2I4,10F10.4)
J=N2
330 NA=N(J)-2
DO 59 I=2,NA
XCON(I,J) = ((E - PC)*XC(I,J) / XLGTH(I,J))
1 +P*((Y(I,J)-Y(I,J-1))*(XLGTH(I,J-1)+3.*XLGTH(I,J)))/(8.*(XLGTH(I,
2 J)**2.))
335 XTEST = XCON(I,J) - ((E*XC(I,J) +PC*(XC(I,J)/TH)*OVP)/XLGTH(I,J))
IF (XTEST) 93, 94, 94
93 XCON(I,J) = (E*XC(I,J) + PC*(XC(I,J)/TH)*OVP) /XLGTH(I,J)
94 YCON(I,J) = 0.0
59 PRINT 77, I,J,TH,OVP,P,PC,X(I,J),Y(I,J),XLGTH(I,J),YLGTH(I,J)
340 1 , XCON(I,J),YCON(I,J)
DO 61 J=2,N1
I = N(J)-1
XCON(I,J) = 0.0
YCON(I,J) = ((E - PC)*YC(I,J) /YLGTH(I,J))
345 1 +P*((Y(I-1,J+1)-Y(I-1,J))*(XLGTH(I-1,J)+XLGTH(I-1,J+1))/(4.*
2 (YLGTH(I,J)**2.))
YTEST = YCON(I,J) - ((E*YC(I,J) +PC*(YC(I,J)/TH)*OVP)/YLGTH(I,J))
IF (YTEST) 95, 61, 61
95 YCON(I,J) = (E*YC(I,J) + PC*(YC(I,J)/TH)*OVP) /YLGTH(I,J)
350 61 PRINT 77, I,J,TH,OVP,P,PC,X(I,J),Y(I,J),XLGTH(I,J),YLGTH(I,J)
1 , XCON(I,J),YCON(I,J)
DO 60 J = 1,N3
NA = N(J)
355 NB = N(J)-1
DO 60 I = 1,NA,NB
XCON(I,J) = 0.0
60 YCON(I,J) = 0.0
DO 62 J=1,N3,N2
NA = N(J)
360 DO 62 I=1,NA
XCON(I,J) = 0.0
62 YCON(I,J) = 0.0
XCON((N(N2)-1),N2) = 0.0
YCON((N(N2)-1),N2) = 0.0
365 PRINT 151
151 FORMAT (23H XCON(I,J), YCON(I,J) )
PRINT 100
DO 72 J = 1,N3
NA = N(J)
370 PRINT 73, XCON(I,J), I = 1,NA)
PRINT 73, YCON(I,J), I = 1,NA)

```

```

73 FORMAT(1X,11E12.4)
72 PRINT 100
MM=0
375 DO 43 J=2,N2
43 MM=MM+(N(J)-2)
PRINT 152
152 FORMAT(32H          MM          LL)
PRINT 100
380 LL = 2*(N(1)-2)+1
PRINT 90,MM,LL
90 FORMAT(8I16)
PRINT 100
385 DO 44 M=1,MM
TAB(M) = 0.0
DO 44 L=1,LL
44 A(M,L) = 0.0
TAB(ITAB1) = TAB1*TH
TAB(ITAB2) = TAB2*TH
390 TAB(ITAB3) = TAB3*TH
L=1
M=N(2)-2
NC = 3
395 K = 2*N(2) - 3
PRINT 153
153 FORMAT(128H          I          J          L          NC
1 K          N(J)
2 NT(J))
PRINT 100
400 DO 45 J=3,N2
NA=N(J)-1
DO 45 I=2,NA
M=M+1
405 NC = NC + 1
IF(I-NA) 46,47,47
46 A(M,L) = YCON(I,J-1)
A(NC,K) = A(M,L)
PRINT 90, M, L, NC, K, I, J, N(J), NT(J)
GO TO 49
410 47 A(M,L) = YCON(I,J-1)
A(NC,K) = A(M,L)
PRINT 90, M, L, NC, K, I, J, N(J), NT(J)
IF(NT(J)) 49,49,48
49 GO TO 45
415 48 L=L+1
K = K - 1
NC = NC + 1
A(M,L) = YCON(I+1,J-1)
A(NC,K) = A(M,L)
420 PRINT 90, M, L, NC, K, I, J, N(J), NT(J)
45 CONTINUE
PRINT 100
L=N(1)-2
M = 1

```

```

425      DO 125 J = 2,N2
          NA = N(J)-1
          DO 125 I = 2,NA
              M = M + 1
          A(M,L) = XCON(I,J)
430      125 A(M-1,L+2) = A(M,L)
          L = N(I)-1
          M = 0
          DO 51 J = 2,N2
              NA = N(J)-1
435      DO 51 I = 2,NA
              M = M + 1
              IF(I-NA) 52,53,53
          52 A(M,L) = -(XCON(I-1,J) + XCON(I,J) + YCON(I,J) + YCON(I,J-1) +
              1CE*AR(I,J) + TAB(M))
          GO TO 51
440      53 IF(NT(J)) 52,52,55
          55 A(M,L) = -(XCON(I-1,J) + YCON(I,J-1) + YCON(I+1,J-1) + YCON(I,J) +
              1CE*AR(I,J) + TAB(M))
          51 CONTINUE
445      PRINT 154
          154 FORMAT(64H
              1      K)
              PRINT 100
              PRINT 90, M,L,NC,K
450      PRINT 100
              WRITE(50) A
              PRINT 100
              IF(ND-1)87,87,88
          87 GO TO 83
455      88 NSUM(2) = 0
          DO 123 J = 2,N1
          123 NSUM(J+1) = NSUM(J) + N(J) - 2
          DO 91 J=2,N2
              NA = N(J)-1
          DO 91 I=2,NA
              M = NSUM(J) + I - 1
              JN1J = JN(I,J)
              MN(M) = NSUM(JN1J) + IN(I,J)-1
          91 AR(M) = AR(I,J)
465      PRINT 156
          156 FORMAT(25H MM, LL, MN(M), M=1,MM )
              PRINT 100
              PRINT 126, MM, LL, (MN(M), M=1,MM)
          126 FORMAT (1X,16I8)
470      TAB(I TAB1) = TAB1*THP
              TAB(I TAB2) = TAB2*THP
              TAB(I TAB3) = TAB3*THP
              WRITE(50)
              MN, TAB, AR, N, NSUM, CE, AHP, MM, LL,
          1 M2, N2
475      END

```

```

1      PROGRAM LEV(INPUT,OUTPUT,DEBUG=OUTPUT, TAPE50)
      C      SOLVING A MATRIX FROM STORED DATA WITH ITERATION
      C      ESR EXPTL RADIAL GRID 1EVR,2EVR. MATRIX SOLUTION
      DIMENSION A(496,496), MM(496), TAB(496), ARM(496), N(27), NSUM(27),
5      1 BN(496,1), EP(496), EN(496), BP(496,1), DP(496), DPA(496),
      2 DN(496), DNA(496), PNPP(496), PNPNI(96), CD(496), XL(12400),
      3 CONDIF(496)
      CS      ARRAYS
      READ 120, IMAX, CRIT
10      120 FORMAT(I4, F8.6)
      PRINT 129, IMAX, CRIT
      129 FORMAT(1X, I4, E15.8)
      PRINT 100
      READ(50) A
      READ(50) A
15      READ(50) MM, TAB, ARM, N, NSUM, CE, AMP, MM, LL, M2, N2
      PRINT 126, MM, LL, (MM(M), M = 1,MM)
      126 FORMAT(1X, 32I4)
      PRINT 101
      20      PRINT 123, (TAB(I), I=1,MM)
      123 FORMAT(1X, 13E10.3)
      PRINT 100
      DO 92 M=1,MM
      25      DN(M,1) = 0.0
      EP(M) = 1.0
      92      EN(M) = 0.0
      ITER = 0.
      110 REWIND 50
      READ(50) A
      30      DO 93 M=1,MM
      MNM = MM(M)
      93      BP(M,1) = -TAB(M) -CE*ARM(M)*BN(MNM,1)
      CALL RESULT( BP,NSUM,N,N2)
      PRINT 100
      35      NLC = N(1)-2
      PRINT 122,NLC
      122 FOPMAT(I10)
      CALL LEQ11B(A, MM, NLC, NLC, MM, BP, 1, MM, 0, XL, IER)
      DO 94 M=1,MM
      40      DP(M)= BP(M,1)-EP(M)
      DPA(M) = ABS(DP(M))
      EP(M) = BP(M,1)
      MNM = MM(M)
      94      BN(M,1) = -CE*ARM(M)*BP(MNM,1)
      45      PRINT 100
      CALL RESULT( BP,NSUM,N,N2)
      PRINT 100
      100 FORMAT (/)
      96      FORMAT (1X,12E11.4)
      50      READ(50) A
      CALL LEQ11B(A, MM, NLC, NLC, MM, BN, 1, MM, 0, XL, IER)
      DO 98 M=1,MM
      BN(M) = EN(M,1) -EN(M)

```

```

55      DNA(M) = ARS(DNM(M))
58      EN(M) = BN(M,1)
      CALL RESULT( RN,NSUM,N,N2)
      PRINT 100
      PRINT 100
      DPM = DPA(1)
      DNM = DNA(1)
      DO 99 M=2,MN
      IF (DPM - DPA(M)) 108,101,101
108     DPM = DPA(M)
      GO TO 101
65     101 IF (DNM - DNA(M)) 102,99,99
      102 DNM = DNA(M)
      99 CONTINUE
      PRINT 103
      103 FORMAT(24H DPMAX DNMAY )
      PRINT 104, DPM, DNM
70     104 FORMAT (2E12,4)
      PRINT 100
      ITER = ITER + 1
      IF(CRIT-DPM)105,106,106
75     106 IF(CRIT-DNM)105,107,107
      105 IF(IMAX-ITER) 109,109,110
      107 CSUM = 0.0
      NC = 0
      PRINT 111
83     111 FORMAT(1H1)
      PRINT 112
      112 FORMAT(29H POSITIVE GRID POTENTIALS )
      PRINT 100
      CALL RESULT( BP,NSUM,N,N2)
85     PRINT 100
      PRINT 111
      PRINT 124
      124 FORMAT (29H NEGATIVE GRID POTENTIALS )
      PRINT 100
90     CALL RESULT( RN,NSUM,N,N2)
      PRINT 111
      DO 116 M=1,MN
      DNM = RN(M)
      PNPP(M) = BP(M) - RN(MNM)
      PNP(M) = BP(MNM) - RN(M)
95     116 CSUM = CSUM + PNPP(M)*CE*ARM(M)
      GO TO 125
      113 CSUM = 0.
      DO 115 M=1,MN
      MNM = MN(M)
100     115 CSUM = CSUM + PNP(M)*CE*ARM(M)
      NC = NC + 1
      125 VOLT = APP/CSUM
      PRINT 118
105     118 FORMAT(11H VOLTS )
      PRINT 119 , VOLT

```



```

119 FORMAT(1X,E15.0)
PRINT 100
AREA = 0.0
110 SCODIF=0.0
SSOCOD=0.0
DO 121 M=1,NM
121 AREA = AREA + ARM(M)*2.
COAVE = AMP/AREA
115 DO 117 M=1,NM
CO(M) = VOLT*PNPP(M)*CE/2.
CODIF(M) = CO(M) - COAVE
SCODIF = SCODIF + (ABS(CODIF(M)))*ARM(M)
117 SSOCOD = SSOCOD + (CODIF(M)**2.)*ARM(M)
ACODIF = (SCODIF/AREA)/COAVE
120 RTMSCD = ((SSOCOD/AREA)/COAVE)**.5
PRINT 119, AREA, COAVE, SCODIF, SSOCOD, ACODIF, RTMSCD
PRINT 100
PRINT 130, CSUM
125 130 FORMAT(1X, 8E15.8)
PRINT 111
PRINT 120
120 FORMAT(5X, CURRENT DENSITY AT GRID SECTIONS AMP/SD INCH )
CALL RESULT( CO, NSUM, N, M2)
130 IF (NC) 113, 113, 114
114 CALL RESULT( ARM, NSUM, N, M2)
PRINT 100
CALL RESULT( PNPP, NSUM, N, M2)
PRINT 100
135 CALL RESULT( PNPH, NSUM, N, M2)
PRINT 100
109 END

```

SYMBOLIC REFERENCE MAP (R=3)

ENTRY POINTS

DEF LINE

REFERENCES

3216 LEV

1

VARIABLES

SN

TYPE

RELOCATION

5050

A

REAL

ARRAY

REFS

4

38

51

DEFINED

14

15

29

5946

ACODIF

REAL

REFS

122

DEFINED

120

5922

AMP

REAL

REFS

103

114

DEFINED

16

5042

AREA

REAL

REFS

113

114

120

121

122

DEFINED

109

113

66370

4PM

REAL

ARRAY

REFS

4

32

44

96

101

113

110

67476

BN

REAL

ARRAY

REFS

4

32

51

53

55

56

90

72356

BP

REAL

ARRAY

REFS

4

33

38

40

42

44

46

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