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Volume 1
Design Study
(NON-PROPRIETAR)

Argonne National Laboratory
Contract No. 31-109-38-3621

**COST AND DESIGN STUDY TO
DEVELOP LEAD-ACID BATTERIES
FOR ELECTRIC VEHICLE PROPULSION**

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ESB INCORPORATED

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Cost and Design Study Submitted to the Argonne National Laboratory
in response to ANL Contract No. 31-109-38-3621

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Executive Summary

At the present time two markets for EV batteries are being supplied by the existing battery industry. The first is the industrial truck which requires a long life heavy duty battery with volume energy density of greater importance than weight energy density. The second is a rapidly growing golf car market which requires a low cost battery of medium life and medium weight energy density.

No market presently exists for on-the-road vehicle batteries. Industry is naturally reluctant to totally fund the development of such batteries without a significant probability of a future market. If the development is left solely to private industry funding, the situation of no market without the proper battery and no battery development without a market will continue.

Government support of electric vehicles and EV batteries is essential to resolution of this stalemate. By acting as a catalyst, the Federal Government can initiate an electric vehicle industry which would be advantageous to the economy, ecology and energy situation in the United States.

In response to the Statement of Work (Appendix B) of the Argonne National Laboratory Contract No. 31-109-38-3621, ESB Incorporated submits a design and cost study for electric vehicle lead-acid batteries and also proposes a 48 month research and development program which will lead to demonstration and testing of 20 to 30 kilowatt-hour lead-acid batteries for electric vehicles within 24 months for Improved-State-of-the-Art (ISOA) batteries and within 48 months for the Advanced batteries. It is recognized that the tasks and goals involved may be revised somewhat during the program - particularly during the 2nd, 3rd, and 4th years for the Advanced battery concept. The contents of this report and proposal represent both work done under the aforementioned ANL contract and work done by ESB in the course of a separate but correlative effort conducted at ESB's own expense.

ESB proposes two approaches for the Improved State-of-the-Art battery, one utilizing the flat pasted plate type and the other utilizing the tubular positive plate type. The rationale is that this dual approach minimizes the risks while maximizing the probability of developing the best final battery within the two year period. The flat pasted plate battery currently manifests the lowest cost and highest specific energy (Wh/kg), while the tubular battery has the longest life. By approaching the development and demonstration goals from these two directions, the chance of success is virtually assured.

ESB will immediately undertake a preliminary flat pasted plate design (FP-1) which will allow certain developmental efforts to be completed while long lead time components are being specified, ordered, manufactured and delivered for the final flat pasted plate version (FP-2). Work on the FP-2 battery will start in the 26th week of the contract.

At the same time a parallel program will be undertaken on the tubular positive plate battery (TP-1). This design will incorporate thin positive plates made from tubular elements for the positive electrodes of the battery. The negative plates and most other aspects will be identical with the FP design. In addition to optimizing the performance of the TP-1 battery, work will be done on techniques to lower the cost of construction of the tubular positive plates.

The ultimate selection between the FP and TP designs is expected to occur at about the 73rd week of the contract, although it is possible that an earlier selection will occur. This will allow ample time for the construction and delivery of fifteen complete electric vehicle batteries to ANL on schedule for testing. ANL will participate in making the decision as to whether the pasted plate or the tubular plate design will be chosen for final testing.

In this proposal ESB has provided detailed drawings and specifications of cell components which will be studied during the program. Performance data of the proposed system is specified, along with the preferred method of charging, including quick recharge. The developmental problems are addressed for the FP and TP ISOA program and a detailed series of experiments are specified to achieve solutions.

Flow diagrams for the projected manufacturing processes are provided and discussed. A floor plan of the pilot production facility is given and capital investment estimates have been calculated. Environmental impact and materials requirements have been estimated. Manufacturing cost estimates of the battery at the pilot and production stages have been calculated and cost breakdowns specified in the accompanying Cost Study volume.

Test procedures and test standards for the specification of battery/cell capacity, power and cycle life have been stated. Pre and post-test examinations specific to the lead-acid battery have been defined. A representative quality assurance manual has been written to cover all phases of the program, and is included in Appendix 3.

In order to develop the Advanced battery, ESB will focus its main effort on a tubular plate approach. The advanced tubular battery approach will use novel composite materials in the plate construction to minimize the amount of lead used as support material. Experimental designs and concepts beyond the present state-of-the-art will be tried to eliminate weight, increase active material utilization, and decrease internal resistance. Initial designs of this battery are included in the proposal.

Additionally, a limited initial effort on development of a bipolar or pile type battery will be undertaken. This will include a program to solve the main problem in bipolar battery development - the partition. Only if this one calendar year, two man-year, effort is successful, will bipolar battery development be continued, otherwise only the Advanced tubular concept will be pursued from this point on.

Battelle Laboratories in Columbus, Ohio (BCL) has been chosen as a sub-contractor to provide computer designs and evaluation of grid structures to be used in both the ISOA and Advanced batteries. BCL will also undertake a computer study to predict the usable energy available from a given lead-acid battery when it is subjected to complex power-time profile discharges. This capability will prove invaluable in sizing batteries for specific vehicles with known driving cycles and for predicting the range of any vehicle-battery-driving cycle combination.

ESB also proposes to evaluate certain single-point watering systems for lead-acid batteries. Such systems are an important component for battery powered vehicles and will remain so unless and until deep-cycle maintenance free batteries are available. Failure to implement such a system would necessitate that vehicle operators separately check and refill approximately sixty individual cells with water as routine maintenance.

2 R & D OBJECTIVES

The goals of the proposed research and development effort are to completely design, evaluate, and construct two grades of electric vehicle batteries - Improved State of the Art (ISOA) and Advanced - with performance characteristics shown in Table 2-1. The ISOA battery development program will involve modifying existing battery concepts in order to improve performance and decrease cost of certain components. The Advanced battery development program, on the other hand, will involve radical departures from standard battery concepts in order to eliminate significant quantities of lead normally present in batteries and not used as electrochemically active material.

In order to accomplish these objectives many varied tasks, experiments, and tests have been detailed and will be thoroughly discussed in subsequent sections of the proposal. In general, however, one of the main efforts pervading this work involves developing methods for holding the positive and negative active material in place and efficiently exchanging electronic current with it in the lightest, most compact, and inexpensive manner possible.

In addition to the battery research, design and development, manufacturing economics were established for the ISOA system at two production levels. As part of this effort, flow diagrams have been drawn. The capital investments for a pilot facility and a full production facility have been estimated. Information on resources and ecological impact studies are presented. Manufacturing of the battery at the pilot and production stages has been estimated, with detailed cost breakdowns and discussion of all assumptions involved

Table 2-1

Performance Characteristics
Of ISOA and Advanced Batteries

	ISOA	ADVANCED
Duty Cycle:	2-4 hr Discharge 4-8 hr Charge	2-4 hr Discharge 4-8 hr Charge
Energy Efficiency: (Turn-Around)	> 60%	>60%
Cycle Life:	800 cycles	1000 cycles
Installed Cost (1976 Dollars)	\$50/kWh	\$40/kWh
Specific Energy:	40Wh/Kg (18 Wh/lb) @ C/3 rate	60Wh/Kg (27 Wh/lb) @ C/3 rate
Specific Power:	20W/Kg sustaining (9 W/lb) 100 W/Kg peak (45 W/lb)	30 W/Kg sustaining (13.6 W/lb) 150 W/Kg peak (68 W/lb)
Typical Installation Size:	20-30 kw-hr	20-30 kw-hr
Environmental Impact:	Minimal	Minimal

3 TECHNICAL - Support Research and Development Activities

3.1 Introduction

Government sponsored lead acid electric vehicle battery development has been undertaken in Japan. In other countries of the world the little development which has occurred has been funded with private capital. Information from Japan suggests that the ISOA battery goals can be met, although reliable confirmation of 40 Watt Hours per Kg with 800 charge-discharge cycles has not been forthcoming. We are not aware that the Japanese battery industry has offered for commercial sale batteries meeting the ISOA goals.

In Europe, electric vehicle development has been along the lines of commercial vehicles rather than passenger vehicles. The trip distances chosen for these vehicles have been rather short so that the requirement has been for a long life battery having an energy density in the range of 25-30 Watt hours per Kg.

In the USA, a competitive market has developed over the last 10 years for golf car batteries. The need for extremely light batteries has not emerged in the golf car market. This is because the duty cycle is related to a very precisely predetermined trip - 18 golf course holes. Often the car must make only one 18 hole trip per charge but on more active golf courses two trips may be needed. It is only in very rare instances that a single car would be able to fit 3 trips into available daylight hours. It has been found that a battery of 27.5 watt hours per Kg is satisfactory for the more active courses and 20 watt hours per Kg will satisfy the less active courses. ESB offers both types of batteries for sale commercially. Advanced design batteries for golf car and other use have been made. The EV - 115, in pilot production, has a life at 100% depth of discharge of 800 cycles. Another developmental battery which has been used in a number of prototype electric vehicles is the EV-140. This battery has an energy density of 35 watt hours per Kg. However, its cycle life is short - under 300 cycles.

The EV-115 and EV-140 designs were developed at the ESB Technology Center. A most recent ESB development and one that is still in the pre-production stage is a greatly improved positive active material paste. The improvement results in a positive plate that has increased cycle life and higher energy density.

In the industrial battery area, ESB has had a long and successful production history with the tubular type battery. The tubular battery makes use of a truly composite (i.e., metal and non-metal) positive grid structure. With this construction the weight of the positive grid for a given battery size is less than the weight of the more usual flat type positive grid of the same capacity and life capability. Further, the weight of active material per ampere hour of capacity is less than the comparable flat plate battery. The tubular battery in Europe has developed along slightly different lines from the U.S. development. The European designs favor a battery for high rate discharges more so than do the present U.S. designs. ESB has recently acquired a prominent manufacturer of high performance tubular type lead acid industrial storage batteries; namely AB Tudor of Sweden, a leader in the design and fabrication of tubular assembly techniques.

In this proposal a dual approach is offered for the ISOA development, involving flat plate technology on the one hand and tubular plate technology on the other.

The flat plate program involves a re-design of the existing EV-140 battery to reduce its weight while maintaining its high energy output. The steps by which the energy density and the cycle life will be brought up to the ANL requirements are fully detailed herein.

In the tubular battery development the principal problems relate to the design and processing of an extremely thin tubular type positive plate. Calculations indicate that this design will out-perform the flat plate design in energy density, and should have no difficulties in meeting the life cycle requirement.

It is expected, however, that in initial phases of production the tubular design battery will be more expensive than the flat plate battery. The higher cost of the tubular battery will be offset by its improved life and the life cycle cost to the user will be less.

The major developments for the flat plate battery include:

1. Positive active material composition and density.
2. Reduction of negative grid weight.
3. Optimization of acid strength and acid volume.
4. Separator optimization.
5. Improved positive grid design.

Tubular design developments include all of the above plus:

6. Improved tubular plate filling methods
7. Improved tubular plate processing.

The Advanced battery goals require a radical departure from state-of-the-art and ISOA lead acid batteries. The high specific energy (Wh/Kg) requirements mean that lead can no longer be used indiscriminately as a convenient current collector and as a supporting member for the active material. The amount of lead in the battery that is not used electrochemically must be kept to an absolute minimum.

Two battery designs have the potential of meeting the Advanced lead acid battery goals. One is the tubular positive plate battery, and the other is the bipolar, or pile type battery. The tubular positive plate battery, which has been described in the ISOA battery discussion, has shown long life and good active material utilization. By combining the advantages of a unique proprietary active material that ESB has had under development for some time, with novel materials such as plated and/or coated lightweight metal and plastic current collectors, and with an innovative negative plate design, the Advanced goals should be met. As with any new, untried technology there are risks and uncertainties, but these will be minimized by thorough planning, experimental design and testing.

The other lead-acid system that shows promise of fulfilling the Advanced battery requirements is the bipolar battery which has demonstrated in the past extremely high energy density but very poor cycle life. The crucial element of this battery, the partition, has always been the weak link. The partition must be electronically conductive, ionically non-conductive, resistant to sulfuric acid attack at the battery's operating potential, lightweight, hermetically sealable at the the edges, leakproof, able to support and maintain good interfacial contact with positive active material on one side and negative active material on the other, and finally, must be inexpensive.

If this one element- the partition - can be developed satisfactorily, the bipolar battery has an excellent chance of meeting the Advanced battery goals and becoming a true breakthrough in battery technology. ESB has had a successful record in bipolar battery developments with the silver-zinc couple and has made significant advances in novel partition material technology. These facts dictate that both the tubular plate and the bipolar approaches be pursued for the Advanced battery development program.

Specifically, ESB proposes a major effort on the tubular approach to increase specific energy and reduce cost, and a secondary effort on the bipolar battery which would focus on challenging partition concepts. Assuming that success or significant progress is achieved in a relatively short time (one calendar year - consisting of a two man-year effort) on the partition problem, the bipolar activity will then be pursued further. This timetable will meet the Advanced battery goals in the four year period.

3.2 Overall Program Activities

Figure 3-1 shows an activity chart for the overall ANL electric vehicle lead acid battery demonstration phase effort. The digits at the upper left and right of the activity boxes refer to weeks after the award of the contract and the difference between these two numbers indicates the activity period. The two main efforts involving the Improved State-of the-Art (ISOA) battery and the Advanced battery will start at the same time. The ISOA program will be completed in two years, and the Advanced program in four. The simultaneous development effort during the first twenty-four months will have a synergistic effect in that certain developments will be mutually beneficial to both systems.

The boxes in Fig. 3-1 labeled "ISOA Program Reduction to Practice" and "Advanced Program Reduction to Practice" are discussed in detail later and are schematically summarized in Figures 3-2 and 3-3 respectively.

COMPLETE DEMONSTRATION PHASES ISOA & ADVANCED CONCEPTS

DESIGNED BY EPN		DATE 11/24/76		ESB INCORPORATED	
DRAWN BY B.C.K.		DATE 2/77		RESEARCH CENTER	
MATERIAL				YARLEIGH, PENNSYLVANIA	
DO NOT SCALE DRAWING					
PERMITTED BY		APPROVED BY		DATE 11/24/76	
BY		BY		REV 1 11/24/76	
BY		BY		REV 2 11/24/76	
BY		BY		REV 3 11/24/76	
BY		BY		REV 4 11/24/76	
BY		BY		REV 5 11/24/76	
BY		BY		REV 6 11/24/76	
BY		BY		REV 7 11/24/76	
BY		BY		REV 8 11/24/76	
BY		BY		REV 9 11/24/76	
BY		BY		REV 10 11/24/76	

Figure 3-1

DEMONSTRATION PHASE - ISOA PROGRAM - REDUCTION TO PRACTICE

Figure 3-2

DEMONSTRATION PHASE - ADVANCED BATTERY PROGRAM - REDUCTION TO PRACTICE

DATE <u>1/10</u>		TIME <u>2:17</u>		ESB INCORPORATED
BY <u>46 M</u>				RESEARCH CENTER		
REVISION				WADSWORTH, PENNSYLVANIA		
DO NOT SCALE DRAWING						
POSITION	REVISION	DATE	DRAWING NO.			
4	8		FC 9231000			

Figure 3-3

4. OPTIMUM CONFIGURATION AND CAPACITY SIZE FOR THE ISOA BATTERY

4.1 Introduction

The purpose of this discussion is to determine the optimum configuration for a lead acid electric vehicle battery having a total energy content of approximately 20 kWh. As a broad generality, the configuration of a battery to perform a specific duty can be varied over a wide range of geometries without greatly changing its specific energy. It is, therefore, necessary to look for small differences and details, since this is where weight and other optimizing features will be found. A discussion of the salient variables follows.

4.2 Battery energy content.

A first requisite in the design of the ANL Electric Vehicle Battery is a statement of the total energy which the battery is expected to deliver. This must be qualified as to whether it represents complete discharge or somewhat less than complete, such as 80%. The value should interface with the value used for life testing. ESB assumed a life cycle rating of 16.2 kWh when discharged for 2.4 hours at the 3 hour rate and a full capacity rating of 20 kWh at the 3 hour rate when discharged to an end voltage of 1.75 volts per cell. On this basis the life cycle rating is 80% of the time of the full capacity rating. A second requisite is a statement of the ratio of the peak voltage to the lowest voltage which the vehicle components can accept. A ratio of 2.4 to 1.0 will cover the normal range of charging and discharge conditions.

4.3 Battery Voltage

Given the energy content, a first and perhaps the most crucial determination must be made - that of the battery voltage.

The choice of battery voltage can not be optimized to benefit battery designers. It is influenced by the electrical equipment with which the battery is interfaced. For optimization of voltage, a systems approach rather than a components approach will give the best answer. However, the effects of voltage on battery design can be defined in considerable detail. These are broken down as follows:

4.3.1 Container Weight

Where a design uses a single container for each cell, it is obvious that with each cell added to the total cell count, two exterior cell walls are added to the battery. In a battery of the size contemplated, it is usual to use multi-cell containers. In this case only one interior wall is added with each cell along with one additional exterior wall for each separate multi-cell container added to the battery. The weight of a container wall for an EV type battery is approximately 0.02% of the total battery weight. Therefore, the effect of a moderate change in the number of cells in a battery is very slight. Even when comparing extremes such as a single cell battery to a 60 cell battery this effect would only amount to about 1% of the total battery weight.

4.3.2 Outside Plate Weight

It has been traditional to build individual cells with an uneven number of plates. For example, a single cell battery of a given energy size might have 100 positive plates and 101 negative plates, a total of 201 plates. If a battery were to be built having an equal energy content as determined by the number of positive plates, but having 100 cells, each cell would have 1 positive and 2 negative plates or a total of 300 plates.

Thus, in such a construction an increase in the number of cells may lead to a considerable weight penalty. An optimizing resolution of this problem is found by making the two outside plates approximately $1/2$ the thickness of the inside plates. When this is done, there is no longer a plate weight penalty against batteries with many cells.

4.3.3 Intercell Connectors and Terminal Connector

For a given power demand, the current required will vary inversely with the voltage. Smaller connectors between cells can be used for higher voltage systems. However, this is offset by the fewer number of intercell connectors required in a low voltage battery. In the final analysis, the comparison turns out to be an exact stand-off as far as the connectors in the battery itself are concerned. On the other hand, the size and weight of the conductor external to the battery for equal resistive losses is exactly in proportion to the current carried.

Figure 4-1 has been prepared to illustrate the statement that for equal losses the intercell connectors for a high voltage and a low voltage battery can be of equal weight. In Figure 4-1(a) a ten cell battery is shown, each cell having a capacity of 10 amperes hours. Figure 4-1(b) shows a two cell battery having a capacity of 50 ampere hours. The ten cell battery requires ten intercell connectors in series having a cross section of 1 area unit each. The two cell battery has 10 intercell connectors (5 in parallel) each of 1 unit area each. The current carried by each connector, the voltage drop, the power loss, and the weight of connectors will be the same.

However, the power lead from the battery to the motor must be 5 units area in cross section for the 2 cell battery but only 1 unit cross section for the 10 cell battery. The weight of the power lead for the 2 cell battery must be 5 times the weight of the 10 cell battery lead if the lead lengths are equal and if the losses are to be equal.

a

10 cell 10AH Battery - 10 connectors

b

2 Cell 50AH Battery
10 connectors

Figure 4-1
Comparison of Connectors
For 2 cell and 10 cell Batteries of Equal Power

ESB recommends a plug-in type of terminal connector for the complete battery. This type of connector has been used with a high degree of reliability for electric truck batteries of all kinds. Similar but lighter weight connectors are standard fittings on AN type aircraft batteries where they have been used for at least 30 years. This form of terminal is quick and easy to make and break. It requires no tools and when properly designed is completely foolproof against reverse connecting.

For safest use, the connector is made with flexible cables on at least one end. However, if the battery module is constructed so that it slides into a location with tolerances of perhaps ± 1 mm, it may be possible to mount both parts of the connector in fixed positions so that contact is made when the battery module is finally locked into position on the vehicle. An example of such a connector is the Anderson Power Products Model 5B 350.

4.3.4 Insulation and Safety

The higher the battery voltage, the greater will be problems relating to insulation and safety. Batteries on occasion tend to lose electrolyte. This can create a conductive path to short-circuit the battery. When the voltage across a liquid short circuit is above approximately 10 volts there is a possibility of current flows sufficient to cause destruction of plastic parts and other components. Thus, with a high voltage system, more care must be used to prevent electrolyte caused short circuits than with a low voltage system.

There are reports that a potential of 60 to 72 volts applied across the human body can in some cases prove lethal. (Technical Committee No. 69 Electric Road Vehicles - Meeting in Dusseldorf September 3, 1976). For this reason proposals have been made to set a maximum on charge voltage in particular.

4.3.5 Other Factors Influencing the Choice of Battery Voltage

In a battery of many cells there is a greater opportunity for battery failure due to a single low capacity cell than in a battery with fewer cells. Battery maintenance and particularly battery watering, if done manually, become more time consuming as the number of cells is increased. We consider these to be matters capable of solution and not factors that should influence the choice of battery voltage.

4.3.6 Decision

As a result of our consideration of these and related factors, ESB believes that a battery having a voltage in the 100 volt range is the best choice for the EV project. A minimum of 72V (36 cells) to a maximum of 144V (72 cells) is implicit in this statement. Over this range we believe that there would be little if any difference in specific energy or other features.

4.4 Cell Configuration

4.4.1 Cell Ampere Hour Capacity and Active Material Quantity

The energy content of each cell will be the total energy requirement divided by the number of cells. The ampere hour capacity of each cell is found by dividing the cell energy content by the average voltage when the cell is discharged at the rating conditions. (such as the 3 hour rate, or other). The cell energy content requirement is met by providing a sufficient quantity of active material in terms of weight and volume.

4.4.2 Plate Area

The maximum power capability is a function of the plate area. With the total volume of active material set by the ampere hour requirement, and the total plate area set by the power capability requirements the plate thickness is fixed.

In making the determination of active material volume and plate thickness, the battery design engineer relies on past experience in the form of constants to be used in an empirical formula or by direct transposition from an existing battery design. As an example, previous experience has shown that a conservative maximum sustained power density for the ESB golf car battery EV-106 is approximately 0.07 watt per cm^2 of positive plate area including the grid and about 0.151 watt per cm^2 for maximum power capability. Further, we have found that about 1.48 cm^3 of positive active material are required per watt hour of capacity at a 2-3 Hr rate.

The ANL requirement calls for a peak power capability of 100 watts per Kg of battery weight and a sustained power capability of 20 watts per Kg. The battery must have an energy capability of 40 Wh/Kg. These values were used to define a 60 cell 20 kWh battery. To meet the energy requirement the battery must weigh no more than 500 Kg and each cell no more than 8.33 Kg. Each cell must have an energy content of 333.3 watt hours. At 1.48 cm^3 per watt hour this dictates that 500 cm^3 of positive active material will be needed per cell. Each cell must have a capability of delivering 833 watts. At 0.151 watts per cm^2 of plate area, 5500 cm^2 will be required. This area represents the total or both sides of the plate. The single side plate area will be one half of this or 2750 cm^2 .

To meet the sustained power requirements of 20 watts per Kg each cell must have a capability of 166.7 watts. This will require 2221 cm^2 of plate area (both sides) or 1111 cm^2 one side.

Because the peak capability is limiting, a plate area of 2750 should be used. Dividing this into 500 cm^3 of positive active material results in a plate thickness of 1.8 mm. (This requires an adjustment for the metal of the positive grids, adding about 0.2 mm. to give a final plate thickness of about 2mm).

4.4.3 Plate Size

Continuing with the design of this cell we have a choice of plate height, width and number of positive plates to supply the required 2750 cm^2 of positive plate area. It is well known that a tall plate will not perform as well per unit of area at high rates of discharge as a short plate. A plate that is nearly square gives the best relation between height and width. Further, the experience of the battery industry has shown that best high rate performance will be obtained from plates with edge lengths of 20 cm or less. This experience covers the automobile and aircraft battery areas.

It should be noted that the factors for peak power capability and energy were taken from a cell design having plates 15.6 cm. high x 16.1 cm. wide. For manufacturing convenience we will therefore take the same plate size 15.6 x 16.1 with an area of 251 cm^2 . To obtain a total area of 2750 a total of 11 positive plates will be required.

4.4.4 Negative Plate Thickness

With each positive plate in a cell there is one negative plate and two separators. To obtain conditions of minimum weight per unit of energy, the negative plates should be somewhat thinner than the positive plates. The exact ratio is usually chosen by experience, and varies from about 0.6 to 0.9 times the positive plate thickness. For the present design a ratio of positive to negative thickness of about 1:0.85 has been chosen to give a negative plate thickness of about 1.7 mm.

4.4.5 Separation

The separator between plates has several functions. It serves to mechanically separate the positive and negative plates, preventing direct electrical contact. It prevents short circuits during life caused by particles of leady materials bridging from positive to negative. It hinders the passage of antimony from the positive plates where it is beneficial, to the negative plates where it can be very harmful.

A separator with ribs also provides a reservoir of electrolyte directly available for use mainly by the positive plate during the discharge reactions. Finally, the separator is very useful in holding the negative active material in place and supporting the positive material when retainer mats are provided in the battery construction. Some characteristics of the separator are compromising. For maximum protection they should be thick and not very porous, however, for best high rate use they should be exactly the opposite. In all instances, they should not deteriorate during the life of the battery; should not give off chemicals that are harmful to other battery components; and finally, should be inexpensive. Thus the choice of separator is controlled by a number of factors. In the ESB ISOA development plan time is allocated specifically for separator study. However, for the present discussion and based on past experience, an overall separator thickness of 1.5mm. is proposed as providing space for sufficient insulation and acid retention and porosity for the required energy output.

4.4.6 Center to Center Distance

Adding the several values which have been selected in the discussion above, i.e.:

1 positive	2.0 mm
1 negative	1.7 mm
2 separators	<u>3.0 mm</u>
a sum of	6.7 mm derived.

To this value a small additional amount is usually added for "clearance." This "clearance" is necessary because of the fact that the large flat areas of the plates and separators do not mesh completely and also because the "thickness" values given for positive and negative tend to be on the minimum side rather than average or maximum. Therefore, a clearance of 0.5 mm. is added to the value of 6.7 mm. give a final center to center distance of 7.2 mm.

4.4.7 Element Length

With a center to center distance of 7.2 mm and 11 positive plates the total element length becomes:

$7.2\text{mm} \times 11 + \text{one outside negative (1.3mm)} -$
 $\text{difference in thickness of one inside negative and one}$
 $\text{outside negative (0.4mm)} = 80.1 \text{ mm.}$

Thus, the final element is 15.6 cm x 16.1 cm x 8.0 cm.

4.4.8 Cell Container Shape

Thinking in terms of minimum container material weight for maximum internal volume, a cube would be the best configuration. However, the total weight of the container in batteries of EV-106 size is only 4% of the total battery weight. An element having more plates, with the plate being shorter and wider would be required for a cubical container. The saving in weight that would be achieved by this configuration is somewhat confused when a study of a multi-cell container is considered. As a practical exercise, a 3 cell container suitable for the 15.6 x 16.1 x 8.0 cm element was found to have 57.2 sq. units of plastic. A second container having the same cell volume but having each cell space in the form of a cube was found to have 56.5 sq. units of plastic. Thus the gain from the cubical design resulted in a weight improvement of 1.3% in a battery part which is only 4% of the total battery weight, and the cubical concept was not considered further.

4.4.9 Practical Considerations and Decision

Up to point 4.4.4 the reasoning used was free from any consideration of existing plant equipment and tooling and other matters relating to batteries and existing battery manufacturing plants. There is a fully developed storage battery manufacturing technology in the U.S.A. Battery sizes are standardized for benefit to the user. Because of this, many internal battery parts are similar in size among different manufacturers, in turn leading to a similarity of production equipment installed in USA battery plants.

As a practical matter, battery designs which are somewhat compatible with existing facilities will reduce the capital cost for producing a new battery and enable the industry as a whole to compete in the business, to the benefit of the ultimate customer, i.e., the general public. On the other hand, if a real advantage can be confirmed with non-standard construction, such an advantage should be pursued. At the current time there is an active golf car battery industry in the US producing some 1 million 3-cell batteries yearly.

The size of the battery is compatible with the present EV battery requirement. The cell element having a size of 15.6 x 16.1 x 8.0 cm and an energy content of 333 Watt hours which has been developed in the above discussion will match exactly with the golf car battery container. Further, the plate sizes chosen are those used in golf car battery manufacture. By making use of this existing production facility the development of the ANL ISOA-EV battery can proceed rapidly and with minimum impact on the manufacturing groups.

4.5 Battery Design

4.5.1 Cooling and Heating

The electrical losses in a 20 kWh high performance battery are great enough to require some means of temperature control. As a first step in heat control, every cell in the battery should have direct access to cooling air affording the same cooling capability. Therefore the cells should not be completely surrounded by other cells such as might be the case in a square battery array. Individual cells with an air passage between provides maximum cooling. A compromise would have the cells arranged in a single line with cooling along each side. A further compromise would have two rows of cells with cooling along one side of each. A 60 cell battery with cells as discussed above, arranged in two rows of 30 cells each, has a total length of approximately 2.7 meters (105 inches). This is a reasonable length in terms of present US vehicle sizes.

Ventilation passages at the bottom, sides and top of the battery should be provided. For low temperature operation extra heat may be desirable. Cooling ducts should close in cold weather and a battery heater, operated during charging, may be desirable.

4.5.2 Ventilation

At the end of charge, and on subsequent open circuit, lead acid batteries evolve hydrogen. It is necessary that this be safely removed and dissipated. A most desirable system is to manifold the cells so as to bring all the gas to one point where it can be passed through a flame arrestor and then either diffused to the atmosphere or recombined by means of a suitable catalyst. The systems approach to this problem is required, and should be integrated with the automatic watering device.

4.5.3 Watering

The type of duty cycle required for electric vehicle batteries precludes maintenance free systems, at least in the near future. This means that the batteries will have to be serviced with water on a regular basis. The electric vehicle battery will consist of approximately sixty cells, each of which will require watering. Further, the battery itself will be in either a single tunnel or as many as four locations within the automobile, each having limited, if any, accessibility to the owner/operator of the vehicle. It is therefore imperative that some sort of remote, single point watering system be fitted to the batteries to ease the required watering service which must be performed.

Single point watering devices for lead-acid batteries must meet several requirements. They must not permit an electrolyte path or bridge from cell to cell, they must operate rather quickly (in a matter of minutes), they must exist for extended periods of time in a hostile environment of acid and shock, and they must be inexpensive.

Several automatic watering device systems are under development throughout the world*. There are two basic operating principles used in such devices. One involves the concept of a valve opened and closed by a flotation device, while the other involves a pressure sensing system which stops inflow of electrolyte when certain pressure changes are sensed. Each method of operation has its advantages and disadvantages. The pressure types have no moving parts, but depend on maintaining sealed cell and case connections to the device. This is fairly easy to accomplish in the laboratory, but more difficult in manufacturing. Furthermore, reliability of such seals in the field under operating conditions is not good, and road shock and handling may cause minor ruptures that will disable such systems. The flotation type devices do not depend on seals, but do have moving parts and seal faces which must be kept clean to function properly.

ESB will evaluate developmental samples of each of the two types of automotive watering devices - one designed by AB Tudor and one designed by Japan Storage Battery Co. Laboratory tests will be conducted on each type to determine its reliability and acceptability of incorporation into the final EV batteries. Plans have been included to equip the ISOA final vehicle batteries with the most appropriate watering device system.

An example of a flotation type device is shown in Figure 4-2. This model was designed by AB Tudor Co., Nol, Sweden (now a part of ESB, Inc.).

*Flotation Type:	(1) Compagnie Europeene d'Accumulateurs,
Paris, France.
	(2) Varta Batteries AG, Hagen, I.W., W. Germany
	(3) Tudor AB, Nol, Sweden
Pressure Type:	(1) Japan Storage Battery Co., Ltd., Kyoto, Japan
	(2) Chloride Industrial Batteries, Ltd.,
Manchester, England

Flotation-Type Watering Device

Figure 4-2

4.5.4 Tray

Some means must be provided for handling the battery inside and outside of the vehicle. Two tray or battery module concepts have been suggested.

These are:

- a) A single large tray to contain and support the entire 500 Kg battery.
- b) Several small partial batteries such as 12 cell blocks, each weighing about 100 Kg.

The first approach is the most convenient for the battery user; however, because of the size and weight of the battery the tray will be quite heavy. The second approach will add little if anything to the weight of individual cells. This is because a 12 cell sub battery can probably be built self sustaining without additional structural members. The partial battery concept will require intertray connections which will slightly decrease the reliability of the battery, but should not require extra structure and is the first choice.

4.5.5 Recommendations for Optimum Battery Configuration

As this discussion has pointed out, there is not a single optimum configuration for the 20 kWh ISOA EV Battery. The final configuration must be arrived at through interaction involving trade-offs with the vehicle suppliers.

However, ESB recommends:

A 60 cell battery having cells of 1/3 kWh capacity assembled in 3 cell units, to give a rated capacity of 20 kWh at the 3 hour rate to an end voltage of 105 volts and a working capacity of 2.4 hours when discharged at the 3 hour rate. The battery weight will be 500 Kg.

5 IMPROVED STATE OF THE ART (ISOA) BATTERY DEVELOPMENT

ESB will undertake on a best efforts basis the design, development and production of an ISOA battery with target specifications shown in Table 5-1.

5.1 Plan A Flat Plate Development

A dual approach will be used in the ISOA project. Both a flat plate type battery and a tubular type battery will be developed. In the flat plate development two complete factorial experiments are planned. ESB proposes the use of the complete factorial experiment rather than partial experiments for two reasons. The first is that there may be interactions between many of the variables which are to be studied. The second is that batteries built on production equipment differ somewhat in performance due to small variations in the manufacture of individual plates. These differences can overshadow minor indications in the partial factorial experiment. We will use two three-cell batteries for each combination. Data will be taken on each cell as far as possible. This will provide an ample base for subsequent statistical analysis. For the first of the factorial experiments the test work will be conducted on battery parts which are presently available and actual test work can start early in the program. Information developed in the first factorial experiment will be used as a base for the second factorial experiment. A description of this test plan and other pertinent matter follows.

5.1.1 First Factorial Experiment (FP-1 Battery)

The purpose of this test is to define optimum relationships between three basic cell components and to determine a superior positive active material.

In the factorial experiments two three-cell battery sub-units will be made for each combination of variables as noted.

Table 5-1

ISOA EV Battery Requirements

	ISOA
Duty Cycle:	2-4 hr Discharge 4-8 hr Charge
Energy Efficiency: (Turn-Around)	> 60%
Cycle Life:	800 cycles
Installed Cost (1976 Dollars)	\$50/kWh
Specific Energy:	40Wh/Kg (18 Wh/lb) @ C/3 rate
Specific Power:	20W/Kg sustaining (9 W/lb) 100 W/Kg peak (45 W/lb)
Typical Installation Size:	20-30 kw-hr
Environmental Impact:	Minimal

A total of 32 variables is scheduled making a total of 64 battery units. Each unit will receive a complete test regime of some 30 charge-discharge cycles. The testing is defined to fully characterize the battery performance within the boundaries set by ANL. At the completion of the 30 test cycles, the more promising of the battery units will be placed on life test.

A complete description of the characterization and life testing planned will be found in the section of this report titled "Cell and Battery Testing".

5.1.1.1 Test Variables

Positive Active Material

Four positive paste mixes will be tried. The first will be the standard mix as used in ESB golf car batteries. The remaining three mixes will cover three variations of an improved positive paste mixes recently developed by ESB. The improved paste has provided at the same time better utilization of positive active material and improved cycle life. The three variations of this new material will be directed to maximize life and performance.

[*]

[*] This section contained proprietary data that has been deleted from this report.

Pages 34-36 inclusive are proprietary and are not included in this volume of the proposal.

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Positive to Negative Ratio

During normal discharge the negative active material operates at higher utilization levels than the positive active material. Two reasons for this are:

- a) The lead sponge of the negative active material is a better electronic conductor than the positive, hence allowing more even and more complete electrochemical utilization.
- b) The discharge reaction of the positive plate produces one mole of water for each mole of sulfuric acid used which hinders diffusion of acid to active sites in the material whereas in the negative plate discharge reaction, no water is produced.

During cycling the negative plate may lose capacity to a greater extent than the positive. This is due to changes in the structure of the lead sponge, growth of larger crystal species and formation of non-reducible lead sulfate crystals. For this reason, battery designers tend to use more negative active material than would be dictated by the performance of plates when new. The net result is that the ratio of positive to negative active material is chosen by experience and varies from about 0.7 to 1.0. The negative active material is more dense than the positive active material, thus the negative plate thickness varies from about 0.6 to 0.9 times the thickness of the positive plate. Two thicknesses of negative plate will be used to optimize the positive to negative ratio.

Acid Strength and Quantity

Batteries designed for high rate discharges have a limited volume of acid. There is sufficient acid to permit a full discharge at the desired rate, but not enough to react stoichiometrically with all the positive and negative active material. This minimizes acid weight and volume. There is, however, an interaction between acid strength, acid volume and utilization of positive and negative active materials that is difficult to predict.

Two variables of acid volume and two variables in acid strength will be included. The presence of antimony alloy causes negative plate deterioration with acid strengths exceeding about 1.285 specific gravity. For these reasons the high gravity chosen for the FP-1 test will be 1.315 and the low gravity 1.285.

The viscosity of sulfuric acid increases with increased acid strength, which reduces the diffusion rate and therefore tends to hinder the discharge reaction.

Grid Alloys for Positive and Negative Plates

The alloying elements in the positive grid metal have a profound influence on the behavior of the positive plate and particularly on the cycle life capabilities of the positive. Lead, when alloyed with antimony becomes much stronger than unalloyed lead. It is stiff, casts easily, thereby making the handling of the plates a simple task. Antimony in the positive grid is slowly leached out and spreads into the positive paste. The antimony has a beneficial effect at the grid-paste interface. Without antimony a non-conductive interface barrier can be formed which may make a non-antimonial grid difficult to recharge.

The antimony in the positive paste is also beneficial. It reduces the "shedding" or slow washing away of the positive active material during life.

However, the antimony is carried over to the negative plate where it has a very undesirable effect. It reduces the hydrogen overvoltage of the plate. This causes the negative plate to lose its capacity by the formation of an antimony-lead couple, and this leads to self discharge. This is a surface phenomenon and is directly related to the quantity of antimony in the positive grid.

Several other elements may be used to harden lead such as calcium and strontium. These metals are not very soluble in lead. When properly used, they increase the tensile strength of pure lead by a factor of two or more.

At this strength the alloys can be handled with conventional storage battery manufacturing equipment. However, when calcium-alloy positive grids are used in deep discharge service they often grow or increase in size. This is due to the expansion of the active material acting against the comparatively weak alloy. Complete discharge of calcium-alloy positive grids often results in a non-conductive barrier which effectively prevents the battery from being recharged.

Tin is often added to calcium-alloy both to improve its castability and to reduce the occurrence of the non-conductive barriers. However, it is not a complete cure for this condition.

Antimony-alloy has been used for negative grids. It affects the overvoltage of the grid and causes self discharge.

Calcium-alloys are desirable for negative grids. The negative grid is not exposed to the expansive forces found in the positive plate, and there is no tendency to form a non-conductive barrier. The only difficulty in using calcium negative grids is casting and processing them during manufacture due principally to their lack of strength. In the ISOA project, ESB has not included an alloy development. This is because enough is known about alloys for us to select suitable ones for EV service. For the positive grid a 2 1/2 antimony-alloy has been chosen and for the negative a calcium-alloy of 0.07%. The positive alloy combines reasonable strength, good recharge capabilities and low antimony transfer. The negative alloy will provide the best negative plate that is currently available, particularly with regard to low stand loss and long life. If during the course of the project weaknesses develop in either the positive or negative grid alloy as chosen, corrective changes will be made.

The effects of self discharge are amplified as the electrolyte strength is increased, but for weight saving the electrolyte should be as strong as possible.

5.1.1.2 Battery Design FP-1

Drawings:

Container (Figure 5-3)
Cover (Figure 5-4)
33 Positive Grids (Figure 5-5)
36 Negative Grids (Figure 5-5)
Separators (Figure 5-6)

Other Details

Acid Strength	1.285 sp.gr.
Alternate:	1.315 sp.gr.
Positive grid alloy	2 1/2% antimony with other additives
Negative grid alloy	0.07% calcium with other additives
Acid height:	top of separators
Alternate:	2 inches above
Separator Systems:	Hard rubber
Length	26.4 cm. (max)
Width	18.3 cm. (max)
Height (over terminal)	26.7 cm. (max)
Weight	28 Kg
Stored energy at 3 hour rate	1.050 kWh
Energy density	37 Wh/Kg

The use of the particular alloys chosen will enable the use of somewhat higher than normal acid strengths without excessive self discharge.

The effect of self discharge is manifested in the amount of overcharge that the battery will need during life. By keeping the self discharge to the lowest possible value the amount of overcharge will also be low. This will result in less oxidation of the positive grid and hence longer grid life. It will also result in lowered watering requirements. The weight breakdown is presented in Table 5-2.

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CONTAINER
"B" CONSTRUCTION
ELECTRIC VEHICLE
(EV PLATED)
SCALE FULL NOTED
MATL APS 321
SEE PAGE

FIGURE 5-3
ISOA BATTERY CONTAINER FP-1
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Table 5-2

Weight Breakdown of ISOA FP-1 Battery

Positive Grids	3.813
Positive Active Material	4.233
Negative Grids	3.648
Negative Active Material	4.613
Straps	1.400
Acid	8.320
Separators	.720
Container & Cover	<u>1.040</u>
	27.8 Kg

Data Collection

ESB will use constant current discharges for the purpose of comparing batteries of different construction, etc. This is because the constant current discharge defines the battery characteristics more concisely than other discharge methods. A series of constant current discharges provides a basis for the ampere-ampere hour plot, the ampere-volt plot, the ampere-time plot and methods of defining battery performance. There are methods available by which constant current discharge information can be converted to constant power curves with questionable reliability. ESB plans to perform constant power discharges on the final ISOA battery as well as on a number of battery units to be selected during the development and demonstration phases of the contract.

The information will be plotted as watts vs watt-hours in graphical form, and will be used to verify the battery modeling task discussed in paragraph 9.4.

In the test plan outlined in the ESB proposal a series of constant current discharges and charges are specified. All test cell designs will receive the same test regime. The direct output of these discharges will be a series of voltage vs. time readings.

Data Reduction, Determination of C Rates

A first step in reduction of this data is the determination of the Time rates C/3, C/5 and C/1 as referenced in the Statement of Work. The ESB method of determining these rates is as follows:

- a) Plots of the voltage vs. time readings are prepared for the various constant current discharges.
- b) Initial and final voltages are plotted against current values.
- c) The average voltage based upon the chosen final voltage for each discharge curve is determined and plotted on the same coordinates as b. The ESB computer will do this automatically. (The average voltage can also be found graphically by the measurement of the area of the discharge curve. This measurement can be made by use of a planimeter.)
- d) The ampere hours to final voltage are computed for each discharge and plotted on rectilinear paper. The ampere hours are plotted on the ordinate; amperes on the abscissa. Unevenness in this curve may be indicative of faulty discharges. Any discharges which are faulty will be repeated. (The faulty discharge may be the result of insufficient charge, temperature variation, incorrect discharge current, etc).
- e) Time lines for relating the 5 Hour, 3 Hour, and 1 Hour current to the corresponding ampere hours are drawn on the ampere vs ampere-hour plot.

The intersection of the time lines with the performance curve supplies the required current rates for these selected discharges. Other time lines may be added to get additional discharge rates.

Note: Throughout the ANL RFP, the corresponding ESB proposal and the Statement of Work dated September 10, 1976, reference is made to C rates. The C rate convention when applied to lead acid batteries may lead to somewhat confusing conclusions. Some battery types, such as nickel cadmium and silver-zinc have an ampere hour capacity which is quite insensitive to the rate of discharge. In this case rates such as C/5, C/3 and C/1 where C is the ampere hour capacity of the cell, represent the 5 hour, 3 hour and 1 hour discharge currents. On the other hand, batteries which are diffusion controlled such as the lead acid system show lower ampere hour capacity at short times of discharge compared to long discharges. Thus in lead acid systems there does not exist a fixed value corresponding to C which exists in the alkaline systems. As example, a particular lead acid battery may have a C (3 hour) of 60 AH. The C/3 rate will then be 20 amperes and the battery will give 3 hours of discharge at 20 amperes. On this basis the C/5 rate is 12 amperes. However, the lead acid battery will actually give 5 1/2 hours or 67 ampere hours at 12 amperes. The C/1 rate is 60 amperes. At this rate, a lead acid battery will only give 41 minutes or 41 ampere hours. Therefore, the use of the C convention must be used with understanding when applied to the lead acid system. ESB believes that a more accurate picture is given by stating that a particular discharge current represents a particular time rate for a given battery.

Discussion of End of Discharge

In the preparation of the performance curves for use in battery evaluation, a voltage - or voltages must be chosen at which the battery has completed its discharge.

This is called the "end voltage." In the selection of the "end voltage" the battery designer is faced with a compromise. On the one hand, going to a low end voltage automatically gives a greater battery rating (more ampere hours) than when the discharge is stopped at a higher end voltage. On the other hand, discharge to a lower voltage is more severe than discharge to a higher end voltage. (Hence the custom of service discharges to 80% of the full rating). The battery designer must choose end voltages at all rates of discharge which will give both acceptable capacity and acceptable cycle life. In establishing end voltages, the battery designer is in effect guaranteeing battery life.

The electrical equipment to which the battery is connected is not sensitive to this rate-voltage limitation. It is usually stated that the electrical equipment will operate satisfactorily between certain voltage limits.

One end voltage has already been used in this discussion, namely 1.75 volts per cell at the 3 hour discharge rate. In preparing the performance curves of the several development batteries in the ISOA program and for use in comparing the several battery designs, ESB will use a straight-line current-end voltage relationship passing through 1.75 volts at the 3 hour discharge rate and 1.00 volts at the 5 minute discharge rate. (This is subject to revision as the electrical requirements for the vehicle become more clearly stated.) Actual discharges will be continued somewhat below the end voltages given by the above curve to provide additional design information.

Anticipated Performance Curves for the FP-1 Cell

Ampere - time curve Figure 5-7

Ampere - Ampere hour curve and ampere-volt curve
Figure 5-8

Discharge Time (Minutes) to Limiting Final Voltage @ 80°F

20 X 1/77

Figure 5-7
Anticipated Ampere-Time Relationship ISOA Battery

Figure 5-8
Anticipated Performance
FP-1 Design at 25°C

ACX 2/77

Cycle Life Demonstration

ESB maintains a facility for the improvement of its golf car battery. A part of this facility includes a multi-station life test on which an average of 36 3-cell golf car units are on life test. The life test is a particularly harsh test which tries to duplicate actual field conditions. Life testing of typical batteries shows:

Standard EV battery with low cost separators: 400 cycle

Special EV battery with high cost separators: 600 cycle

Special EV battery with improved positive grids: 900 cycle

The duty cycle of this life test combines a discharge at 75 amperes to 1.75 V per cell followed by a modified constant current charge to a final voltage of 2.50 V per cell. We believe that by making use of information generated on this test along with improved grid metals and more sophisticated charging techniques the goal of 800 cycles for the ISOA battery designs can be met.

Low Temperature Performance

At constant current discharges between the 2 hour rate and the 12 minute rate at -20°F , a reduction in the discharge time to approximate 26% of the time of discharge at 77°F . has been found. There is also a reduction in the voltage characteristics. The voltage at -20°F will be about 80% of the room temperature voltage at high rates of discharge. It should be noted that the temperature of a battery is not necessarily fixed by the ambient temperature. During low temperature discharge and particularly low temperature high rate discharge the battery warms itself, which in turn improves the performance. Further, a large battery will heat up more than a single cell. Therefore it is anticipated that actual performance of an EV battery will be somewhat better than these values. Until the exact load profile is known and tests can be made, the true effect of temperature will be somewhat uncertain.

5.1.2 Second Factorial Experiment (FP-2 Battery)

The objective of the second factorial experiment is to further refine the design of the flat plate ISOA battery. The general plan of the test is similar to the plan of the first factorial experiment. In the second test a total of 36 variables is planned and 72 3-cell battery units will be tested. The time span between construction of the cells and the final decision point is short. In order to get the maximum life cycles, the entire group of 72 batteries will be duplicated. The duplicate battery units will be placed on life test at the same time that the first battery group is started on characterization. By this means 13 weeks of life testing will be gained.

5.1.2.1 Test Variables

Positive Grid Design

Three positive grid designs are contemplated. Battelle's Columbus Laboratories (BCL) will act as a consultant in the design and evaluation of the grid structure. The grid design work will consist of two tasks. The first analytical task will conceptualize or use available grid designs in conjunction with an existing computer program to calculate the voltage and current density distribution over these grids as a function of an applied current. The second predictive task will be directed to the development of an optimized grid by minimizing the voltage, at any given current, using a functional relationship relating grid structure to performance. The result anticipated is a grid design which is theoretically the best possible for any selected grid weight. The complete proposal from Battelle is presented in Appendix 1.

Negative Grid Design

The design of the negative grid used in conventional batteries has been based to a large extent on the plate pasting equipment. Experimental data suggests that there is far more metal in the negative grid than is necessary. It has been reported that a negative plate with no grid structure other than a connecting lug gave as good a discharge as a negative plate with complete grid structure. In a test run at ESB grids having 2/3 of the normal grid bars have given normal golf car battery performance. It appears that the negative grid represents one feature where considerable weight savings are possible. Two designs of negative grid will be evaluated in Factorial Experiment No.2. The first design is aimed at reducing the total grid weight by about 20%. This weight reduction has been used in the projected weight calculations for the FP-2 battery. The second grid design will represent a further weight reduction approaching a saving of 40% in weight over the grid used in present golf car batteries. The use of light weight negative grids will require greater care in the pasting operation. A study of the type of pasting device required to handle the light grids will be made. The principal area of development therefore becomes that of solving the pasting and handling problems. If the second grid design can be reduced to manufacturing practice a further weight reduction of the FP-2 battery will result.

Separators

There will be six separator variations in the test plan as follows:

1. Hard rubber
2. Hard rubber with glass
3. Microporous polyethylene
4. Hard rubber and glass with edge sealing
5. Microporous polyethylene with edge sealing
6. Microporous polyethylene envelopes

5.1.2 2 Battery Design FP-2

Drawings:

Container (Figure 5-9)
Cover (Figure 5-10)
33 Positive Grids (Figure 5-11)
30 Inside Negative Grids (Figure 5-12)
6 Outside Negative Grids (Figure 5-13)
Separator (Figure 5-6)
Lead Parts (Figure 5-14)

Other Details:

Acid Strength	determined from FP-1 tests
Positive grid alloy	2 1/2% antimony with other additives
Negative grid alloy	0.07% calcium with other additives
Acid Height	determined from FP-1 tests

The weight breakdown of the ISOA FP-2 battery is
presented in Table 5-3.

Table 5-3

Weight Breakdown of ISOA FP-2 Battery

Positive Grids	3.813
Positive Active Material	4.235
Negative Grids (inside)	2.550
Negative Active Material	3.810
Negative Grids (outside)	.348
Negative Active Material	.528
Straps	.525
Acid	8.320
Separators	.720
Container and Cover	<u>1.040</u>
	25.9 Kg

SECTION C-C, NOTE THESE RIBS TAPER TO
NORMAL RIB WIDTH AT POINTS SPECIFIED.

FIGURE 5-11
ISOA POSITIVE GRIDS FP-2

DWC
NO

PAGE 57

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34510A ESB INCORPORATED
AUTOMOTIVE DIVISION
DESIGN ENGINEERING
CLEVELAND, OHIO

GRID
9- SECTION
POSITIVE
(PROPOSAL)

SCALE FULL + NOTED
MAT'L
AP5 305

PART NO.
MUST APPEAR
ON EACH PAGE

FIGURE 5-12
DW ISOA NEGATIVE GRIDS (INSIDE)
NC
PAGE 58

ISSUE	DATE	NAME	CHANGE	FILE
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[illegible]

JAN 2 1964

FIGURE 5-14
ISOA BATTERY LEAD PARTS

DWG
NO

TOLERANCES
TWO PLACE DECIMAL $\pm .01$
THREE PLACE DECIMAL $\pm .008$
ANGLES $\pm 1/4^\circ$
UNLESS OTHERWISE SPECIFIED

7517 ESB INCORPORATED
AUTOMOTIVE DIVISION
DESIGN ENGINEERING
CLEVELAND, OHIO

CAST ON STRAP
TERMINAL & INTERMEDIATE
EV ANL
PROPOSAL

SCALE		PART NO MUST APPEAR ON EACH PART
MAT'L

Tabulation of Performance Data and Battery Statistics

The anticipated 3 hour capacity of the ISOA FP-2 battery to 1.75 volts / cell is 180 AH. This is the C rate. On the basis of the C rate convention as discussed in the section "Data Reduction - Determination of C rates" the C/5 rate is 36 amperes and the C rate is 180 amperes. However, the actual anticipated 5 hour discharge anticipated current is 39 amperes (195 AH). The actual 1 hour discharge anticipated current is 140 amperes (140 AH).

A 3 cell battery FP-2 unit will then have the following characteristics:

Length:	26.4 cm. (max)
Width:	18.3 cm. (max)
Height:	26.7 cm. (max)
Weight:	25.9 Kg
Stored Energy at 3 hour rate:	1.05 KWh
Energy Density:	41 Wh/Kg

Anticipated Performance Curves for the FP-2 Cells

Ampere vs. time curve: Fig. 5-7

Ampere vs. Ampere-hour curve and Ampere vs. Voltage
Curve: Fig. 5-15

5.2 Plan B Tubular Plate Development

The plates of most lead acid storage batteries are rectangular in shape. They comprise a lead-alloy grid to provide structure and electrical conductivity, and a mass of active material located within the lead grid framework. This type of plate has been termed a "flat"-plate. It is used for both positive and negative electrodes. In another type battery the positive plate is comprised of individual vertical members connected together at top and bottom (Figure 5-16). Each vertical member (A) has an outer containing tube (B) made of chemically resistant fabric (chemically resistant glass).

Figure 5-15

Anticipated Performance
FP-2 and TP-1 Designs at 25°C

Figure 5-16

ISOA Tubular Plate (cutaway)

Within the tube is a layer of active material (C) and a conductive spine (D) or spines made of lead alloy. The tubes may be round or rectangular in cross section. A conductor bar (E) attaches to each spine at the plate top and a non-conductive bottom bar (F) spans and connects the bottom of the several tubes together. This form of plate is known as a "tubular" type plate. The complete plate is also rectangular in shape and is used with negatives of conventional flat plate design.

With a flat plate positive the particles of the active material slowly swell and lose mechanical contact. They then are washed away from the plate surface by the circulation of electrolyte in the cell and end up either deposited on metallic surfaces in the cell or at the bottom of the cell in a space known as the "sediment" space. The battery reaches the end of its life when enough active material has been removed from the positive plate so that the plate capacity is below a pre-established minimum. Numerous methods for retaining the active material have been tried. Most of these retard the diffusion of electrolyte, while others render the active material less efficient than it would be without the retainer. In the tubular type plate the thin fabric tube acts as the retainer. The geometry of the tubular member - a conductor surrounded by active material which in turn is held in place by the fabric tube - causes the active material to be more efficient than in flat plate designs. The conductor structure of the tubular plate also requires less metal than the flat plate design. Finally, the tubular plate will give better life than flat plate cells. Therefore, the tubular battery design offers improved cycle life and improved energy density when compared to flat plate designs. However, these ends are achieved only by an increase in manufacturing cost.

In order to obtain the required power output at high rates of discharge the tubular battery or this development will make use of plates of the same thickness as the flat plate cells of Plan A.

The negative plate design will be the same as that of Plan A and one of the negative plate designs discussed in the FP-2 testing will be available for the TP-1 test cells. Throughout the tubular plate development, manufacturing methods and equipment will be studied to reduce plate costs.

5.2.1 Preliminary Studies

5.2.1.1 Tube Filling

In tubular plate construction it is necessary to fill the tubes with lead oxide while at the same time locating the spine centrally within the tube. This is done in commercial plants by feeding powdered lead oxide into the open, upended tube bottoms using jigs which position the spine in the tubes. The plate is vibrated during the filling operation and the lead oxide shakes down to fill the tube. After the tubes are filled a bottom bar is placed over the open tube ends, locking the spines and tubes. The tubes in the TP-1 battery design are narrower than those presently used by industry for tubular battery construction. For this reason, a study of the tube filling operation will be conducted near the beginning of the TP-1 development. Experiments will involve filling with freshly dried oxides and pelletized oxides, making use of adjustable frequency shaking devices. In another series of experiments the oxide will be put into paste form to allow tube filling by extrusion methods. Additives will be used to improve the flow characteristics of both wet and dry oxide mixes.

5.2.1.2 Soaking, Drying and Formation

Calculations indicate that the dry active material weight needed to achieve the ISOA goals must have a density no greater than 3.8 gm/cc.

Tests on tubular plates having mix densities lower than this show that there may be a problem relating to their processing. Therefore, a companion project to the tube filling work will be a study of processing. There are three steps involved:

- (1) soaking of the filled plate (principally to aid handling),
- (2) drying (also for improved handling;) and
- (3) formation (to achieve the required battery performance).

These problems will be investigated as described later making use of the engineering talents at ESB's Exide Power Sources Division, the Technology Center and ESB's AB Tudor Subsidiary.

5.2.2 First Factorial Experiment (TP-1 Battery)

As with the flat plate development, a complete factorial experiment will be used for the optimization of the tubular plate ISOA battery. The study will comprise 32 battery assemblies. Two three-cell batteries of each assembly will be tested for performance and a second group of 64 batteries will be tested for life. The performance testing and the life testing will be started at the same time so as to provide a maximum of life test information by the time that the final decision point, i.e., plate selection, is reached.

5.2.2.1 Test Variables

Positive Active Material

Two variations in filling densities will be tested, 3.6 gms per cm^3 and 3.2 gms per cm^3 .

Positive Tube Structure

Two positive tube types will be tested. The variable will be the total quantity of glass fiber used to make the tube. The tube is one of the high cost items in the TP-1 battery. The tubing cost varies directly with the quantity of glass used.

The tubes' performance decreases with increased glass quantity but the life improves with a larger quantity of glass per tube. Background information available indicates that two test sizes should be ample to optimize the tube. The first tube will have a specific weight of 20 mg/cm² the second 15 mg/cm².

Acid Strength and Volume

The diffusion parameters in the tubular type battery differ from those of the flat plate battery. As with the FP-1 test, two variables of acid volume and two variables of acid strength will be included.

Separators

The separator problem in tubular cells differs considerably from the flat plate separator problem. In the tubular design a principal requirement is to provide electrolyte space adjacent to the positive plate. The rectangular cross section of the ISOA tubes keeps them from supplying full support to prevent swelling of the active material. This support must be provided via the separators and negative plates, backed up by the battery case itself. Thus, there is a considerable pressure tending to crush the separator. Two separator variables have been included in the test design. One will be a ribbed microporous material such as hard rubber. The second will be a thin sheet material as sold in Japan along with a plastic mesh to provide the electrolyte reservoir.

5.2.2.2 Battery Design TP-1

Drawings

The 3 cell TP-1 battery will consist of parts as shown in the following drawings:

Container (Figure 5-9)
 Cover (Figure 5-10)
 33 Positive Plates (Figure 5-17)
 30 inside negative grids (Figure 5-12)
 6 outside negative grids (Figure 5-13)
 Separator (Figure 5-6)
 Lead Parts (Figure 5-14)

Other Details

Acid Strength:	1.285 sp.gr.
Alternate:	1.315 sp.gr.
Positive grid alloy:	2.5% antimony with other additives
Negative grid alloy:	0.07% calcium with other additives

The weight breakdown of the ISOA TP-1 battery is presented in Table 5-4.

Table 5-4

Weight Breakdown of ISOA TP-1 Battery

Positive Grids	3.390
Positive Active Material	4.658
Negative Grids (inside)	2.550
Negative Active Material	3.810
Negative Grids (outside)	.348
Negative Active Material	.528
Straps	.525
Acid	8.320
Separator	.720
Container & Cover	<u>1.040</u>
	25.9 Kg

Figure 5-17

TP-1 Battery: Positive Plates

Tabulation of Performance Data and Battery Statistics

The anticipated 3 hour capacity of the ISOA TP-1 battery to 1.75 volts is 180 AH. This is the C rate. On the basis of the C rate convention as discussed in the section "Data Reduction - Determination of C Rates" the C/5 rate is 36 amperes and the C/1 rate is 180 amperes. However, the actual anticipated 5 hour discharge current is 39 amperes (195 AH). The actual anticipated 1 hour discharge current is 140 amperes (140 AH).

Length:	26.4 cm (max)
Width:	18.3 cm. (max)
Height:	26.7 cm. (max)
Weight:	25.9 Kg
Stored Energy at 3 hour rate	1.05 kWh
Energy Density	41 Wh/Kg

Anticipated Performance Curves for the TP-1 Battery

Ampere - time curve: (Figure 5-7)

Ampere-Ampere hour curve and Ampere-Volt curve
(Figure 5-15).

5.3 Charging

5.3.1 Charging - General Discussion

It has been stated that batteries wear out during charge rather than discharge. This is because the two most common causes of failure, washing of positive active material and corrosion of the positive grid, occur on the charge cycle. To reduce these to a minimum it is desirable to keep the overcharge to a minimum, consistent with maintaining the battery capacity. The amount of overcharge is dependent to a large degree upon the antimony content of the grids. Batteries with a large amount of antimony require more overcharge than batteries with a small amount. This overcharge is required to overcome the self discharge of the negative plate.

Batteries without antimony have practically no self discharge. Overcharge is required, however, to provide proper mixing of the electrolyte. In the laboratory it is usual to control the recharge by time, using constant current with the ampere hours returned, based upon the previous discharge. It is also usual to start the charge at a high rate (5 Hour) and change to a lower (20 Hour) rate when the cell voltage approaches the gassing voltage. (2.37 volts per cell).

In the field the exact discharge removed from the battery is usually unknown. A typical field procedure is to charge the battery at an average initial rate (5 Hour) to the gassing voltage and then continue at the finishing rate (20 Hour) for a time period selected by the battery user. A charging plan desirable for batteries having little or no antimony and which has been used with success in submarine service calls for several cycles cut off at the gassing voltage (approximately 100% return) and then a single charge having an overcharge of approximately 10%.

The charging methods to be used for the Test Standards evaluation and for the life test evaluation are fully defined in Sections 9.3.2.3 and 9.3.3.8 respectively. Although the primary benefit of a low overcharge regime will be the optimization of storage battery life, there is a secondary benefit in that minimum overcharge will result in a minimum consumption of water and a consequent low maintenance requirement. The disadvantage is that unless sufficient charging occurs at regular intervals, electrolyte stratification will occur and negative plate performance will be adversely affected. The charge regimes noted above will require 6 to 8 hours for completion.

Quick recharge (less than one hour) may be accomplished only at some compromise in completeness of charge and/or battery life. For minimum time-of-charge a constant potential charge is used (set at a nominal 2.35 volts per cell).

With this regime the starting current can be very high, perhaps 1000 amperes or more. It is usual therefore to include a current limitation in the charger design such as twice the numerical cell ampere hour size. In any case of rapid charging, the battery temperature will rise at a fairly rapid rate. Fast charging therefore will require additional cooling and the charging source must include thermal safety devices so that the battery is not heated beyond a safe limit.

Another fact relating to fast charging is that such a charge will only return at best some 70%- 80% of the capacity of the battery, due principally to inadequate time allowed for diffusion controlled phenomena.

The energy efficiency of charge is controlled by two Principal factors. The first is the ratio of discharge ampere hours to charge ampere hours. The second is the ratio of the discharge to the charge voltage. Unfortunately the discharge voltage and often the charge voltage are not constant. It is customary to use the average discharge voltage and the maximum charge voltage in computing charge efficiency. The first regime described above applied to the ISOA battery would yield an efficiency of:

$$\frac{100\% \text{ discharge}}{106\% \text{ charge}} \times \frac{1.95 \text{ V avg. discharge}}{2.35 \text{ V avg. charge}} \times 100\% = 78\%$$

The submarine type regime, based on a repeat cycle of 6 charges per week, would yield an efficiency of:

$$\frac{5}{6} \frac{100\% \text{ discharge}}{100\% \text{ charge}} \times \frac{1.95 \text{ V avg. discharge}}{2.30 \text{ V avg. charge}} + \frac{1}{6} \frac{100\% \text{ discharge}}{110\% \text{ charge}} \times \frac{1.95 \text{ V avg. discharge}}{2.67 \text{ v avg. charge}} \times 100\% \approx 82\%$$

For rapid charge to 75% capacity the efficiency will be:

$$\frac{75\% \text{ discharge}}{75\% \text{ charge}} \times \frac{1.95 \text{ V avg. discharge}}{2.33 \text{ V. avg. charge}} \times 100\% = 84\%$$

The charging method to be used for the test standards evaluation is fully defined in Sections 9.3.2.3 and 9.3.3.8 respectively.

5.3.2 Recommended Charging Regime for Actual or Field Use

In actual use the exact number of ampere hours withdrawn cannot be used to control the subsequent recharge with present state-of-the-art equipment. ESB recommends a modified constant potential charge, with temperature and time controls. Specifically, the charging current must be limited to the 5 hour rate of the battery (approximately 39 amperes for a 120 V, 20 kWh battery) with a voltage cross-over of 2.40 V per cell at 25°C. The voltage limit override will be automatically controlled by a temperature sensor or sensors strategically placed in the battery. This temperature feedback will vary the voltage limit override by -5.5 mV/°C/cell. This will assure that the gassing limitation is the same with varying battery temperature. A timer will limit the entire charge cycle to a maximum of 8 hours.

Such a system will function in the following manner: Once turned on, the charging current will reach approximately 30 amperes if the terminal voltage is less than or equal to 2.40 V per cell (at 25°C.) Once the battery voltage reaches this value (adjusted for temperature), the current will automatically decrease to maintain the voltage. After eight hours elapse, the charger turns off automatically.

Quick recharge in the field will be carried out as specified in the "Charging - General" section.

Although the above methods are the best regimes based on present equipment and art, additional work is desirable beyond the intended scope of the contract. One possible development would involve an ampere hour "fuel guage" that would only not inform the vehicle operator how much range is left, but would be used to control subsequent charge input.

5.4 ISOA Design Modification

At the ANL meeting on January 17, 1977 a battery tunnel height of 295 mm was proposed as being the most acceptable to battery suppliers and vehicle designers.

The ISOA battery described in this proposal was designed prior to that meeting and does not make maximum use of the allowable tunnel height. In order to meet the project deadlines the original designs and calculations had to be included in the body of this report. An estimated 20% increase in capacity for the FP-2 or TP-1 batteries can be obtained by increasing their height to 280 mm, which would still allow air space above them for cooling purposes. The specific energy would be improved by an estimated 0.1 Wh/Kg. A 120 volt battery would have a total energy of 24 kWh, an energy to 80% of full capacity of 19.2 kWh, and a weight of 600 Kg.

5.5 Attainment of ISOA Goals

The final ISOA battery will meet the following goals:

	<u>Goals</u>
Duty cycle	2 - 4 Hr Discharge 4 - 8 Hr Charge
Energy efficiency (Turn-around)	> 60%
Cycle Life	800
Installed Cost	< \$50/kWh
Specific Energy	40 Wh/Kg @ C/3 rate 100 W/Kg Peak
Typical Installation Size	20-30 kWh
Environmental Impact	Minimal

6 ISOA REDUCTION TO PRACTICE - FLAT PLATE AND TUBULAR

The general plan by which the ISOA battery will be reduced to practice is shown on the Activity Chart Figure 6-1. At the top of each box will be found a pair of numbers indicating the weeks from time zero by which each task must be started and completed in order to meet the contract schedule. A second series of numbers will be found in the boxes. These key with the description of tasks which follow.

6.1 Description of Tasks - Activity Chart (Figure 6-1) FP

EVENT NUMBER-1

TITLE OF EVENT: Prepare Test Design FP-1 Battery Units

DESCRIPTION OF EVENT: In this one week period the planning presented in Phase A of the program will be firmed up and personnel assignments will be formalized. The test equipment required for the testing phases will be placed on order. Laboratory space will be cleared and prepared for the project. Drawings of battery parts will be finalized.

EVENT NUMBER-2

TITLE OF EVENT: Grid Design

DESCRIPTION OF EVENT: Grid modifications as shown on grid drawings will be made. Altered grid molds will be broken in and all other existing molds needed will be checked out. This work will be done in house.

EVENT NUMBER-3

TITLE OF EVENT: Order Molds and Tooling

DESCRIPTION OF EVENT: Molds including alterations and other tooling to be purchased outside of ESB will be placed on order. Purchased parts for the FP-1 program will be ordered.

EVENT NUMBER-4

TITLE OF EVENT: Cast Grids

DESCRIPTION OF EVENT: This is the first operation in actual battery construction. Lead alloy parts, positive grids, negative grids and straps will be cast from the alloys selected and described in Phase A. Casting of parts will be done on production type equipment either in the laboratory or where possible in actual factory locations.

DEMONSTRATION PHASE - ISOA PROGRAM - REDUCTION TO PRACTICE

Figure 6-1

EVENT NUMBER-5

TITLE OF EVENT: Paste Grids

DESCRIPTION OF EVENT: This is the second operation in battery construction. Positive and negative paste mixes will be prepared using production equipment. The grids prepared in Event 4 will then be pasted with the prepared pastes using production pasting machines.

EVENT NUMBER-6

TITLE OF EVENT: Assemble Cells

DESCRIPTION OF EVENT: In this operation the several lead parts used in the cell assembly are welded together to form the positive group and the negative group. The two groups are intermeshed and separators placed between adjacent plates, to form an element. These elements are placed in a battery container, and electrical connections between cells are completed. The battery cover is affixed to the top of the container and sealed. The battery is filled with electrolyte and is given a formation or first electrochemical cycle. Suitable electrical checks and other examinations are made during the assembly to see that the work has been properly carried out (see pre-test examination section). The battery is then complete and ready for the test regime.

EVENT NUMBER-7

TITLE OF EVENT: Start Test Sequence

DESCRIPTION OF EVENT: The first 6 discharges as spelled out in the Test Schedule and Standards section will be completed. This work is done under exacting laboratory conditions.

EVENT NUMBER-8

TITLE OF EVENT: Determine C Rate

DESCRIPTION OF EVENT: The results of the initial testing completed in Event 7 are now analyzed. The information is reduced to graphical form, any discrepancies are noted and if any data appears to be inconsistent, repeat tests will be

scheduled. From the graphic analysis, the actual C rate and rates related to the C rate are determined. These values will be used in the final evaluation of each particular battery combination.

EVENT NUMBER-9

TITLE OF EVENT: Complete Test Sequence

DESCRIPTION OF EVENT: The testing as outlined in TEST SCHEDULE AND STANDARDS will then be continued to completion. It is anticipated that the nominal rates as used in the initial testing will be reasonably close to the exact C rates as found in Event 8, and will be used for the remainder of the testing. If, however, the nominal C rates differ from the actual C rates by amounts which might prejudice the final test results, the testing will be continued using the actual C rates.

EVENT NUMBER-10

TITLE OF EVENT: Cells Available for ANL

DESCRIPTION OF EVENT: At this point, ANL may wish to obtain one or more 3 cell battery units for their testing. It is contemplated that extra battery units will be built in Event 10 to provide for this eventuality.

EVENT NUMBER-11

TITLE OF EVENT: Life Test

DESCRIPTION OF EVENT: Although it would be of interest to life test the entire group of battery units used in the testing to this point, it is anticipated that the performance of some of the combinations will not warrant further testing. Therefore, a selection will take place and the most promising battery types only will be continued on life test. We plan to provide life test equipment for about 1/2 of the battery combinations. However, this will not be a fixed limitation and if the results warrant, additional circuits for life testing will be made available.

The life test that is contemplated will provide approximately 27 cycles per 2 weeks or about 55 cycles per month. We have allowed 45 weeks for life test selection during which time some 600 cycles are possible. Battery units still active at week 71 will be continued on life test until failure.

EVENT NUMBER-12

TITLE OF EVENT: Analyze Data: Select Best Combination
DESCRIPTION OF EVENT: During and upon completion of the test profile of Events 7 and 9 the entire mass of test data will be reduced and put in condition for efficient comparison. Comparisons will be made and the most desirable combination of positive to negative ratio, positive paste, and acid quantity and strength will be selected for use in the design of the FP-2 battery units.

EVENT NUMBER-13

TITLE OF EVENT: Prepare Test Design FP-2 Battery Units
DESCRIPTION OF EVENT: The battery parameters selected as a result of the FP-1 development will be fed into the FP-2 design. In the FP-2 work optimization is sought for the negative grid design, positive grid design and separator selection. In Event 13 the various factors relating to the FP-2 design and test plan will be correlated, additional manpower and test equipment as needed will be allocated and all plans will be finalized.

EVENT NUMBER-14

TITLE OF EVENT: Design Grids
DESCRIPTION OF EVENT: It is planned to use input from the Battelle Columbus mathematical modeling of the positive grid structure in the design of a new positive grid. Two grid concepts are planned, one with emphasis on minimum electrical losses and a second with emphasis on maximum life.

Two or three new negative grids will be designed, the two (or three) designs having successively less metal for weight reduction. It is believed that one of the negative grid designs will be identical with the grid already developed for the TP-1 battery thus saving the expense of one grid mold. It must also be noted that if ANL at this time changes the final battery configuration the battery design of Events 13 and 14 will be chosen to match and complete new drawings will be prepared.

EVENT NUMBER-15

TITLE OF EVENT: Order Molds and Tooling

DESCRIPTION OF EVENT: New grid molds and molds for other parts including containers as needed will be ordered. Special tooling as required will be ordered as well as parts for the battery unit requirements of the FP-2 development. Four months lead time has been allowed for mold cutting.

EVENT NUMBER-16 to 23

DESCRIPTION OF EVENTS: The routine follows exactly Events 4 to 11. However, in order to obtain the maximum amount of life test information, a complete duplicate set of batteries will be built and started on life test at the same time that the performance test sequence is started. Additional life test circuits will be made available for this testing.

EVENT NUMBER-24

TITLE OF EVENT: Analyze Data: Select Best Combination

DESCRIPTION OF EVENT: At Event 24 a complete analysis of all battery units will be made, including weights and weight breakdowns. From this analysis the optimized flat plate battery design will be selected.

ISOA Program - Reduction to Practice Tubular Plate Program

EVENT NUMBER-1

TITLE OF EVENT: Prepare Test Design

DESCRIPTION OF EVENT: In this one week period the planning presented in Phase A of the program will be completed. Personnel assignments will be made. Experimental and test equipment required for development and testing will be placed on order. Laboratory space for short term work will be cleared and prepared for the project. Space required for the long term work will be scheduled.

EVENT NUMBER-2

TITLE OF EVENT: Design Grids

DESCRIPTION OF EVENT: Tentative grid designs prepared in Phase A of the project will be finalized and put into proper form for use by the Mold Cutter. One positive and two negative molds will be required.

EVENT NUMBER-3

TITLE OF EVENT: Exploratory Filling

DESCRIPTION OF EVENT: In the tubular type battery plate it is necessary to fill a number of tubes with lead oxide. Classically this has been done by vibrating lead oxide powder into the tube. This method is subject to variation with the type of oxide and the moisture content of the oxide as well as variations in the time, intensity, and frequency of the vibration cycle. Tubes have also been filled by forcing them full of a wet lead oxide paste. The filling is also affected by the nature of the tube itself. In this phase of the work a method for filling will be developed which gives the required filling density with maximum repeatability. In the initial portion of Event 4 positive grids and tubing presently available and close to the sizes needed in the TP-1 battery will be used. As soon as actual TP-1 grids and TP-1 tubes become available they will be used for the remainder of the development.

EVENT NUMBER-4

TITLE OF EVENT: Exploratory Formation

DESCRIPTION OF EVENT: Preliminary studies of tubular plates similar to those contemplated for the TP-1 battery indicate that modified methods for the chemical and electrochemical treatment may be necessary in order to develop maximum capacity and maximum life. In this period of Event 4 systematic studies will be made leading to an optimized chemical (conditioning) and electrochemical (forming) process. In actuality the work of Events 4 and 5 will tend to run concurrently in order to minimize the development period.

EVENT NUMBER-5

TITLE OF EVENT: Order Molds and Tooling

DESCRIPTION OF EVENT: As soon as the grid drawings are complete (Event 2) the grid and other molds needed for the TP-1 battery units will be placed on order. At the same time orders will be placed for all the required purchased parts such as tubes, separators, containers, and covers.

EVENT NUMBER-6

TITLE OF EVENT: Cast Grids

DESCRIPTION OF EVENT: When the new molds are received they will be placed in suitable production type machinery and sufficient positive and negative grid castings made for the entire TP-1 project. The alloy to be used for the positive grid is tentatively selected as a 2 1/2% antimony-lead alloy with other additives. The negative will be made from a lead-calcium or modified lead-calcium alloy.

EVENT NUMBER-7

TITLE OF EVENT: Fill Positive and Paste Negatives

DESCRIPTION OF EVENT: Making use of skills developed in Event 3 the positive tubes will be filled with pilot plant equipment. The negatives will be pasted on standard production machinery. Post filling treatment of the positive will be as developed in Event 4.

EVENT NUMBER-8

TITLE OF EVENT: Assemble Cells

DESCRIPTION OF EVENT: Battery parts will be assembled as described in FP-1 Event 6. The cells will then receive the electrochemical processing developed in Event 4.

EVENT NUMBERS-9 to 13

TITLE OF EVENT: Testing

DESCRIPTION: Follow exactly the procedures outlined under FP-1 Events 7 to 11.

EVENT NUMBER-14

TITLE OF EVENT: Analyze Data: Select Best Combination

DESCRIPTION OF EVENT: From the data obtained from Events 9, 10, 11 and 13 an evaluation of the variables of the TP program will be made and the optimum battery unit selected.

EVENT NUMBER-15

TITLE OF EVENT: Select ISOA Design

DESCRIPTION OF EVENT: It must be pointed out that at FP Events 13 - 14 (weeks 26-28) the flat plate program can be readily switched from the EV-106 battery unit to a new unit or assembly, if dictated by ANL studies. For the tubular program the only opportunity for such a change is at either week 3 or week 72. In any case at week 72 information will be available to make a selection between the optimum flat plate and optimum tubular plate design, although the complete life test information will probably not be available. If the tubular design is chosen and if the flat plate battery is already converted to the final ANL requirement a new tubular type grid mold will be needed. In order to hold to the schedule a special effort will be required to obtain the new mold in the shortest possible time. Preparation including the new grid drawings for this must be started at week 26. Other parts will be the same as the FP-2 design.

6.2 Decision Points

It is to be noted that several decision points are shown on the ISOA Activity Chart (Figure 6-1). These include Events 12 and 24 in the flat plate program, Event 14 in the tubular plate program and the final Event "Select ISOA Design". At each of these points ESB will review all test and other pertinent data with ANL. It is proposed that the decisions reached will combine input from both ANL and ESB. The decision to eliminate either the flat plate or the tubular plate approach may be made at any time whenever experimental data or economics dictate such a decision is valid.

7 ADVANCED LEAD ACID BATTERY PROGRAM

7.1 Introduction

The objective of the proposed advanced battery program is to design, develop, and fabricate a lead acid battery which will meet the technical, economic and ecological goals of electric vehicle operation and service.

In designing high specific energy density lead acid batteries for electric vehicles emphasis must be placed on three areas: (a) reducing the weight of the battery, (b) maximizing the active material utilization and (c) providing sufficient heat transfer to and from the battery during service. The solution to these problems must be made within the economic constraints of an installed battery cost of \$40/kWh. Some of the impediments to high rate applications of the system can be minimized by employing the designs and approaches proposed earlier for the ISOA battery. Further progress can be achieved only by more pronounced departures from present motive power designs. ESB will undertake on a best effort basis the design, development and production of an advanced electric vehicle battery with target specifications shown in Table 7-1.

7.2 Program Outline

Two approaches will be taken. The primary effort will be directed toward the development of an electric vehicle battery based on the tubular positive electrode concept. This construction has the inherent virtue of long life and estimated specific energy at electric vehicle rates of discharge equal to or better than flat plate constructions.

The approach taken for the ISOA battery will be expanded to incorporate consideration of box and composite grid constructions using lightweight materials and designs different from those presently used in the battery industry. Efforts will be focused on drastic battery weight reduction and active material utilization while retaining or improving the good cycle life characteristics of tubular construction when operating at the higher rate regimes.

Table 7-1

ADVANCED EV BATTERY SPECIFICATIONS

Duty Cycle	2-4 hr discharge 4-8 hr charge
Energy Efficiency (turn around)	80%
Cycle Life*	1000 cycles
Installed Cost (1976 dollars)	\$40/kWhr
Specific Energy	60 Wh/Kg (27 Wh/lb) @C/3 rate**
Specific Power***	30 W/kg sustaining (13.6 W/lb) 150 W/kg peak (68 W/lb)
Typical Installation Size	20-30 kWh
Environmental Impact	Minimal

* Corresponding to 70-80% depth-of-discharge

** "C" is defined as the capacity in ampere hours to 1.75 V/Cell at the 3-hour discharge rate under a constant current regime, at 25°C.

*** Assuming a 108V or greater system.

A secondary effort will be undertaken concurrently with the primary study to investigate a pile type electric vehicle battery. This design is capable of delivering the high specific energy required by electric vehicles but presently does not have the required cycle life. The bipolar concept would radically reduce the weight of the current collecting structure and at the same time provide the shortest current path between cells. The ultimate objective will be to develop an advanced battery with suitable cycle life without sacrificing the high energy density inherent in bipolar construction.

This dual approach increases the probability of developing a viable electric vehicle advanced battery. It places the greatest development effort on an advanced version of a well established tubular design while directing a parallel effort to solve the major barrier problems associated with the bipolar battery. The chance of success is therefore greatly enhanced with an efficient expenditure of effort.

7.3 Tubular Battery Approach - Initial Design

The design parameters (Table 7-2) incorporated in the initial model (AB-1) of ESB's advanced tubular battery address themselves to five major requirements: (a) weight reduction, (b) increase in active material utilization, (c) maintenance of cycle life, (d) heat transfer during service, (e) low maintenance operation. The approaches used to achieve each of these requirements will be discussed in subsequent paragraphs.

7.3.1 Positive Electrode

The initial model will have 23 plates, 11 positive and 12 negative. A drawing of the positive electrode is shown in Figure 7-1. Each positive plate will be composed of 12 tubes containing a low density active material. The tubes

Figure 7-1

Table 7-2

Design Parameters for the Advanced Tubular Battery

Model AB-1

3-Cell Battery Components

Positive grids	2.640 Kg.
Positive active material	6.000 Kg.
Negative grids	1.020 Kg.
Negative active material	4.950 Kg.
Electrolyte	9.600 Kg.
Separator	0.200 Kg.
Plastic & tubes	0.600 Kg.
Straps (neg.Cu)	0.300 Kg.
Container & Cover	1.040 Kg.
	<hr/>
	26.350 Kg.
Separator Thickness - mm	0.1
Spacers - mm	0.9
Spine dimensions (mm) 1.9 x 1.1 tapered to 1.9 x 0.5 and 171 mm long.	

Projected Performance Calculation Based on Model AB-1

Average voltage @ 3 hr rate = 2.03V with sulfuric acid
of 1.34 sp.gr.

Capacity	250 Ah
kWh	1.522
Whr/Kg - Battery	57.7

Development efforts will be directed toward increasing the performance to the 60 Wh/Kg goal.

will have a rectangular cross section and will have the thickness of the positive plates used in the ISOA flat plate design. Each tube will contain two spines tapered from top to bottom to allow a more uniform active material utilization along the path of the tube. Variations in grid-active material geometry including the size, amount of taper, and spacing of the spines will be studied to optimize active material utilization without increasing the grid corrosion beyond acceptable limits. Non-antimonial alloys such as Pb-Te-As-Ag and Pb-Ca-Sn will be used for these spines. The first alloy has been used successfully by AB Tudor in deep cycle submarine batteries for the last ten years. Deep cycle behavior of some of these alloys in EV applications is not well established and so must be characterized. Studies will be made to evaluate the effect of pre-anodization of spines followed by treatment with hydrophobic organics as a corrosion retardant. The amount of water loss during cycling of these alloys will also be measured to determine the amount of water required for the single point automatic watering system planned for use with the EV battery during its operation.

Thin braided glass fiber, reinforced by cross linked polyethylene will initially be used for the tubes, but other materials may be evaluated.

7.3.2 Positive Active Material

The spines will be embedded in a low density positive paste with proprietary paste formulations [*].

[*] This section contained proprietary data that has been deleted from this report.

The lower weight per volume will permit more efficient active material utilization. This active material will be loaded into the tubes either in the form of a dry granulated lead oxide or as an extruded paste. A free-flowing granulated pre-sulfated lead oxide powder has been developed at ESB for filling tubes, and its efficiency will be verified by tests in fuel size cells.

The top bar weight of the positive electrode will be reduced by using aluminum instead of lead. The aluminum will be sequentially coated with lead and plastic for corrosion protection. The positive lug will be located near the center of the plate rather than towards one side to equalize the current paths in the plate.

A bottom bar made of plastic will be used to close the ends of the tubes in the positive electrode. The spines will not touch the bottom bar to allow space for a nominal amount of spine growth.

A unique tube assembly of the positive electrode will be used in which the assembly is wrapped in one layer of a polyolefin plastic net fused to the tubes to impart additional physical strength to the electrode. Thin flat plastic separators rather than rib type separators will be used in the cell assembly.

7.3.3 Negative Electrode

The negative electrode will consist of a framework type plastic spacer to hold the active material (Fig. 7-2). This will be covered by a perforated metal coated plastic current collector which will be bonded by fusion to the underlying plastic spacer. The perforated current collector will be sequentially plated on both surfaces with copper and then lead. Thus the negative current collector will rest against the outside surface of the active material rather than being embedded in the interior as in standard constructions.

This will expedite the formation and cycling reactions which normally proceed from the outer surface on the negative electrode. The composite negative electrode concept has the appeal of offering a potential method for continuous electrode production. A process must be designed to fabricate the electrodes on a commercial scale. Some steps in the envisioned process such as the fusion of plastic networks to plastic spacers filled with lead paste, and the metal plating of plastic, are known technology.

7.3.4 Negative Active Material

The negative active material paste formulation will contain up to 30 volume percent of graphite in addition to the normal amount of negative expander. Graphite will increase the conductivity of the active material.

7.3.5 Separator

The selection of a suitable plastic separator material for the advanced battery will be undertaken. It will be non-ribbed and thin and will be selected on the basis of high electrical conductivity, suitable strength and porosity as well as resistance to sulfuric acid, oxidation and heat. The initial separator of choice will be Yumicron of 0.1 mm. thickness made by Yuasa Co. Ltd. of Japan.

7.3.6 Electrolyte

The specific gravity of the sulfuric acid electrolyte will be increased from the normal 1.290 to 1.340 to obtain an additional increase in energy density. Provision may be made to pump the electrolyte during charge to prevent acid stratification and to insure more efficient utilization of the active material.

7.3.7 Battery Case

The positive and negative electrodes after being formed will be assembled into elements and placed in a three compartment EV-106 battery case. High Heat transfer plastics will be evaluated as the initial battery case material of choice.

7.3.8 Heat Transfer

Provision for adequate transfer of heat is mandatory for the Advanced high energy density battery. Heat dissipators will be included in the assembly of the EV battery from the sub-module (EV-106) units. The outer surface of each sub-module unit will be sprayed with aluminum. Sheets of aluminum or aluminum foil projecting above the battery will be placed between each sub-module during assembly of an EV battery. These "heat fins" will be cooled by small auxiliary fans or by intake vents built into the electric vehicle design. The completed 120 V electric vehicle battery module will contain twenty 6V sub-modules in two equal rows. It will be approximately 264 cm long, 40.5 cm wide and 28 cm high. The width dimension includes an allowance of 4.5 cm spacing around the rows or modules to allow air cooling.

ESB will create an analytical thermal network model of the actual battery configuration which will predict temperature distribution within the battery when cooled by alternative cooling configurations and fin material.

An individual battery and different "close packed" battery arrangements will be evaluated. The thermal model will be confirmed by testing some of the analyzed configurations to see if actual temperatures agree with predictions.

7.3.9 Alternate Electrode Designs

The initial tubular design described in the preceding paragraphs was conceived to optimize performance, i.e., high specific energy density and adequate cycle life as primary objectives. A value analysis of the developed electrodes will be made with the goal of retaining the optimized performance but lowering the projected manufacturing costs. Tubular designs have inherently high cost factors such as tube weaving machines, tube filling equipment and electrode assembly labor. Cost reductions can be accomplished through the elimination of the tubular construction and the development

of designs more suitable for automated production. Composite grid concepts such as those illustrated in Figs. 7-3 and 7-4 will be investigated in an effort to achieve lower costs.

The positive electrode (Fig. 7-3) will consist of tapered alloy spines sandwiched between plastic rectangular frameworks which are thermally joined to impart strength to the electrode. This construction will be pasted and conditioned in the usual manner for flat plates. It will be inserted into a separator envelope composed of crossed layers of glass fibers thermally bonded to a thin polyethylene net.

The negative (Fig. 7-4) will be composed of a polyethylene framework to hold the active material. A relatively open mesh screen of interwoven strands of polypropylene and lead plated copper wires, which serves as a current collector is placed over the framework and thermally welded to it. Development studies will be made to determine if pasting can be accomplished most satisfactorily before or after emplacement of the current collector screen. Different types of pasting procedures will be evaluated to assure adequate active material distribution and to minimize damage to the lead plating of the screen. Electrode constructions along the lines of the concept described offer potential advantages of decreased weight i.e., higher specific energy density, and lower costs because of amenability to automated manufacturing methods.

7.4 Bipolar Battery Approach

7.4.1 Bipolar Battery Advantages

A one calendar year - two man year effort will be undertaken to develop a bipolar electrode partition suitable for an electric vehicle pile type battery. Development studies will be focused on two main problem areas: (a) corrosion of the partition and (b) retention of the positive and negative active material on the partition during the deep-cycle high discharge rate regime. Assuming this effort is totally successful, then the bipolar program will be continued.

Figure 7-3

Figure 7-4

The bipolar system potentially fulfills many of the requirements for the electric vehicle propulsion, namely high active material utilization, low internal resistance and low weight. In this design the positive and negative active material are respectively spread over the surfaces of opposite sides of a supporting partition. The active material can be applied in a relatively thin layer affording excellent access to electrolyte and high active material utilization. A series of these bi-polar electrodes are stacked together with separators to constitute a battery. In such a construction the active material contact area with grid and electrolyte is maximized. Energy losses arising from the electronic resistance of the active material and the high ionic resistance of the electrolyte within the pores of the active material are minimized. In normal plate constructions there is uneven electrochemical cycling of the material because of IR losses along the plate as one moves away from the current collector tab. The material closest to the tab is cycled to a greater degree than material farther away. In the bipolar configuration electronic current flows through the partition from the positive of one cell to the negative of the next cell transversely rather than longitudinally as would be the case in the flat plate or tubular construction. Uniform working of the active mass is thus achieved and IR losses associated with intercell connectors, straps, etc. are eliminated. Such decreases in IR losses translate into a higher rate capability for the same weight of active material.

The intrinsic disadvantage of the bipolar design arises from the fact that all cells in the battery must be linked in series. Accordingly, the system requirements for individual plate reliability are higher than those for the other configurations where intra-battery paralleling of plates reduces the need for high individual plate integrity.

7.4.2 Bipolar Battery Disadvantages

Theoretically the lead acid system ought to be bipolar, yet today's systems are not. The question "Why not bipolar?" should be addressed in some detail.

The requirements for a suitable bipolar partition in the Pb acid system are the following:

1. A thickness of $<1\text{mm}$.
2. Negligible corrosion rate.
3. Absence of rectifying contacts.
4. High overvoltages for O_2 and H_2 evolution.
5. Good electrical conductivity.
6. Ability to maintain contact with the active material.

The problem has been to find a material which can satisfy all these requirements. For example, lead itself would be an obvious choice satisfying conditions 3-6, but unfortunately it has a corrosion rate which is too great. Intergranular corrosion on the positive side of the bipolar element soon penetrates to the negative side and the partition develops an ionic short (electrolyte penetration).

On the other hand, titanium has outstandingly good corrosion resistance but, when polarized anodically, builds a highly resistive surface layer of TiO_2 ; i.e., it exhibits rectifying behavior and does not permit current flow in the anodic (or charging) direction. This property, however, is not totally debilitating and in the past titanium has been investigated by a number of people, particularly S. Ruben, as a grid material in the lead acid battery. Most such studies have involved precoating or preplating the titanium surface with a thin layer of titanium carbide, titanium silicide, gold or nickel, etc. to prevent contact of the titanium surface itself with the electrolyte, and hence circumvent the formation of a rectifying layer. The precoat is then plated with a layer of lead and corrosion of this lead layer helps maintain the active material contact to the titanium grid. As with all such attempts to place something

Over or on the titanium oxide barrier layer, failure occurs when the lead coating is completely corroded through to the gold or nickel sub-surface. In the latter case, the nickel is anodically dissolved permitting the titanium-acid interface to form a rectifying barrier layer. With gold-coated titanium grids the corroded lead layer detaches from the gold and contact is lost between the grid and the active material. Many promising areas of research, however, remain to be pursued with titanium and we shall discuss to this later (7.4.3.1).

The fact that there are very few metals or alloys which have the required oxidative stability in sulphuric acid solutions has directed attention to the concept of conductive plastic partitions. Here electrical conductivity of the partition becomes a variable of increased concern, and most prior work has primarily focused on carbon or graphite as the current carrier. Many plastic materials exhibit excellent chemical stability - particularly the thermoplastics such as polycarbonate, PVC and polysulfone. When made electrically conductive with carbon, however, there is severe attack at the carbon-plastic interface since carbon is not a chemically inert material under strong oxidizing conditions.

[*]

[*] This section contained proprietary data that has been deleted from this report.

Pages 101-118 inclusive are proprietary and are not included in this volume of the proposal. They deal with detailed research, design, and development plans for the bipolar lead-acid battery effort.

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8 Advanced Battery Reduction to Practice

8.1 Description of Tasks - Activity Chart

An activity flow chart presenting the principal events in ESB's proposed program for the Advanced battery development using the two approaches previously described is shown in Figure 8-1. The numbers on the upper corners of each event represent the time in weeks scheduled for that event after the initiation of the project.

EVENT NUMBER-1

TITLE OF EVENT: Tubular Battery

DESCRIPTION OF EVENT: Notify and confirm all personnel and task assignments, reporting Procedures, work locations and review the objectives of the Advanced Tubular Battery Development Program. Order all required materials for prototype cell constructions.

EVENT NUMBER-2

TITLE OF EVENT: Preparation of Prototype Cell Designs

DESCRIPTION OF EVENT: Finalize dimensional drawings showing construction details of the initial design of the tubular battery. Drawings will include the positive and negative electrodes, the cell element assembly and the sub-module battery configuration. Order the mold for fabrication of the negative grid spacer.

EVENT NUMBER-3

TITLE OF EVENT: Positive Electrode Development

DESCRIPTION OF EVENT: A positive electrode for the tubular battery will be developed and the construction and evaluation of the initial conceptual design will begin. A series of development studies will be undertaken and will include the following investigations:

DESIGN BY		DATE		ESB INCORPORATED	
DRAWN BY		DATE		RESEARCH CENTER	
CHECKED BY		DATE		VANDERBILT UNIVERSITY	
DO NOT SCALE DRAWING					
FUNCTION	REVISION	APPROVED	MANUFACTURED	DATE	SCALE
A	1	A	CC	8231000	

Figure 8-1

(a) the corrosion behavior of the Pb-Ca-Sn and Pb-Te-As-Ag alloys under deep discharge high rate regimes;

(b) the effect of anodic pre-treatment of the spines on corrosion;

(c) adhesion of positive active material to the grid of Pb-Ca-Sn and Pb-Te-As-Ag alloys.

(d) evaluation of the electrochemical performance and fabrication problems associated with the use of light materials such as lead plated aluminum in the top bar construction. Single tube cycling according to the PMS* Test regime will be used to evaluate capacity, cycle life and active material/grid retention parameters. Constant current charge tests will be used to evaluate grid corrosion. In addition to the electrical tests, elemental, x-ray diffraction, optical and SEM analysis will be employed as investigative tools in these studies. The use of alternate electrode materials and processes will be evaluated as required and will be based on economic considerations and on the results obtained during the developmental studies. All electrode construction and processing concepts will be developed in close cooperation with ESB's manufacturing divisions in order to evaluate their production feasibility

EVENT NUMBER-4

TITLE OF EVENT: Negative Electrode Development

DESCRIPTION OF EVENT: A light-weight negative electrode for the tubular battery will be designed and developed commencing with the construction of the initial conceptual design described in Section 7.3.3. A series of development studies will be undertaken and will include the following investigations:

(a) an evaluation of the physical and chemical behavior of plastic cell components;

(b) the integrity and electrochemical effectiveness of the plated negative Current Collector;

* Positive material shedding

(c) optimization of the negative active material;
(d) evaluation of alternative negative current collectors for lower cost. The same test regimes and analytical procedures outlined for the Positive Electrode Development will be used for the negative investigations.

EVENT NUMBER-5

TITLE OF EVENT: Alternate Cell Models Assembly

DESCRIPTION OF EVENT: The cells based on the initial design as well as test cells made to evaluate alternate materials and processes will be assembled. Each cell will be identified by number and documented with component weight and dimensional data.

EVENT NUMBER-6

TITLE OF EVENT: Alternate Cell Module Testing

DESCRIPTION OF EVENT: The initial cell design and other test cells made to evaluate alternate materials and processes will be tested to determine: Capacity vs discharge rate at normal, low and high temperature; charge acceptance vs temperature, charging rate or maximum allowed charge voltage, and charge retention according to the schedules outlined in Section 9.

EVENT NUMBER-7

TITLE OF EVENT: Life Testing

DESCRIPTION: Five - 23 plate cells of each alternate model will be life tested according to the test schedule specified in Section 9.

EVENT NUMBER-8

TITLE OF EVENT: Alternate Cell Models Data Analysis and Model Selection

DESCRIPTION OF EVENT: The test data from Event-7 will be compiled and analyzed. A report of the analysis will be issued. A prototype cell model will be selected based on an evaluation of the test data and a consideration of manufacturing cost.

EVENT NUMBER-9

TITLE OF EVENT: Prototype Battery Design Preparation
DESCRIPTION OF EVENT: Detailed drawings of a prototype Advanced EV battery with the selected cell design will be made. The design package will include sub-assembly instructions and drawings. A bill of materials and a listing of all required tooling will be included.

EVENT NUMBER-10

TITLE OF EVENT: Order Tooling and Materials
DESCRIPTION OF EVENT: All required tooling and materials for the construction of ten (1) sub-module test batteries will be ordered. The availability and schedule of delivery dates for all items will be determined.

EVENT NUMBER-11

TITLE OF EVENT: Positive Spine Casting
DESCRIPTION OF EVENT: Spines will be cast for the tubular positive electrode. The dimensions and alloy type used will be those selected on the basis of development studies and data analysis in Events-3 and -7.

EVENT NUMBER-12

TITLE OF EVENT: Positive Tube Fabrication
DESCRIPTION OF EVENT: Positive tubes of fine glass braid will be fabricated. The tube dimensions, and weave specifications will be based on the development studies in Event-3.

EVENT NUMBER-13

TITLE OF EVENT: Negative Spacer Fabrication
DESCRIPTION OF EVENT: A plastic, rectangular framework spacer to hold the negative active material will be fabricated by injection molding.

EVENT NUMBER-14

TITLE OF EVENT: Negative Current Collector Fabrication
DESCRIPTION OF EVENT: A perforated metal coated plastic negative Current Collector will be designed and fabricated.

EVENT NUMBER-14 (cont)

A polyolefin plastic may be used which will be sequentially coated with copper by electroless plating and then with lead by electroplating. The plastic is included for strength considerations. It is conceivable that alternative constructions not requiring plastic may be developed in Event-4 and would influence the fabrication process in this event.

EVENT NUMBER-15

TITLE OF EVENT: Positive Paste Preparation

DESCRIPTION OF EVENT: The positive paste will be prepared using the paste formulation optimized in the development studies. A sufficient quantity of paste will be made to paste 330 positive electrodes.

EVENT NUMBER-16

TITLE OF EVENT: Positive Plate Assembly

DESCRIPTION OF EVENT: The spine and top bar assembly will be inserted into the braided glass tubes which will, in turn, be filled with positive active material. The bottom of the tubes will be closed by being heat sealed to a plastic bottom bar. The assembled plate will then be conditioned as worked out in the ISOA tubular plate studies.

EVENT NUMBER-17

TITLE OF EVENT: Negative Paste Preparation

DESCRIPTION OF EVENT: The negative paste will be prepared using the paste formulation optimized in the development studies. A sufficient quantity of paste will be made for 360 negative electrodes.

EVENT NUMBER-18

TITLE OF EVENT: Negative Plate Assembly

DESCRIPTION OF EVENT: The plastic rectangular framework spacer will be pasted with negative active material. The pasted spacer will be covered with a perforated metal coated plastic current collector which will be bonded by fusion to the underlying spacer. The assembled negative plate will then be conditioned.

EVENT NUMBER-19

TITLE OF EVENT: Tubular Prototype Formation

DESCRIPTION OF EVENT: Completed prototype batteries will be tank formed against dummy negative plates as worked out in the ISOA tubular plate studies.

EVENT NUMBER-20

TITLE OF EVENT: Tubular Prototype Battery Assembly

DESCRIPTION OF EVENT: The positive and negative electrodes separated by plastic separators will be assembled into 23-plate elements. Three of these elements will be assembled into a complete battery using EV-106 containers. Ten (10) prototype batteries will be constructed.

EVENT NUMBER-21

TITLE OF EVENT: Tubular Prototype Battery Testing

DESCRIPTION OF EVENT: Ten (10) completed prototype batteries will be submitted to the Q.C. group for the performance tests specified under Section 9 of this Proposal.

EVENT NUMBER-22

TITLE OF EVENT: Battery Test Data and Prototype Analysis

DESCRIPTION OF EVENT: Test data on the tubular prototype battery will be compiled, analyzed and the result included in a report which will serve as a basis for the battery model selection in EVENT-36. The report will include performance data summaries, duty cycle of test, cycle life, specific energy, specific power, installed cost, environmental impact, special tool, material or processing aspects, comments on advantages and/or limitations of the prototype. Copies of the report will be furnished to ANL for their review and for their input in EVENT-36.

EVENT NUMBER-23

TITLE OF EVENT: Bipolar Battery

DESCRIPTION OF EVENT: Notify and confirm all personnel and task assignments, reporting procedures, work locations and review the objectives of the bipolar electrode development program.

EVENT NUMBER-24

TITLE OF EVENT: Preparation and Acquisition of Test Materials

DESCRIPTION OF EVENT: Order materials required for bipolar partition fabrication. Initiate the preparation of experimental bipolar partitions.

EVENT NUMBER-25

TITLE OF EVENT: Bipolar Partition Development and Fabrication

DESCRIPTION OF EVENT: Two (2) alternative bipolar substrate configurations will initially be constructed and evaluated.
[*]

EVENT NUMBER-26

TITLE OF EVENT: Testing of Alternate Bipolar Cell Model

DESCRIPTION OF EVENT: Bipolar electrodes will be made from substrates which demonstrate suitable electrochemical characteristics. Batteries composed of three bipolar electrodes and a positive and negative terminal electrode will be constructed and subjected to an accelerated life cycle test. The following cycle test will be performed at a temperature of 55°C, corresponding to an acceleration factor of 10: discharge for 100 minutes at the 2 hour rate; charge for 8 hours using a modified constant potential technique starting at the 4 hour rate until the gassing point is reached which will be 2.3 volts per cell for pure lead at this temperature. For the remainder of the charging period the potential will be kept at this value. The total charge input should be 103% to 105%.

EVENT NUMBER-27

TITLE OF EVENT: Test Data Analysis and Bipolar Decision Point

DESCRIPTION OF EVENT: The test data from EVENT-25 will be compiled and analyzed. A decision will be made whether a suitable bipolar electrode for electric vehicle applications can be developed.

[*] This section contains proprietary data that has been deleted from this report.

EVENT NUMBER-27 (cont)

If such a development study does not appear attractive, further work on the advanced bipolar battery concept will be cancelled and EVENTS-27-32 will be eliminated. A report of the analysis will be issued.

EVENT NUMBER-28

TITLE OF EVENT: Bipolar Battery Development

DESCRIPTION OF EVENT: If the work in bipolar partitions will have been successful, a detailed program to further develop the complete pile battery will be laid out. Details for this program must await final design of the partition. Major tasks will include peripheral sealing design, heat transfer considerations, venting, materials selection, and electrolyte filling. It is expected that before the actual decision point (Event 27) is reached, plans will be started.

EVENT NUMBER-29

TITLE OF EVENT: Life Testing

DESCRIPTION OF EVENT: The selected bipolar cell model will be life tested. Five (5) test cells containing three (3) bipolar electrodes and a positive and negative terminal electrode for each alternate model will be tested according to the schedule outlined in Section 9.

EVENT NUMBER-30

TITLE OF EVENT: Positive Paste Preparation

DESCRIPTION OF EVENT: The positive paste formulation will be mixed. The paste will meet specified density and plasticity requirements developed in FVENT-29.

EVENT NUMBER-31

TITLE OF EVENT: Negative Paste Preparation

DESCRIPTION OF EVENT: The negative paste formulation will be mixed. The paste will meet specified density and plasticity requirements developed in EVENT-29.

EVENT NUMBER-32

TITLE OF EVENT: Bipolar Electrode Fabrication

DESCRIPTION OF EVENT: Bipolar electrodes will be fabricated to conform to the model developed in EVENT-29. Sufficient electrodes will be fabricated to construct fifteen (15) cells containing three (3) bipolar electrodes.

EVENTS NUMBER 33-35

TITLE OF EVENTS: 33. Bipolar Battery Formation

34. Bipolar Battery Assembly

35. Bipolar Prototype Battery Testing

DESCRIPTION OF EVENTS: These events will be planned in detail only if the bipolar battery partition work is successful (see Event Number 28).

EVENT NUMBER-36

TITLE OF EVENT: Prototype Battery Model Selection

DESCRIPTION OF EVENT: A prototype model will be selected based on the test data and prototype reports generated in EVENTS 21 and 35. A meeting to discuss the selection will be held. ANL representatives will be invited to participate in the meeting.

EVENT NUMBER-37

TITLE OF EVENT: Prototype Battery Production Documentation

DESCRIPTION OF EVENT: Pre-Production Specifications of the selected prototype battery will be prepared. Included in this documentation will be material specifications, sub-assembly instructions with drawings, a bill of materials and a listing and description of all required tooling.

EVENT NUMBER-38

TITLE OF EVENT: Order Tooling and Materials

DESCRIPTION OF EVENT: All required tooling will be ordered for the construction of seventeen (17) prototype electric vehicle batteries. The availability and scheduled delivery dates of each required item will be determined.

NOTE: Future Events (39-45) assume that the tubular plate battery will have been chosen. These will be modified for the bipolar battery if it is chosen.

EVENT NUMBER-39

TITLE OF EVENT: Positive Paste Preparation

DESCRIPTION OF EVENT: The positive paste formulation will be mixed. The paste will be tested to meet specified density and plasticity requirements. The positive electrodes will be pasted or filled with active material. The weights of the completed electrode will be checked to verify that they are within the specified range. Electrodes will be conditioned according to procedures outlined in the pre-production specifications.

EVENT NUMBER-40

TITLE OF EVENT: Positive Electrode Fabrication

DESCRIPTION OF EVENT: Positive electrodes will be fabricated in accordance with pre-production specifications.

EVENT NUMBER-41

TITLE OF EVENT: Negative Paste Preparation

DESCRIPTION OF EVENT: The negative paste formulation will be mixed. Final paste will meet specified density and plasticity requirements.

EVENT NUMBER-42

TITLE OF EVENT: Negative Electrode Fabrication

DESCRIPTION OF EVENT: Negative electrodes will be fabricated in accordance with pre-production specifications. Negative electrodes will be pasted. The weights of the completed electrode will be checked to verify they are within the specified range. Electrodes will be conditioned according to procedures outlined in the pre-production specifications.

EVENT NUMBER-43

TITLE OF EVENT: Prototype Battery Assembly

DESCRIPTION OF EVENT: Individual EV battery sub-modules will be assembled in accordance with pre-production specification. Q.C. checks will be preformed for proper cell polarity, electrical shorts and proper cover to container sealing.

EVENT NUMBER-44

TITLE OF EVENT: Prototype Battery Formation

DESCRIPTION OF EVENT: Batteries will be container formed in the assembled condition or tank formed depending upon the prototype model selected and cost considerations. Formation will precede battery assembly if tank formation is used.

EVENT NUMBER-45

TITLE OF EVENT: EV Battery Construction

DESCRIPTION OF EVENT: Seventeen (17) EV Batteries will be constructed from individual prototype sub-modular units. The EV batteries will conform to ANL dimensions.

EVENT NUMBER-46

TITLE OF EVENT: ESB Testing of EV Batteries

DESCRIPTION OF EVENT: Two (2) EV batteries will be tested according to performance schedules similar to those used by ANL (Event 47).

EVENT NUMBER-47

TITLE OF EVENT: ANL Testing of EV Batteries

DESCRIPTION OF EVENT: Fifteen (15) EV batteries will be shipped to ANL. All batteries will be numbered and accompanied by production background data. They will be packaged and shipped in a manner that will afford adequate protection against physical and environmental damage during shipment, handling and limited in-transient storage. Interior packages and exterior shipping containers will be marked in accordance with MIL-STD-129.

8.2 Decision Points

Three major decision points are indicated in the activity charts. In Event-8 the data obtained from testing the initial tubular model as well as other alternative models fabricated during the development studies will be evaluated. The tubular model which most adequately satisfies the E.V. battery performance and cost goals will be selected during this event.

ESB's secondary effort will involve a one calendar year - two man year effort to develop a bipolar electrode partition suitable for an electric vehicle pile type battery. Development studies will be focused on two main problem areas: (a) corrosion of the partition and (b) retention of the positive and negative active material on the partition during a deep cycling high discharge rate regime. At the end of this calendar year another decision point (Event-27) will be reached. The progress achieved toward obtaining a viable bipolar electrode for EV applications will be evaluated and a go/no go decision will be made regarding continuation of the bipolar program.

A third decision point will occur in Event 36. The final sub-module prototype for the advanced electric vehicle battery will be selected.

9 TESTING AND EXAMINATION OF CELLS/BATTERIES

9.1 Pre-Test Examination

Prior to testing, all batteries will be identified by type and number. Consecutive numbers for batteries and decimal for individual cells of a battery will be used. This information will be engraved on the battery cover and will be traceable to detailed assembly records giving a complete description of cell components. Knowledge of active material weight and distribution is necessary to estimate appropriate discharge rates.

An inspection of the exterior of the battery will note the presence of leaks at terminals, cover seals or damaged areas. Terminals should be clean and dry and be of specified type and configuration. If the battery is composed of a number of individual units, the interconnections should also be clean, secure and properly insulated. After visual inspection, the exterior will be washed if necessary with a gentle stream of water and wiped or blow-dried with low pressure air.

The following will be recorded to establish compliance with design specifications:

- Battery weight (dry and filled if applicable)

- Battery dimensions

- Electrolyte specific gravity (corrected to 25°C)
measured at full state of charge and normal
electrolyte level.

Electrical measurements which are to be conducted prior to test to assure conformance to specification are:

- Open circuit voltage

- Internal resistance

- Charging voltage (corrected to 25°C) measured at a
current corresponding to one-half the 20 hr rate
(including both cell and half-cell data)

9.2 Post-Test Examination - Applicable to Life Test Cells

Destructive inspection following test is often carried out to determine the condition of cell components or to establish a reason for failure in the case of life tests. In addition, such inspections are usually the only way of verifying that the cell or battery was constructed according to specifications. Therefore, records of inspection will include a detailed inventory of cell components.

Prior to the examination of the interior of a battery, it will be charged (after adding water as required to restore normal level) to a constant specific gravity at the 25 hr rate. When this condition is attained, the following data will be recorded:

- Cell and half-cell potentials during charge

- Cell temperatures

- Specific gravity (corrected to 25°C) for each cell

- Battery weight and dimensions (note any bulging of end walls)

After removal of electrolyte the battery will be opened in such a way as to minimize disturbance of plates, separators and sediment. When the element has been exposed, a photo record may be made before proceeding with the inspection. The flat plates and separators (or tubular plates and retainers) can then be removed in sequence and samples retained for record before and after stripping the active material to expose the grid or spines. If there is visible evidence of separator or sediment shorting or tubing failure, it will be photographed before continuing tear-down. Separators will be inspected for evidence of pinholes, splits or oxidative attack. The condition of the negative active material will be noted as to extent of expansion or shrinkage and visible indications of sulfate zones such as white material on the surface of the plate. In some cases it may be desirable to determine the PbSO_4 content of the active material.

Positive plates will be inspected to record degree of active material shedding and condition of remaining active material. For positive grids, the amount of corrosion and grid growth can be established by measuring weight loss and dimensional changes. The condition of tubular positive plates should be recorded by noting the number and location of tube splits and extent of spine corrosion. A change in the cross-sectional shape of the tube will also be noted.

Chemical analyses will be carried out to detect harmful impurities when their presence is indicated, e.g., by abnormally low charge voltage or other anomalous behavior. Microscopic examination (optical and SEM) will be carried out when unusual corrosive attack is noted or when it is desirable to record the condition of the grid (or spine) to active material interface.

9.3 Test Schedule and Standards

9.3.1 Objective

Electrical capacity tests will be conducted (1) to thoroughly characterize performance of new cell designs and (2) to establish the cycle life of selected batteries. To be selected for life testing, a cell design must meet the minimum performance standards for appropriate development phase (ISOA or advanced battery design).

9.3.2 Design Evaluation Testing

All new designs will be subjected to a maximum of thirty-four complete discharge-charge cycles to determine the following characteristics:

Capacity vs discharge rate at normal, low and high temperature

Charge acceptance vs temperature, charging rate or maximum allowed charge voltage.

Charge Retention

The time period required for completion of the full 34 cycle program is 14 weeks. Equipment and personnel resources are allocated on the assumption that the maximum number of 3-cell 6 volt batteries which will be undergoing

test at any given time will not exceed 72. This number of batteries covers 36 construction variations, each variation being represented in six identical cells or two batteries. The initial tests are also scheduled to avoid conflicts among the several development phases of the 48 month program.

9.3.2.1 Test Equipment

The electrical test equipment planned for the ISOA and Advanced Battery development will comprise the following:

A large constant voltage rectifier feeding the several individual circuits: Power from the rectifier will be used for battery charging.

A series of load modules: Each module will have a power dissipation capability of 3 kW with a limit of 150 amperes or 50 volts. Where loads greater than these limits are required, modules can be placed in parallel or series arrays. However, ESB plans to operate additional modules of greater capacity. The load modules comprise a series of transistor banks controllable by a DC voltage input. Load modules will be used for the control of charge as well as discharge current.

A fully automatic data logging memory: This memory will collect all pertinent data relating to the performance of each three cell battery unit throughout the test schedule. Permanent records will be placed on magnetic tape and print-outs will be obtained as required.

The use of programmable load modules will permit ESB to test battery units under transient as well as static load conditions. At any time constant power discharges can be programmed or more realistic vehicle load profiles may be fed to the programming signal. Carrying this one step further, this test equipment can be programmed to life test a battery unit on a pre-recorded vehicle operation profile.

9.3.2.2 Scheduling

FP-1 Tests

Figure 9-1 depicts the complete test sequence outline for the FP-1 testing. The numbers above each block indicate the day number that testing for the blocks must start and end to meet the ANL schedule.

Figures 9-2, 9-4, 9-6, 9-8, 9-10, 9-12 and 9-14 show the individual test sequences outlined in Figure 9-1. Figures 9-3, 9-5, 9-7, 9-9, 9-11, 9-13 and 9-15 show the load module requirements for the test sequences of Figure 9-1.

FP-2 Tests

Figure 9-16 depicts the complete test sequence outline for the FP-2 testing. The numbers above each block indicate the day number that testing for the block must start and end to meet the ANL schedule.

Figures 9-17, 9-19, 9-21, 9-23, 9-25, 9-27, and 9-29 show the individual test sequences outlined in Figure 9-16. Figures 9-18, 9-20, 9-22, 9-24, 9-26, 9-28 and 9-30 show the load module requirements for the test sequences of Figure 9-16.

TP-1 Tests

Figure 9-31 depicts the complete test sequence outline for the TP-1 testing. The numbers above each block will indicate the day number that testing for the block will start and end.

Figures 9-32, 9-34, 9-36, 9-38, 9-40, 9-42 and 9-44 show the individual test sequences outlined in Figure 9-31.

Figures 9-33, 9-35, 9-37, 9-39, 9-41, 9-43 and 9-45 show the load module requirements for the test program of Figure 9-31.

Figure 9-46 shows the load module requirements for the entire test program. The requirements are separated in two sections, modules required for evaluation tests and modules required for life tests.

Advanced Tubular Battery Tests

Figure 9-47 depicts the complete time event summary outline for the test sequence of the Advanced Tubular battery.

Figures 9-48, 9-50, 9-52, 9-54, 9-56, 9-58 and 9-60 show the individual test sequences outlined in Figure 9-47. Figures 9-49, 9-51, 9-53, 9-55, 9-57, 9-59 and 9-61 show the load module requirements for the tests of Figures 9-48 to 9-60.

Advanced Bipolar Battery Tests*

Figure 9-62 depicts the complete time event summary outline for the test sequence of the advanced bipolar battery.

Figure 9-63, 9-65, 9-67, 9-69, 9-71, 9-73 and 9-75 show the individual test sequences outlined in Figure 9-62.

Figures 9-64, 9-66, 9-68, 9-70, 9-72, 9-74 and 9-76 show the load module requirements for the tests of Figures 9-63 to 9-75.

* Assuming partition work is successful.

Design Evaluation Tests ISOA FP-1
Time-Event Summary

Figure 9-1

Design Evaluation Tests FP-1
Sub-sequence 1
Initial Performance and C-Rating

Figure 9-2

DAYS	CYC. NO.	TYPE OF DISCHARGE	24	4	6	8	10	12	14	16	18
0-3	1	5 hr	[Bar from 2 to 16]								
3-4	2	3 hr	[Bar from 2 to 16]								
7-9	3	2 hr	[Bar from 2 to 16]								
9-10	4	1 hr	[Bar from 2 to 8]								
10-12	5	20 hr	[Bar from 2 to 16]								
15-16	6	0.5 hr	[Bar from 2 to 8]								

Equipment Schedule - FP-1

Sub-sequence 1

Figure 9-3

Design Evaluation Tests - FP-1
Sub-sequence 2
Low Temperature Performance

Figure 9-4

Equipment Schedule - FP-1
Sub-sequence 2.

Figure 9-5

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Design Evaluation Tests - FP-1
Sub-sequence 3
High Temperature Performance

Figure 9-6

DAYS	CYC. NO.	TYPE OF DISCHARGE	24 NUMBER OF TEST CIRCUITS IN USE
31-32	12	5 hr	16
36-37	13	3 hr	16
38-39	14	2 hr	16
43-44	15	1 hr	8
45-46	16	0.5 hr	8

Equipment Schedule - FP-1

Sub-sequence 3

Figure 9-7

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Design Evaluation Tests - FP-1

Sub-sequence 4

Charge Acceptance vs Temperature

Figure 9-8

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
50-51	17	3 hr
51-52	18	3 hr
52-53	19	3 hr
56-57	20	3 hr
57-58	21	3 hr
59-60	22	3 hr

Equipment Schedule - FP-1

Sub-sequence 4

Figure 9-9

Design Evaluation Tests - FP-1

Sub=sequence 5

Charge Acceptance vs Rate

Figure 9-10

Equipment Schedule - FP-1

Sub-sequence 5

Figure 9-11

Design Evaluation Tests - FP-1

Sub-sequence 6

Special Charge Tests

Figure 9-12

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
70-71	27	3 hr
71-72	28	3 hr
72-73	29	3 hr
73-74	30	3 hr
77-78	31	3 hr
79-80	32	3 hr

Equipment Schedule - FP-1

Sub-sequence 6

Figure 9-13

Design Evaluation Tests - FP-1

Sub-sequence 7

Charge Retention

Figure 9-14

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE									
			2	4	6	8	10	12	14	16	18	
94-95	33	3 hr
95-96	34	3 hr

Equipment Schedule - FP-1

Sub-sequence 7

Figure 9-15

Design Evaluation Tests - FP-2

Time-Event Summary

Figure 9-16

Design Evaluation Tests FP-2
 Sub-sequence 1
 Initial Performance and C-Rating
 Figure 9-17

DAYS	CYC. NO.	TYPE OF DISCHARGE	24	2	4	6	8	10	12	14	16	18
NUMBER OF TEST CIRCUITS IN USE												
0-3	1	5 hr										
3-4	2	3 hr										
7-9	3	2 hr										
9-10	4	1 hr										
10-12	5	20 hr										
15-16	6	0.5 hr										

Equipment Schedule - FP-2

Sub-sequence 1

Figure 9-18

Design Evaluation Tests - FP-2
Sub-sequence 2
Low Temperature Performance
Figure 9-19

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
16-17	7	5 hr
21-23	8	3 hr
23-25	9	2 hr
25-26	10	1 hr
29-31	11	0.5 hr

Equipment Schedule - FP-2

Sub-sequence 2.

Figure 9-20

Design Evaluation Tests - FP-2
Sub-sequence 3
High Temperature Performance

Figure 9-21

DAYS	CYC. NO.	TYPE OF DISCHARGE	24	4	6	8	10	12	14	16	18
NUMBER OF TEST CIRCUITS IN USE											
31-32	12	5 hr									
36-37	13	3 hr									
38-39	14	2 hr									
43-44	15	1 hr									
45-46	16	0.5 hr									

Equipment Schedule - FP-2

Sub-sequence 3

Figure 9-22

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Design Evaluation Tests - FP-2

Sub-sequence 4

Charge Acceptance vs Temperature

Figure 9-23

DAYS	CYC. NO.	TYPE OF DISCHARGE	2	4	6	8	10	12	14	16	18
50-51	17	3 hr									
51-52	18	3 hr									
52-53	19	3 hr									
56-57	20	3 hr									
57-58	21	3 hr									
59-60	22	3 hr									

Equipment Schedule - FP-2
Sub-sequence 4

Figure 9-24

Design Evaluation Tests - FP-2
Sub-sequence 5
Charge Acceptance vs Rate

Figure 9-25

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
63-64	23	3 hr
64-65	24	3 hr
65-66	25	3 hr
66-67	26	3 hr

Equipment Schedule - FP-2

Sub-sequence 5

Figure 9-26

Design Evaluation Tests - FP-2

Sub-sequence 6

Special Charge Tests

Figure 9-27.

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DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
70-71	27	3 hr									
71-72	28	3 hr									
72-73	29	3 hr									
73-74	30	3 hr									
77-78	31	3 hr									
79-80	32	3 hr									

Equipment Schedule - FP-2

Sub-sequence 6

Figure 9-28

JO/2-77

Design Evaluation Tests - FP-2

Sub-sequence 7

Charge Retention

Figure 9-29

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
94-95	33	3 hr
95-96	34	3 hr

Equipment Schedule - FP-2

Sub-sequence 7

Figure 9-30

Design Evaluation Tests - TP-1

Time-Event Summary

Figure 9-31

Design Evaluation Tests TP-1
 Sub-sequence 1
 Initial Performance and C-Rating

Figure 9-32

DAYS	CYC. NO.	TYPE OF DISCHARGE	24	4	6	8	10	12	14	16	18
NUMBER OF TEST CIRCUITS IN USE											
0-3	1	5 hr	[Redacted]								
3-4	2	3 hr	[Redacted]								
7-9	3	2 hr	[Redacted]								
9-10	4	1 hr	[Redacted]								
10-12	5	20 hr	[Redacted]								
15-16	6	0.5 hr	[Redacted]								

Equipment Schedule - TP-1

Sub-sequence 1

Figure 9-33

Design Evaluation Tests - TP-1

Sub-sequence 2

Low Temperature Performance

Figure 9-34

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
16-17	7	5 hr									
21-23	8	3 hr									
23-25	9	2 hr									
25-26	10	1 hr									
29-31	11	0.5 hr									

Equipment Schedule - TP-1

Sub-sequence 2.

Figure 9-35

Design Evaluation Tests - TP-1
Sub-sequence 3
High Temperature Performance

Figure 9-36

Equipment Schedule - TP-1

Sub-sequence 3

Figure 9-37

Design Evaluation Tests - TP-1

Sub-sequence 4

Charge Acceptance vs Temperature

Figure 9-38

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
50-51	17	3 hr	[Bar chart showing 16 test circuits in use]								
51-52	18	3 hr	[Bar chart showing 16 test circuits in use]								
52-53	19	3 hr	[Bar chart showing 16 test circuits in use]								
56-57	20	3 hr	[Bar chart showing 16 test circuits in use]								
57-58	21	3 hr	[Bar chart showing 16 test circuits in use]								
59-60	22	3 hr	[Bar chart showing 16 test circuits in use]								

Equipment Schedule - TP-1
Sub-sequence 4

Figure 9-39

Design Evaluation Tests - TP-1

Sub-sequence 5

Charge Acceptance vs Rate

Figure 9-40

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
63-64	23	3 hr
64-65	24	3 hr
65-66	25	3 hr
66-67	26	3 hr

Equipment Schedule - TP-1
Sub-sequence 5

Figure 9-41

Design Evaluation Tests - TP-1

Sub-sequence 6

Special Charge Tests

Figure 9-42

DAYS	CYC. NO.	TYPE OF DISCHARGE	24	2	4	6	8	10	12	14	16	18
NUMBER OF TEST CIRCUITS IN USE												
70-71	27	3 hr										
71-72	28	3 hr										
72-73	29	3 hr										
73-74	30	3 hr										
77-78	31	3 hr										
79-80	32	3 hr										

Equipment Schedule - TP-1

Sub-sequence 6

Figure 9-43

Design Evaluation Tests - FP-1

Sub-sequence 7

Charge Retention

Figure 9-44

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
94-95	33	3 hr
95-96	34	3 hr

Equipment Schedule - TP-1

Sub-sequence 7

Figure 9-45

Figure 9-46

Design Evaluation Tests - Advanced Tubular
Time-Event Summary

Figure 9-47

Design Evaluation Tests - AT
 Sub-sequence 1
 Initial Performance and C-Rating
 Figure 9-48

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
0-3	1	5 hr
3-4	2	3 hr
7-9	3	2 hr
9-10	4	1 hr
10-12	5	20 hr
15-16	6	0.5 hr

Equipment Schedule - AT

Sub-sequence 1

Figure 9-49

Design Evaluation Tests - AT
Sub-sequence 2
Low Temperature Performance

Figure 9-50

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Equipment Schedule AT

Sub-sequence 2.

Figure 9-51

Design Evaluation Tests AT
Sub-sequence 3
High Temperature Performance

J0/2-77

Figure 9-52

Equipment Schedule AT
Sub-sequence 3

Figure 9-53

J0/2-77

Design Evaluation Tests - AT

Sub-sequence 4

Charge Acceptance vs Temperature

Figure 9-54

J0/2-77

Equipment Schedule - AT
Sub-sequence 4

Figure 9-55

J0/2-77

Design Evaluation Tests - AT

Sub-sequence 5

Charge Acceptance vs Rate

Figure 9-56

J0/2-77

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
63-64	23	3 hr
64-65	24	3 hr
65-66	25	3 hr
66-67	26	3 hr

Equipment Schedule - AT

Sub-sequence 5

Figure 9-57

J0/2-77

Design Evaluation Tests - AT

Sub-sequence 6

Special Charge Tests

J0/2-77

Figure 9-58

DAYS	CYC. NO.	TYPE OF DISCHARGE	24 NUMBER OF TEST CIRCUITS IN USE
70-71	27	3 hr	5
71-72	28	3 hr	5
72-73	29	3 hr	5
73-74	30	3 hr	5
77-78	31	3 hr	5
79-80	32	3 hr	5

Equipment Schedule - AT
Sub-sequence 6

Figure 9-59

J0/2-77

Design Evaluation Tests - AT

Sub-sequence 7

Charge Retention

Figure 9-60

J0/2-77

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
94-95	33	3 hr
95-96	34	3 hr

Equipment Schedule - AT

Sub-sequence 7

Figure 9-61

J0/2-77

Design Evaluation Tests - Advanced Bipolar
Time-Event Summary

Figure 9-62

J0/2-77

Design Evaluation Tests - AB
 Sub-sequence 1
 Initial Performance and C-Rating

J0/2-77

Figure 9-63

DAYS	CYC. NO.	TYPE OF DISCHARGE	2	4	6	8	10	12	14	16	18
NUMBER OF TEST CIRCUITS IN USE											
0-3	1	5 hr									
3-4	2	3 hr									
7-9	3	2 hr									
9-10	4	1 hr									
10-12	5	20 hr									
15-16	6	0.5 hr									

Equipment Schedule - AB

Sub-sequence 1

Figure 9-64

J0/2-77

Design Evaluation Tests - AB
Sub-sequence 2
Low Temperature Performance

Figure 9-65

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
16-17	7	5 hr									
21-23	8	3 hr									
23-25	9	2 hr									
25-26	10	1 hr									
29-31	11	0.5 hr									

Equipment Schedule - AB

Sub-sequence 2.

Figure 9-66

Design Evaluation Tests - AB

Sub-sequence 3

High Temperature Performance

Figure 9-67

J0/2-77

DAYS	CYC. NO.	TYPE OF DISCHARGE	2	4	6	8	10	12	14	16	18
NUMBER OF TEST CIRCUITS IN USE											
31-32	12	5 hr									
36-37	13	3 hr									
38-39	14	2 hr									
43-44	15	1 hr									
45-46	16	0.5 hr									

Equipment Schedule - AB

Sub-sequence 3

Figure 9-68

J0/2-77

Design Evaluation Tests - AB
Sub-sequence 4
Charge Acceptance vs Temperature

Figure 9-69

J0/2-77

DAYS	CYC. NO.	TYPE OF DISCHARGE	2	4	6	8	10	12	14	16	18
			NUMBER OF TEST CIRCUITS IN USE								
50-51	17	3 hr									
51-52	18	3 hr									
52-53	19	3 hr									
56-57	20	3 hr									
57-58	21	3 hr									
59-60	22	3 hr									

Equipment Schedule - AB

Sub-sequence 4

Figure 9-70

Design Evaluation Tests - AB

Sub-sequence 5

Charge Acceptance vs Rate

Figure 9-71

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
63-64	23	3 hr									
64-65	24	3 hr									
65-66	25	3 hr									
66-67	26	3 hr									

Equipment Schedule - AB

Sub-sequence 5

Figure 9-72

J0/2-77

Design Evaluation Tests - AB

Sub-sequence 6

Special Charge Tests

Figure 9-73

J0/2-77

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
70-71	27	3 hr									
71-72	28	3 hr									
72-73	29	3 hr									
73-74	30	3 hr									
77-78	31	3 hr									
79-80	32	3 hr									

Equipment Schedule - AB

Sub-sequence 6

Figure 9-74

Design Evaluation Tests - AB

Sub-sequence 7

Charge Retention

Figure 9-75

DAYS	CYC. NO.	TYPE OF DISCHARGE	NUMBER OF TEST CIRCUITS IN USE								
			2	4	6	8	10	12	14	16	18
94-95	33	3 hr									
95-96	34	3 hr									

Equipment Schedule - AB

Sub-sequence 7

Figure 9-76

9.3.2.3 Charging

As indicated, the load modules will function as charge control units. In this mode, charging will take place in a two-step regime. The first step is a constant current charge at the 5-hour rate (40 A max). This rate of charge will be reduced to the 25-hour rate (5 A max) after the battery voltage reaches 2.37 volts per cell. The 25-hour rate will be continued until a full state of charge is attained. An accurate indication of full charge is stable specific gravity. If the specific gravity (corrected to 25°C) does not change more than ± 0.003 when measured at three intervals of one hour each, the battery has been fully charged. The time allotted for recharge in the test schedule is 24 hours for most of the planned cycles although a shorter time is allowed following tests such as high-rate discharge at low temperature in which the ampere-hour output is relatively low. The 24 hour charge period will be sufficient to restore full capacity while providing enough time on open circuit for the batteries to be cooled to the normal test temperature of 25°C. The following example shows the probable time periods involved in recharge of a typical electric vehicle battery subsequent to laboratory discharge at the 5-hour rate:

Capacity at 5 hr. rate (40A):	200 Ah
Desired total recharge (115%)	220 Ah
Capacity restored in high-rate charge mode (0.9 x 200):	180 Ah
Time in high-rate mode:	4.5 hr
Amp-hr input in low-rate charge mode (220-180);	40 Ah
Time in low-rate mode:	18.0 hr
Total amp-hr input:	220 Ah
Total time on charge:	12.5 hr
Time remaining for temperature adjustment:	11.5 hr

Additional time is scheduled for equilibration of battery temperature when tests are to be conducted below or above normal ambient temperature.

9.3.2.4 Data Required

Prior to testing, the following information will be recorded for each battery:

Battery weight (dry)

Battery weight (after formation and adjustment of specific gravity

Battery dimensions

Active material and grid weights - obtained from data taken during assembly

Specific gravity of each cell's electrolyte

Charge data:

1. During charge: Record current, voltage, temperature, for use in calculating turn-around efficiencies.

2. At end of charge: Record cell and half-cell potentials (V), electrolyte temperature (°C), specific gravity (corrected to 25°C) and water addition (ml per cell).

Discharge data:

1. Initial conditions (open circuit): Record cell and half-cell potentials (V), electrolyte temperature (°C) and specific gravity (corrected to 25°C).

2. Initial conditions (closed circuit): Record actual discharge current (A) and adjust as required; cell and half-cell potentials at minimum and stabilized voltage under load.)V).

3. During discharge: Record battery temperature, voltage and discharge current vs time. Acquire sufficient data to completely define discharge curve.

4. Termination of discharge: Record discharge time to end-points, half-cell potentials at end-points and specific gravity (corrected to 25°C).

The above items constitute the routine data to be acquired in each discharge-charge cycle. For a number of planned tests there are special data or data processing requirements which are listed below:

Data Category	Required For
Internal resistance of cells as function of temperature and state of change	Initial performance rating Low temperature testing High temperature testing
Calculation of specific energy and efficiencies (ampere-hour and watt-hour) by integration of current-time and voltage-time data	Initial performance rating Charge acceptance Potential-limited charging
Detailed record of half-cell potentials throughout discharge or during charge acceptance tests to define capacity or rate-limiting electrode.	Initial performance rating Low temperature testing High temperature testing Charge acceptance

9.3.3 Test Standards

9.3.3.1 Sub-Sequence 1: Initial Performance and C-Rating

The six test cycles, ranging approximately from the 30 minute to the 20 hour rate, will serve to characterize a new cell design in terms of rate capability. This data will be used to compare actual with predicted performance and will serve as a guide in further refinement of design. The discharge rates listed in the following schedule will be (of necessity) based on estimates of performance for these previously untested variations. For all discharges in this series, the starting temperature of the batteries will be 25°C and ambient temperature will be kept at 25°±2°C throughout discharge. Charging will be done as described in Section 9.3.2.3.

CYCLE	DISCHARGE RATE	RECORD TIME TO:	
		VOLTS/CELL	
		<u>Read:</u>	<u>Carry to:</u>
1	5-hour	1.84	1.70
2	3-hour	1.80	1.65
3	2-hour	1.78	1.60
4	1-hour	1.68	1.50
5	20-hour	1.88	1.75
6	0.5-hour	1.58	1.40

The true 3-hour capacity will be determined by plotting capacity vs rate and specific energy will be calculated at the 3-hour rate.

9.3.3.2 Sub-sequence 2: Performance at low temperature

Five discharges will be conducted to define the moderate to high-rate performance of a cell design at 0°C. An environmental chamber will be used which is large enough to contain at least 100 6-volt EV batteries. The batteries will be discharged in the chamber after their temperature has been lowered to 0°C. The ambient temperature during discharge will be 0°C $\pm$ 1°C. Batteries will be recharged as in Section 9.3.2.3 at an ambient temperature of 25°C.

CYCLE	DISCHARGE RATE	RECORD TIME TO:	
		VOLTS/CELLS	
		<u>Read:</u>	<u>Carry to:</u>
7	5-hour	1.84	1.70
8	3-hour	1.80	1.65
9	2-hour	1.78	1.60
10	1-hour	1.68	1.50
11	.05-hour	1.58	1.40

Plot of capacity vs rate and specific energy vs rate will be made for each cycle.

9.3.3.3 Sub-sequence 3: Performance at High Temperature

This series of discharges will be identical to those described for sub-sequence 2, except that battery temperature will be 40°C at the beginning of discharge which will take place at an ambient temperature of 40°C $\pm$ 1°C. As before, ambient temperature will be adjusted to 25°C before charging per Section 9.3.2.3. Similar performance plots will be made.

CYCLE	DISCHARGE RATE	RECORD TIME TO:	
		VOLTS/CELL	
		Read:	Carry to:
12	5-hour	1.84	1.70
13	3-hour	1.80	1.65
14	2-hour	1.78	1.60
15	1-hour	1.68	1.50
16	0.5-hour	1.58	1.40

9.3.3.4 Sub-Sequence 4: Charge Acceptance vs Temperature

All discharges in this series will be carried out at the 3-hour rate at 25°C as determined in Cycles 1-6, the variable being battery temperature at the beginning of charge. Normal 3 hour rate discharges (at 25°C) will be conducted at the start of the series and following charge acceptance measurement at 25°C and 40°C to assure that initial conditions for each test are as identical as possible. The charging procedure at each temperature (following the "normal" cycle) is given below:

Adjust battery temperature to 25°, 40° or 0°C and charge at the 5-hour rate to a voltage corresponding to the onset of moderate gas evolution at the particular temperature existing in the battery. This voltage is 2.37 V at 25°C. The temperature compensating factor for the lead acid battery is -5.5mV/°C/cell. For example, cut-off voltage for these charge acceptance measurements would be 2.29V at 40°C and 2.51 V at 0°C.

At the lower temperature, especially, a rise in battery temperature will occur during charge. Thus, the charge process will be closely monitored and terminated when the temperature-voltage relationship indicates that significant gassing has begun.

After the charge has been ended, battery temperature will be adjusted to 25°C prior to discharge at the 3 hour rate. The order of tests is listed below:

CYCLE	CHARGE METHOD	DISCHARGE RATE	RECORD TIME TO:	
			VOLTS/CELL	
			<u>Read:</u>	<u>Carry to:</u>
17	normal	3-hour	1.80	1.65
18	5-hr rate at 25°C to onset of gassing	3-hour	1.80	1.65
19	normal	3-hour	1.80	1.65
20	5-hr rate at 40°C to onset of gassing	3-hour	1.80	1.65
21	normal	3-hour	1.80	1.65
22	5-hr rate at 0°C to onset of gassing	3-hour	1.80	1.65

9.3.3.5 Sub-Sequence 5: Charge Acceptance vs rate of Charge

Charging efficiencies will be compared at two relatively high rates of charge, starting in each case with a battery (at 25°C) which has previously been discharged completely at the 3 hour rate. As in Cycles 17-22, each charge acceptance test will be preceded by a "normal" cycle. The temperature voltage relationship described in the previous section will be used to terminate charge. In each cycle, battery temperature will be adjusted to 25°C for discharge

CYCLE	CHARGE METHOD	DISCHARGE RATE	RECORD TIME TO:	
			VOLTS/CELL	
			<u>Read:</u>	<u>Carry to:</u>
23	normal	3-hour	1.80	1.65
24	3 hr rate to onset of gassing	3-hour	1.80	1.65
25	normal	3-hour	1.80	1.65
26	1 hr rate to onset of gassing	3-hour	1.80	1.65

9.3.3.6 Sub-sequence 6: Special charging tests

Six cycles will be carried out at 25°C to compare the response of various cell designs to a charging technique which minimizes water losses whether due to evaporation or electrolysis. After the first 3 hour rate discharge, the recharge will be carried out in two steps: (1) at the 5 hour rate (40 A max) to 2.35 F/cell at 25°C and (2) maintain cell voltage at 2.35 V for 4 hours. The exact change-over voltage will be calculated for the prevailing battery temperature using the factor: - 5.5mV/°C/cell. This routine will be repeated four times to determine the effect on capacity. Recharge from the fifth and sixth cycles will be conducted in the normal manner per Section 9.3.2.3 to measure capacity recovery.

CYCLE	DISCHARGE RATE	READ TIME TO:		CHARGE METHOD
		VOLTS/CELL		
		<u>Read:</u>	<u>Carry to:</u>	
27	3-hour	1.80	1.65	5 hr rate to 2.35V/cell maintain at 2.35V/cell for 4 hours
28	3-hour	1.75	1.60	same as Cy.27
29	3-hour	1.75	1.60	same as Cy.27
30	3-hour	1.75	1.60	same as Cy.27
31	3-hour	1.75	1.60	per Par 9.3.2.3
32	3-hour	1.75	1.60	per Par 9.3 2.3

9.3.3.7 Sub-Sequence 7: Charge Retention

Self-discharge of all cell designs will be determined by measuring the loss of capacity resulting from a two week open circuit stand at 25°C. Prior to the stand period, the batteries will be fully charged in the normal manner. The same charge procedure will be followed after obtaining discharge capacity from stand.

CYCLE	DISCHARGE RATE	RECORD TIME TO:	
		VOLTS/CELLS	
		<u>Read:</u>	<u>Carry to:</u>
33	3-hour rate from stand	1.80	1.65
34	3-hour rate from full charge	1.80	1.65

9.3.3.8 Life Test

A deep cycle life test will be used on battery units as discussed in the ISOA and Advanced Battery development programs.

The test will combine a 2.4 hour constant current discharge at the 3 hour discharge rate followed by a two step recharge. The recharge will comprise a first portion charge at the 5 hour rate until the voltage reads 2.37 volts per cell followed by a second portion charge at the 25 hour rate until a total of 108% of the charge is returned. The schedule will be 2 cycles per 24 hours with a catchout cycle every two weeks giving 27 cycles every two weeks.

This life test regime is subject to revision as the development proceeds.

9.4 Battery Modeling Study

Although the total usable capacity (watt hours to a specific current or voltage limit) for any given lead acid battery can be empirically determined by testing under defined discharge regimes, the task takes much time and equipment. Efforts to predict performance on complex power-time profile discharges have not been acceptably accurate. The ability to predict such performance, however, is required in vehicle design and driving simulation studies.

ESB will subcontract a task to develop a computer modeling program to specify lead acid battery performance under complex discharge regimes. The goal of the computer modeling program is to be able to predict the dynamic performance, i.e., the current vs voltage outputs and the total energy that may be obtained from a given battery under various and complex repetitive discharge profiles at different ambient temperatures.

The discharge profile may be specified as a function of time vs current or as a function of time vs power. Voltage at any instant during the discharge would be predictable as one of the outputs of the model. Profiles may be repeated until a maximum current or minimum terminal voltage is reached.

A computer modeling program yielding such dynamic performance data based strictly upon theoretical design parameters of a battery would be immensely complex and is beyond the scope of this program. Rather, the less ambitious goal of extrapolating this information from actual discharge tests on real batteries is what is sought. Some questions that will be answered by this study include determining the minimum number of those discharge tests and what particular form the tests must take.

ESB has asked Battelle's Columbus Laboratories to respond to the computer battery modeling task, and their proposal of work is included in Appendix 2. This task would be completed by the eighteenth month of the ANL contract effort.

10 MANUFACTURING CONSIDERATIONS

10.1 Flow Diagram of Projected Manufacturing Process

Since the final version of the ISOA battery may be either a normal pasted plate type or a tubular positive plate type, ESB has projected manufacturing steps, plant and equipment costs, and floor diagrams for the two alternate versions. The cost information is presented in the separate cost study volume.

10.1.1 Flat Pasted Plate Battery

Figure 10-1 is a projected flow diagram for the production of the flat pasted plate (pasted positive and negative electrode) battery. It includes the relative cost importance (expressed as percentages) of each major process step. A brief description of the production of three batteries in a pilot production facility (5,000 EV batteries, or 90,000-100,000 3-cell batteries per yr) is described in the nine steps that follow. The proposal for the pilot production facility is based on the most advanced state-of-the-art currently in use in manufacturing processing.

- (1) The production requirements for the lead oxide for the pilot production facility will not economically support an oxide mill but the lead oxide will either be purchased from an outside vendor or if economically feasible shipped in from another ESB facility. We will purchase pure lead and convert it to lead oxide using an attrition mill for the large production facility. The oxide will be stored in bulk storage hoppers.
- (2) At the grid casting operation, a controlled amount of molten lead [*] is poured into a vertical book-type mold, cooled, ejected from the mold and trimmed to size.

[*] This section contained proprietary data that has been deleted from this report.

Page 224 is proprietary and not included
in this volume of the report.

- [*] This is the best method of obtaining the critical dimensional tolerances for thickness necessary to achieve the consistent electrical and mechanical qualities in the product.
- (3) Plate pasting includes the accurate mixing of the lead oxide, sulfuric acid and water to form a paste. The paste is mechanically trowled [*] over the grid to specific thickness dimensions.
 - (4) The twin pasted plates will be broken apart [*] for negatives and positives. The positive will be wrapped in an envelope separator, [*] and stacked with the negative plate to form an element.
 - (5) The lugs of the positive and negative plates in the group will each be fused into a strap on a Cast-On-Strap machine [*]. The elements so formed will then be placed in the battery container.
 - (6) The straps will be connected from cell to cell by welding [*] through the partitions of the container. The same assembly line will automatically test each battery for mechanical defects. The cover of the battery will be heat sealed [*] to the container. The weld will be pressure tested for pinhole leaks. The battery terminal posts will be fused to the terminal cell elements.
 - (7) The battery is filled with acid and placed on charge [*] to convert the positive and negative plates to sponge lead for the negative and lead peroxide in the case of the positive.

[*] This section contained proprietary data that has been deleted from this report.

- (8) After the conversion of the positive and negative plates, the battery will be washed, decorated, and electrically tested.
- (9) The battery will then be palletized and shipped.

10.1.2 Tubular Plate Battery

Figure 10-2 is a projected flow diagram for the production of tubular positive plate batteries. Once again the relative cost importance of the major steps is designated as percentages. The block labeled "Tubular Positive Plate Making" is broken down in the separate flow diagram presented as Figure 10-3.

The flow chart is numbered from 1 through 34 for quick correlation with detailed process description.

- 1,2 Lead [*] alloy will be purchased from an outside supplier or ESB smelter to ESB specification. The suppliers shall furnish certified analysis and samples from randomly selected pigs.
- 3 - Positive grids will be cast on pressure grid casting machines casting two grids at a time. Two machines are operated by one operator [*]. The machines are hydraulically operated with automatic unloading of castings.
- 4,13 - Trim slam-assembly operation is conducted on ESB designed equipment. At this station, the grid is cut off to length, cleaned, inspected by the operator and inserted into tubes prepacked in specially designed cartons.
- 5,6 - The tubes can be purchased from outside sources or fabricated in house as indicated on the flow chart [*] and described below. The tubing is prepacked in cardboard boxes for assembly as described above.

[*] This section contained proprietary data that has been deleted from this report.

Pgs. 227 & 228 - proprietary and not included in this volume of the proposal.

- 7,8 - Purchased woven glass yarn tubing for the above is made of continuous filaments to ESB specifications for $\text{PbO}_2/\text{H}_2\text{SO}_4$ environment. This product is inspected and accepted by incoming inspection for production processing.
- 9 - In this operation, the woven glass yarn tubing is processed through the forming mandrels with application of starch and heat. Here the tubing is formed to elliptical shape and transferred to an in-line cutter, which completes the extrusion and cut-off cycle. The extrusion and cut-off system consists of in-line forming and cutting machines.
- 10 - The elliptical shaped tube is cut to the final dimension and coated on both ends with polyethylene bottom powder for subsequent scaling operation to the polyethylene bottom cap and top grid. The polyethylene coater machine is highly automated and deposits a thin layer of polyethylene material on the tube.
- 11 - Upon completion, the tubing is packaged in programmed arrangements for automatic or manual assembly with grids.
- 12 - Final tube inspection per ESB process instructions.
- 14 - Storage or staging area for plate assembly [*] for filling machines.
- 15,25 - Oxide and red lead may be purchased or manufactured in-house depending on economics. [*]
- 26-29- Assembled tubes and grids are subsequently filled with active material [*] to specified weight by means of a filling machine, step 29.

[*] This section contained proprietary data that has been deleted from this report.

The filling machine was designed by ESB. The machine is run by two operators and contains a built in weighing scale and transfer conveyor for self-contained operation. Oxide-red blending operation is done separately in steps 26 through 28 and delivered to the filling machine via a screw type conveyor.

- 30 - Heat sealing of tubes, grids and bars will be sealed simultaneously [*].
- 31 - An automatic dip is performed by an overhead conveyor. Holding fixtures containing plate assemblies are submerged in sulfuric acid solution, while being pulled by the conveyor.
- 32 - Plates are washed by a spray operation as part of the automated dipping system. The unit was designed by ESB.
- 33 - Plates are cured in batch or continuous type ovens [*]. For lower volume, a batch type oven will be designed as a self contained unit. For higher volume, a continuous type oven will be designed and built.
- 34 - A storage area will be provided for purchased and manufactured battery parts prior to assembly.

[*] This section contained proprietary data that has been deleted from this report.

10.2 Floor Plan

Floor plans have been laid out for the production of both the flat pasted plate ISOA and the tubular positive plate ISOA batteries.

10.2.1 Flat Pasted Plate Battery

A floor plan for the production of the flat pasted plate ISOA battery is presented in Figure 10-4.

10.2.2 Tubular Plate Battery

A floor plan for the production of the tubular positive plate ISOA battery is shown in Figures 10-5 and 10-6. Figure 10-6 is a detailed plan for the production of only the tubular positive plate.

10.3 Other Manufacturing Details

Lists of equipment including required production quantity numbers, production rates, number of machines required, and detailed cost breakdowns are presented in the separate proprietary cost volume of this proposal. This information includes assumption of land costs, floor space costs, costs required to meet OSHA regulations, and all other details needed to accurately cost a pilot plant facility for the ISOA battery.

The time required to complete such a pilot production facility is estimated to be 1 year.

Figure 10-4
Production Floor Plan
Flat Plate ISOA Battery

Figure 10-5
Production Floor Plan
Tubular ISOA Battery

Figure 10-6
 Production Floor Plan
 Tubular ISOA Battery
 Positive Plates

11 ENVIRONMENTAL IMPACT AND SAFETY CONSIDERATIONS

11.1 Manufacturing Aspects

Pollution from lead acid battery manufacturing takes three principal forms. These are:

- Lead dust in air,
- Lead dissolved in waste water,
- Acid in waste water.

The pilot facilities as well as the manufacturing facilities discussed in this proposal will be built and operated to meet all current federal, state and local environmental ordinances.

11.1.1 Atmospheric Lead Wastes

All operations where any lead dust is generated, including mixing, pasting, slitting, wrapping and stacking will be exhausted through either a wet scrubber or a fabric filter to eliminate discharges of lead to the atmosphere to the extent that current technology permits.

The exhaust ventilation of such operations will ensure that the acceptable levels of lead prescribed by law will be maintained for all employees at their breathing zone.

11.1.2 Lead and Acid in Effluent

All battery formation will be in containers so that the only effluent containing acid or lead will result from washing batteries and floors. The system to be installed will neutralize any acid and remove lead from the effluent before discharge resulting in a total discharge of 0.5 lbs/yr.

If tubular positive plates are used, they must be rinsed after the acid soak resulting in an increased neutralization requirement.

11.1.3 Solid Wastes

All wet paste will be reclaimed and recycled in the pasting area. All dry lead scrap will be accumulated and returned to a lead smelter for reclaim and recycle. All other scrap material such as cartons, pallets etc., will be removed from the premises by a qualified waste removal contractor.

11.2 Impact on Natural Resources

In examining the demand supply situation for lead, a forecast period of ten years was chosen with an annual sale of 100,000 new vehicles for the first four years. From the fifth to tenth year an estimated 100,000 additional batteries would be required for the replacement market. Estimated lead requirements for these vehicles were calculated on the basis of the initial advanced tubular battery design. Total lead required per EV battery (60 cell-20 KWH) was calculated to be 0.27 metric tons and includes lead oxide expressed as lead metal. Assuming the industry's present battery recycling pattern continues, 80% of the lead for replacement EV batteries would come from recycled EV lead scrap. Lead requirements for the forecast period are shown in Table 11-1.

Table 11-1

Lead Requirements for Electric Vehicle Batteries

<u>Forecast Period</u>	<u>No. of EV Batteries/yr</u>	<u>Load Requirements</u>	
		<u>Metric tons</u>	
		<u>New</u>	<u>Recycled</u>
1 - 4	100,000	54,000	-----
5 - 10	200,000	32,400	21,600

The U.S. resource base for lead has increased since 1965 and annual mine production has more than doubled and is more than adequate to support these increases in primary demand⁽¹⁾. Sufficient secondary lead smelter capacity is available in the U.S. to process the increased tonnage in EV battery scrap.

11.3 Safety Aspects of Operating EV Batteries

11.3.1 Hydrogen Evolution

ESB recommends a charge regime in which there is a minimum amount of gassing. However, the gassing that will occur will involve hydrogen, and the mixture of hydrogen and air can be explosive.

(1) Lead - Mineral Facts and Problems 1975 Edition

To properly safeguard the user of an electric vehicle, ESB recommends that cells be vented into one or more manifolds and that the manifolds terminate in explosion arresting vents. A highly effective vent has been developed for submarine battery use and ESB recommends the use of this ceramic type flash protector.

There is a problem with manifolding series cells in a battery. This is the formation of liquid paths from cell to cell due to electrolyte spray entering the vent tube. The liquid paths can short the battery and often cause hot spots and sparks. To avoid this possible trouble ESB will place a spray trap at the outlet of the vent from each cell. This will reduce the possibility of spray emission. Further we will use connecting tubing having an inner surface of Teflon. The non-wetting characteristics of this material are ideal for the prevention of liquid paths in the vent and manifold tubing.

11.3.2 Poisonous Metal Hydride Gasses

Under certain normally encountered conditions, potentially harmful materials escape from certain types of lead acid cells. These materials are hydrides of metals used in the positive grid alloys.

[*]

The safe toxicity levels for the hydrides of these materials are given as follows in "Toxic and Hazardous Industrial Chemical Safety Manual", International Technical Information Institute, 1975.

[*] This section contained proprietary data that has been deleted from this report.

Arsine	TLV	(Safe working conditions long exposure)	0.05 PPM
Stibine	TLV	(Safe working conditions long exposure)	0.1 PPM

[*]

The hydrides are evolved during the gassing phase of the charge cycles.

ESB has conducted a comprehensive study of the composition of the gasses evolved by lead acid cells having alloy positive grids. Figures 11-1 and 11-2 are graphic representations of some of the test results of this test.

Figure 11-1 shows the evolution of stibine from lead alloys containing antimony. Figure 11-2 shows the evolution of arsine. Tests were made on the cells when new, after 200 deep discharge cycles and after 480 cycles.

Note: The tests were made at room temperature with the cells on overcharge in equilibrium, under carefully controlled conditions.

The greatest evolution of stibine using an alloy of 3% nominal antimony is 0.0018 cc per ampere hour.

Taking the normal end of charge current for the 20 KWh EV battery of 10 amperes, each cell will evolve 0.018 cc stibine per hour. Rounding this to 0.02 cc and multiplying by 60 for the total battery, an output of 1.2 cc per hour of stibine is found. To reduce this to a dilution of 0.1 part per million (by volume) will require 12 cubic meters of air per hour. Similarly, the greatest evolution of arsine at a 10 amp finishing rate from an alloy containing 0.2% arsenic is 0.0025 cc. Multiplying this by 10 and by 60 a total evolution of arsine per battery per hour is found to be 1.5 cc. To reduce this to a dilution of 0.05 parts per million will require 30 cubic meters of air per hour.

[*]

[*] This section contained proprietary data that has been deleted from this report.

Figure 11-1
Evolution of Stibine on Overcharge

Figure 11-2
Evolution of Arsine on Overcharge

A comparatively large quantity of air will be needed for cooling the battery during charge. This will amount to several hundred cubic meters per hour. Therefore the amount of air required for temperature control during charging will be many times that required for control of the toxic agents. However, ESB recommends that positive ventilation be provided for the vehicle charging area.

Readings were taken on batteries during stand and discharge. Only trace amounts of stibine were detected under these conditions.

On stand, the arsine evolution was found to be about 3% of the evolution on overcharge, thus requiring about 1 cu. meter of diluting air per hour. On discharge the evolution of arsine was found to be about 1/10 of the evolution on overcharge or about 3 cu meters of diluting air per hour.

In summary: for complete safety during charge, positive ventilation of at least 30 cu meters per hour air circulation must be provided.

During stand: ventilation of one cubic meter per hour

During operation: the vehicle motion will provide the 3 cu meters of air required for complete safety.

11.3.3 Other Safety Aspects

Lead acid storage batteries contain sulfuric acid solution. The hazards associated with this material are well known and understood. It is harmful when in contact with human skin, must not be taken internally, and is extremely harmful to eye. For these reasons storage battery suppliers are required by law to put cautioning labels on their products. There is also an electrical hazard problem with storage batteries. If a large lead acid battery is short-circuited by chance such as by a metallic tool or other conductive object there can be sufficient current flow to raise the object to red heat or even to cause it to melt. Therefore it is desirable to transport and use the battery without any exposed electrical contacts. This will be accomplished by insulating the terminals and the cables.

All ESB consumer-type batteries bear a caution label which meet legal requirements.

12 ORGANIZATION, MANAGEMENT AND QUALITY ASSURANCE PLAN

12.1 Program Organization

To accomplish the program set forth in this proposal ESB has assembled a team of managers, scientists, engineers, and technicians experienced in the disciplines, technology, and techniques required. The work will be a combined effort carried out by four units of the corporation with the following general areas of responsibility:

- ESB Corporate Headquarters
 - Electric Vehicle Task Force
 - Contract Administration
- ESB Technology Center
 - Technical Management
 - Research, Development, and Testing
 - Design Coordination
- ESB Automotive Division
 - Flat Pasted Plate Battery Manufacturing and Production Equipment Design
- Exide Power Systems Division
 - Tubular Plate Manufacturing and Production Equipment Design.

Key members of the planned team now working on the electric vehicle battery program and their present principal areas of responsibility are listed below.

A.J. Salkind	- Vice President - Technology
N.J. Masington, Jr.	- Contracts Administrator
G.S. Hartman	- Manager, Battery Department ESB Technology Center
G.C. Kugler	- Technical Program Manager Electric Vehicles
C.J. Venuto	- Principal Investigator
J.B. Doe	- Principal Investigator
J.B. Ockerman	- Principal Investigator
T.W. Blickwedel	- Quality Assurance
F. Vergilii	- Flat Pasted Plate Batteries
F.A. Vengrofski	- Tubular Plate Batteries

Upon award of Phase II of the ANL electric vehicle contract, we will strengthen the management team and add other members of the Technology Center staff (and the Divisional Engineering staffs) to the program on a full-time or as needed basis. The technical staff under Dr. Kugler will be enlarged. A Program Organization such as that shown in Figure 12-1 is proposed.

12.2 Program Management Plan

The Contracts Administrator will be responsible for ANL-ESB interfaces affecting terms, performance, administration, and funding control. The Technical Program Manager (TPM) will serve as the technical program leader and will be the focal point for technical communication. Beginning with the contract award the TPM will prepare work statements, schedules and funding plans for each work package under normal Technology Center practices. This will be monitored by the Contract Administrator to assure conformance with the contract terms.

The Technology Center has a matrix system of program/department management which provides effective technical leadership and financial controls to major projects. This has been successfully demonstrated in current EPRI, ERDA and Dept. of Defense contracts.

The TPM will be responsible for insuring that technical milestones are accomplished on time. He will work with the Principal Investigators to plan and administer tasks to be carried out in line with contractual requirements, funding and schedule commitments. All commitments and expenditures will be authorized by the TPM and approved by the Department/Program Management Control System of the Technology Center and the Contracts Administrator. The Contracts Administrator will prepare and issue to ANL the required financial reports for the "current period" and "contract to date" expenses.

The TPM will work directly with ANL on all technical aspects of the contract. All technical reports will be his responsibility, will be approved and reviewed by ESB Technology Management and will be submitted by the Contracts Administrator.

FIGURE 12-1 ANL EV LEAD ACID PROGRAM ORGANIZATION

Detailed Semi-Annual, Annual and Final reports will be prepared and submitted to ANL within 30 days following the completion of the appropriate work periods. These reports will detail all work performed under the contract and include analyses, interpretations, descriptions, as well as summarizing discussions. Drawings, schematics and appropriate diagrams will also be included.

Formal Program Reviews will be held 3 months after the initiation of the work and at least annually thereafter. ESB suggests that frequent informal meetings be held with ANL. These meetings will permit exchanges of data with contractors working on the vehicle development.

Financial Reports will be prepared and submitted semi-annually and will include the expenditures for the current period and cumulative costs to date. Man hours expended as well as percentage of costs and percentage of completion will be shown in the report.

ESB has in existence an Electric Vehicle Task Force composed of the senior officers of the company whose areas of responsibility include all operations affecting electric vehicle battery research, development and marketing. The task force serves as a corporate nerve center to coordinate EV efforts throughout the company. The direct link with this body for the ANL program will be the task force chairman, Mr. Warren Mang, Vice President of Corporate Planning and Development.

12.3 Quality Assurance

A quality assurance manual has been prepared for this project and is included with this report as Appendix 3. This manual has been reviewed by personnel in the operating divisions that will be concerned with the project. It provides policy and procedure for the control of designs, materials, processes, tools and gages, and data. It must, of course, be recognized that the detailed contents of the manual are subject to modifications as the specifics of the proposed program and ultimate program goals become more clearly and concretely defined.

SECTION 13

RESUMES OF KEY PERSONNEL

ESB INCORPORATED
ESB TECHNOLOGY CENTER

Key Personnel

ALVIN J. SALKIND

Position: Vice-President - Technology

Responsibility: Management responsibility for ESB Technology Center and technical direction for the Corporation.

Education: 1949 - Polytechnic Institute of New York - BChE
1952 - Polytechnic Institute of New York - MChE
1958 - Polytechnic Institute of New York - DChE
1965 - Pa. State University - Postgraduate (Summer)
1976 - Industrial Research Institute, Harvard
Business School
Professional Engineer: New York-1954; New Jersey-1960

Job Experience: ESB Incorporated - 1958 to present.
Director of Technology and Vice-President, Technology.
Responsibilities include selection, planning and budgeting programs, direction of the Technology Center and director of several special ventures.

Rutgers University Medical School - 1970 to present.
Prof. Bioengineering, Dept. of Surgery
Lecture to medical students and research in bio-galvanic energy, cardiac sensing, and electro-chemical aspects of surgery and medicine.

University of Missouri Medical School
Space Science Department 1969-1970
Consultant on Biologic Energy Sources

Polytechnic Institute of New York
Adjunct Professor of Electrochemical Engineering 1960-1970
Research Associate - 1956-1958

Sonotone Corporation - 1954-1956
Scientist

U.S. Electric Manufacturing Company - 1952-1954
Chemical Engineer

Memberships and Activities in Professional Societies:

The Electrochemical Society, presently Chairman of the Battery Division, formerly Chairman of the New York Section. Chairman of the 1969 Symposium on Alkaline Batteries, and Chairman of the 1970 Symposium on Electrochemical Aspects of Bioengineering. Member of the New Technology Committee.

American Institute of Chemical Engineers, Chairman of the Electrochemical Engineering Session, 1968 Tripartite Meeting, Montreal.

Member; American Chemical Society, New York Academy of Science, Association for the Advancement of Medical Instrumentation, Sigma XI, Phi Lambda Upsilon.

Publications: Author, coauthor, coeditor of numerous scientific publications.

ESB INCORPORATED
ESB TECHNOLOGY CENTER

Key Personnel

GEORGE C. KUGLER, Ph.D.

Position: Technical Program Manager, Electric Vehicles

Responsibility: Program planning and management, Electric Vehicle Battery development.

Education:

- 1963 - LaSalle College - BA in Chemistry
- 1967 - University of Pennsylvania - Ph.D. in Chemistry
- 1970 - ACS course - Business Aspects of Chemistry
- 1971 - ACS course - Heterogeneous Catalysis
- 1972 - Scientific Methods, Inc. - Grid Management Course Phase I
- 1973 - Scientific Methods, Inc. - Grid Management Course Phase II
- 1974 - Ohio State University - Research and Development Management Program
- 1975 - Present - Florida Atlantic University - Presently enrolled in program leading to the degree of Masters in Business Administration.

Job Experience: Dr. Kugler joined ESB Inc. at their Yardley, Pa. Technology Center in 1967 and has been with them since, except for a two year tour in the U.S. Army Chemical Corps, spent at the Army Materials and Mechanics Research Center at Watertown, Mass. He was discharged with the rank of Captain.

Dr. Kugler did his doctoral dissertation in the field of electroanalytical chemistry on fundamental studies of glass electrodes, and worked in the Army on thermometric studies of complex ions of heavy metals. At ESB he has been project leader on many battery system developments, including zinc-air, nickel zinc, silver zinc, pulse charging techniques of lead-acid batteries, and molten salt battery systems. He has designed a hybrid electric vehicle power train, and was head of the Analytical Service Laboratory. He is now involved in electric vehicle battery program planning and management.

He is a member of the American Chemical Society, the Franklin Institute, and the Electrochemical Society. He presently holds the position of Chairman of the Philadelphia Section of the Electrochemical Society, and is enrolled at Florida Atlantic University in a program leading to the degree of MBA.

ESB INCORPORATED
ESB TECHNOLOGY CENTER

Key Personnel

C. JOSEPH VENUTO

Position: Scientist

Responsibility: Principal Investigator, ISOA Battery

Education; 1948 - BS - City College of New York
1950 - MA - Harvard University

Supplemental Education and Training:

Technical; 1958 - X-Ray Diffraction Summer Course
Brooklyn Polytechnic Institute
1965 - Basic Electronics for Scientists - ESB Course
1965 - RCA Electron Microscopy Course - Camden, New Jersey
1966 - Norelco X-Ray Diffraction and Fluorescence School
1967 - Fortran Programming Course - Bala Cynwyd, Pa.

Business and Management:

1956/1957 - Wharton Evening School, University of Pennsylvania
Manufacturing Industries of U.S.
1956/1957 - Wharton Evening School, University of Pennsylvania
Commercial Law
1964 - ESB Management Development - In-House Course
1965 - Pennsylvania State University, State College, Pa.
Basic R & D Management Program
1966 - Seminar for the Development of R & D Managers
Pennsylvania State University, Champion, Pa.
1968 - ESB Managerial Grid, Phase I - St. Clair, Michigan
1970/1971 - Wharton Evening School, University of Pennsylvania
International Business Management
1972 - Wharton Evening School - Managerial Accounting
1972 - Wharton Evening School - Administration

Job Experience; Mr. Venuto joined ESB, Inc. at their Yardley Technology Center in 1958 and has acquired a broad range of experience in battery research and development of lead acid systems. He has been Project Leader in lead acid battery investigations involving fundamental studies of active material reactions, development studies to improve the performance and processing of water activated batteries, sealed cylindrical cells, golf car batteries, and sealed prismatic batteries with titanium grids. These activities were performed in close rapport with ESB's marketing and production groups.

Mr. Venuto is a member of the Electrochemical Society and past Chairman of its Philadelphia Section; the American Crystallographic Association, and the AIME.

ESB INCORPORATED
ESB TECHNOLOGY CENTER

Key Personnel

JAMES B. DOE

Position: Research Associate

Responsibility: Principal Investigator
Advanced EV Battery

Education: 1963 - University of Wisconsin - BS in Chemistry
1970 - New York University - ME -Chemical Engineering

Job Experience: ESB Incorporated 1974-Present
Research Associate
Technology Surveillance and Planning Department

ESB Incorporated 1970-1974
Head, Primary Battery Laboratory

U.S. Army Electronics Command 1968-1970
Research Electrochemist

P.L. Howard Associates, Inc. 1967-1968
Instructor of General Chemistry

Melpar 1965-1967
Electrochemical Engineer

Pratt & Whitney Aircraft Corporation 1964-1965
Analytical Engineer
Advanced Power Systems Group

Allis-Chalmers Manufacturing Company 1963-1964
Engineering Scientist
Energy Conversion Systems Section

University of Wisconsin 1963
Research Assistant

ESB INCORPORATED
ESB TECHNOLOGY CENTER

Key Personnel

JOHN B. OCKERMAN

Position: Research Associate

Responsibility: Principal Investigator
Test and Evaluation

Education: 1952 - University of Wisconsin - BS

Job Experience: ESB Incorporated - 1970
Senior Scientist, Lead Acid Products
Design, construction and testing of high-efficiency
lead-acid batteries for electric vehicle propulsion.
Characterization of low loss lead-acid cells for
long-term float or unattended operation.

Gould, Inc. 1966-1970
Senior Engineer, Battery Development
Development and testing of water activated lead-
acid batteries, primary and mechanically rechargeable
zinc-air batteries.

ESB Incorporated 1956-1966
Scientist, Electrochemistry
Application of gas electrodes in sealed cells,
radio-isotope studies of separators for cells
having alkaline and acid electrolytes. Development
of new seawater cell systems.

Ray-O-Vac. 1953-1956
Research Engineer, Research Division
Investigation of aluminum and magnesium anodes for
dry cells of LeClanche type.

ESB INCORPORATED
ESB TECHNOLOGY CENTER

Key Personnel

THEODORE W. BLICKWEDEL

Position: Senior Scientist

Responsibility: Application of Quality Control
Engineering methods to new product and process developments.

Education: 1946 - Rose Polytechnic Institute - BS
1949 - Iowa State University - MS

Job Experience: ESB Incorporated - 1970
Senior Scientist, Process Engineering
Process capability studies, design of experiments, design
of sampling plans, analysis of data, application of
statistical methods, preparation and evaluation of test
plans, economic studies.

General Telephone & Electronics Labs - 1965-1970
Engineering Specialist, Energy Storage & Conversion
Department
Research and Development on primary and secondary battery
systems.

Sylvania Electric Products, Inc. 1949-1965
Engineer-in-Charge, General Engineering Department,
Electronic Components Group
Process and product development, hermetically sealed
nickel-cadmium cells. Development of electrophoretic
coating process.

ESB INCORPORATED
AUTOMOTIVE DIVISION
Key Personnel

WILLIAM R. CLINGENPEEL

Position: Manager of Manufacturing Services

Responsibility: Supervises the Managers of Industrial Engineering, Plant and Equipment Engineering, Material Control and the Applications Engineer.

Education: 1942 - Purdue University - BSChE

Job Experience: Thirty-five years in the battery industry with Delco, Eltra, and since 1964 with ESB. Process Engineer with Delco, Assistant Chief Engineer and Plant Manager with Eltra, Manager of Equipment Engineering, Manager of Manufacturing and Manager of Manufacturing Services with ESB.

Holder of several U.S. and Canadian patents on battery components and equipment.

ESB INCORPORATED
AUTOMOTIVE DIVISION

FRANKLIN VERGILII

Position: Manager of Product Development

Responsibility: Electric Vehicle Battery Development
Electric Vehicle Battery Technical Services
Coordination of Company EV Battery Projects
Evaluation and Development of Battery Test Equipment
Special and Non-Standard Testing
Battery and Component Prototype Models

Education: 1961 - Kenyon College - AB
1962 - Graduate Work in Chemistry
1963 - University of Pittsburgh - MBA

Job Experience: Mr. Vergilii joined ESB in 1966 as Applications Engineer.
Other positions held: Project Engineer, Supervisor Special
Projects, and Supervisor Grid Casting.
Employed 1963-1966 by Republic Steel Corporation as Research
Technologist. Primary work involved metal plating, annealing,
and corrosion studies.

ESB INCORPORATED
EXIDE POWER SYSTEMS DIVISION

Key Personnel

FRANK A. VENGROFSKI

Position: Senior Engineer

Responsibility: Design and development of sealed lead-acid batteries. Devised and tested methods required for evaluation of various batteries. Design of various types and sizes of batteries and chargers.

Education: 1944 - Villanova University - BS

Job Experience: Mr. Vengrofski joined ESB in 1954 and has had a variety of positions including Project Engineer, Project Leader and since 1971, his present position of Senior Engineer.

Mr. Vengrofski has been instrumental in the design and development of new batteries for various applications including motive power, mine lamp, golf car, marine, diesel, and locomotive starting.

He has been a leader in component evaluation involving the study and design of new types of tubing, grids and active materials leading to improved operating efficiency and reduced manufacturing cost.

Mr. Vengrofski has been granted three patents: Battery Terminal construction, Battery Assembly and a Canadian patent on Battery with Modular Construction. He also has a Canadian patent applied for, on the Sealed Cell.

ESB INCORPORATED
EXIDE POWER SYSTEMS DIVISION

Key Personnel

S. F. BROHOSKI

Position: Manager, Process & Equipment Development

Responsibility: Complete responsibility for design, development and purchase of all equipment and tooling for three Lead Acid plants. Responsible for value analysis, process development and design analysis of all new products. Responsible for divisional cost reduction program.

Education: McGill University - Bachelor Engineering, Mechanical Engineering
Supplementary courses in Industrial Engineering, Finance, Computers, etc.

Job Experience: Warnoch Hersey Company, Montreal, Canada
Manager, Expediting Division
Also involved in inspection, appraisal and consulting for the above.

Chrysler Corporation
Product Testing & Development Engineer, Tooling Engineer

General Motors Corporation
Sr. Project Engineer, Central Mfg. Staff
Work involved equipment, tool development, value analysis, product cost study, financial and engineering studies, encompassing all General Motors divisions in U.S. and abroad.

ESB, Inc., Exide Power Systems Division
Sr. Mfg. Engineer - Special Projects
Manager, Manufacturing Engineering
Manager, Industrial Engineering
Manager, Shop Reporting and Timekeeping

Professional Societies:

Corporation of Professional Engineers, Canada
Technical Chairman

American Society of Tooling & Mfg. Engineers

Society for the Advancement of Management

Appendix 1

Battelle Columbus Laboratories' Proposed Research

Program for Grid Design and Evaluation

PROPOSED RESEARCH PROGRAM

on

ELECTRIC VEHICLE BATTERY DEVELOPMENT STUDIES

to

ESB INCORPORATED
TECHNOLOGY CENTER

December 13, 1976

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

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PROPOSED RESEARCH PROGRAM

on

ELECTRIC VEHICLE BATTERY DEVELOPMENT STUDIES

to

ESB INCORPORATED
TECHNOLOGY CENTER

from

BATTELLE
Columbus Laboratories

December 13, 1976

INTRODUCTION

Battelle's Columbus Laboratories (BCL) is pleased to have this opportunity to respond to a request from Dr. George C. Kugler for a proposal to assist ESB Incorporated in one of its activities to develop an improved state of the art lead-acid battery. In this proposal we address the problem of optimizing lead-acid battery grid design, and suggest that a computer modelling approach developed by Dr. Vaaler of BCL be modified to accomplish the program objectives. Existing or intuitive grid designs can be analyzed with the computer program with some modification; however, more extensive effort will be needed to adapt the program to design optimized grids from first principles. Hence, two tasks are proposed herein, describing the required R&D for the analytical and predictive modelling.

The proposed research program will be performed in the Corrosion and Electrochemical Technology Section of the Chemistry Department at BCL. Researchers responsible for battery development within this Section will be supported in their activities by personnel experienced in modelling from the Statistical and Mathematical Modelling Section who are familiar with battery technology, having worked on interdisciplinary programs before. BCL is confident that these talents applied to the proposed program will enhance the potential for the eventual development of lead-acid battery grids of greatly improved performance.

TECHNICAL BACKGROUND

ESB Incorporated has embarked on a development program to design and build (1) improved state of the art (ISOA) and (2) advanced lead-acid batteries for use in electric vehicles. The ISOA batteries will use as the basis of their design philosophy conventional golf-cart battery technology. However, in order to meet the anticipated performance specifications considerable improvements through modification of cell design and materials will be necessary. One opportunity for improvement, particularly for relatively high power applications, is the redesign of the grid. Such a design optimization should ensure more even current density distribution over the plate, hence more even utilization of the active materials. The latter, in turn, would promote a longer useful cycle life, a more compact cell and hence battery design.

Another aspect is that several components in the battery contribute to voltage losses on charge and discharge because their electrical resistance contributes to the overall internal resistance. The metal grids are one such component which becomes more critical as they are made lighter and thinner, and thus provide increased resistance. Traditionally such grids have been designed with essentially an uniform cross section with grid elements running vertically and horizontally in the battery with a contact tab in the upper corner. However, lines of current flow are likely to diverge (in the form of a fan) out from the tab into the grid so that it should be advantageous to design grids that follow these current lines. Also the grid elements near the tab should be heavier than those that are farther away, due both to spreading out of the electrode areas and the passage of current through the electrolyte.

Assuming that a specific amount of lead alloy is available for a grid for each electrode and that the mechanical requirements for grid elements will be met, e.g., sufficient strength, the grid structure can be optimized. Two methods which are in part complementary are proposed for developments toward optimizing the electrode structure. These methods are described under Tasks 1 and 2 below.

In addition to the weight and mechanical properties constraints, overall dimensions; minimum bar size; maximum pellet size; electrical con-

ductivity (composition) of the grid alloy; overall shape of the grid; and number of tabs, are some of the other variables which influence grid design. All pertinent variables will be considered in the proposed Task 2 predictive studies; however, in the Task 1 analytical studies, the existing or intuitive designs will influence the results obtained.

PROPOSED RESEARCH PROGRAM

As mentioned above, the proposed program will consist of two tasks. The first analytical task will conceptualize or use available grid designs in conjunction with the existing computer program to calculate the voltage and current density distribution over these grids as a function of an applied current. The second predictive task will be directed to the development of an optimized grid by minimizing the voltage, at any given current, using a functional relationship relating grid structure to performance. The result anticipated is a grid design which is theoretically the best possible for any selected grid weight.

Task 1: Calculation of Voltage Drop and Current Distribution of Conceptual Designs

As a control, a conventional rectangular grid, similar to that shown in Figure 1 will be analyzed using the BCL computer modelling approach already developed for applications in industrial electrolysis cells, and suitable for modification to similar battery problems.

For a conventional electrode made up of orthogonal vertical and horizontal grid members, Kirchoff's Law can be applied to each intersection. The expressions for the potentials at each grid point (node) can then be solved simultaneously, which is practical for a large number of grid points with computer. The output includes the voltage from the tab to the counter electrode and the current density and potential at each point. The model for this program assumes that resistance in the counter electrode is negligible and that the current density on the grid

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

surface is proportional to the potential difference between the grid point and counter-electrode. A simpler model has been described by Tiedeman, Newman and DeSua⁽¹⁾ in which the current density is assumed to be the same at all grid points.

Euler⁽²⁾ has described a technique for evaluating an electrode without installing it in an electrolysis system. A current is applied to each grid point and the potential measured simultaneously. Thus, in addition to the requirement for an actual specimen upon which measurements must be made, a tedious procedure must be followed. Also in the Euler approach, the current density is assumed to be the same at all grid points. However, the actual uniformity of current that is obtained in practice is a good measure of the efficiency of a grid design. Hence, the BCL modelling program, which does not assume uniform current density distribution, should be more useful for optimizing cell design. Euler does describe a figure of merit for a grid, however, which could be used irrespective of the type of model selected for analysis.

The BCL program can be readily modified for use with other grid networks with grid points that occur in a reasonably regular manner. For example, grid lines may follow approximate equipotential lines as they do in some battery grid designs. In any event the grid consists of continuous or broken lines that cross each other. The sequence of steps in calculating parameters of these grids are:

- (1) Find the cartesian coordinates for all grid points
- (2) Find the average width of each line between adjacent grid points (assume constant grid thickness).

These data can be obtained quickly and accurately by a low cost computer graphics technique where a pattern of the grid is projected, a light pointer focused on each grid point, and each point digitized. Line widths

(1) W. Tiedeman, J. Newman, and F. DeSua, "Potential Distribution in the Lead-Acid Battery Grid", Preprint No. 2, 10th Int. Power Sources Symposium, Brighton, U.K. (1976).

(2) K. J. Euler, "Zur Ermittlung des effektiven elektrischen Widerstandes der Gitter in Bleiakumulatoren", Arch. für Electrotechnik, 54(1971) 122.

are obtained by touching the pointer to opposite edges of a grid line, the area associated with each grid point, the voltage, current, and current density distribution throughout the grid, and the voltage at the tab. The modelling program could also be modified to take account of the conductance of the paste in the holes of the grid.

Thus, in the Task 1 studies it is recommended that three grid designs be studied in detail using the BCL modified modelling program. One would be the control design supplied by ESB Incorporated. Another would be an intuitive grid design based upon ESB Incorporated experience, and consultation with others knowledgeable in the battery field. The third would be another intuitived design conceptualized by BCL researchers in this field. Of course, further designs can be analyzed subject to time and costs available. Alternatively, additional effort could be contracted with BCL for this type of study, subject, of course, to mutual commitments at the time.

Task 2: Design of a Grid from First Principles

In contrast to the analytical methods previously discussed, where electrode designs are derived from a general qualitative knowledge of electrode requirements and a certain amount of intuition, there is the possibility of describing an electrode mathematically, imposing requirements on the mathematical model (boundary conditions) and subjecting the model to a numerical routine that will provide a theoretically optimum design.

A modelling procedure is proposed that should provide the optimum design for a given set of boundary conditions. An electrode that is a continuum, rather than one made up of discrete grid elements, is first simulated by use of an orthogonal grid pattern that is as fine as is practical for the use of computational procedures. Solution of the potential distribution for this system will determine current distribution and direction in the electrode as well as current density distribution to the counter electrode. It will also provide the relative amount of conductivity in the grid elements in the various sections of the electrode. From these results a conceptual design is made in which the grid elements follow as closely as possible the ideal current lines, have sufficient structural strength, and provide suitable sized (pellet)

holes for pasting. The performance parameters of the conceptual design may then be confirmed by the program previously described.

In a rectangular orthogonal grid made with a given mass of metal the sum of the conductances of all of the grid elements is a constant. If the conductance of one grid element is increased another must be decreased. If E represents the total voltage seen at the plate tab, and $C_1 \dots C_n$ represent the various conductances of all the lead-alloy grid elements (total n), and if C_e represents the conductance of the electrolyte related elements, for a current flow I , then the mathematical problem may be stated as:

$$\begin{aligned} \text{Minimize } E &= f(C_1, C_2, \dots, C_n; C_e; I) \\ \text{subject to: } C_1, C_2, \dots, C_n &= \text{constant} \end{aligned}$$

where the functional form of f must take account of Kirchhoff's Law and the series/parallel arrangement of the grid elements. It is expected that the resulting non-linear minimization problem can be solved using computer algorithms available at BCL. Algorithms based on geometric programming^(3,4) or dynamic programming⁽⁵⁾ appear to be applicable. It is recommended that the final solution be derived in stages, beginning with a single, one-dimensional grid with few nodes (intersection points) and gradually extending the solutions to more refined two-dimensional grids with many nodes. The solutions obtained from these simplified problems are expected to provide guidance for the scale-up to practical grid configurations. Such guidance should not only result in an improved understanding of optimal grid design, but may also prevent costly computer runs resulting from improper or slowly converging formulations of the many node problem.

As expressed above, optimizing the grid design involves a problem of allocating a given amount of material (conductance) among the grid nodes. The geometric and dynamic programming algorithms are identified

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- (3) R. J. Duffin, E. L. Peterson and C. Zener, Geometric Programming-Theory and Application, John Wiley and Sons, Inc. New York (1967)
 - (4) C. S. Beighler and D. T. Phillips, Applied Geometric Programming, John Wiley and Sons, Inc., New York, New York (1967)
 - (5) R. E. Bellman and S. E. Dregfus, Applied Dynamic Programming, Princeton University Press, Princeton, New Jersey (1962).

as candidate methods of approach because both are general purpose resource allocation algorithms. However, once the mathematical structure, and the solution properties become more explicit as a result of the initial analysis, it is possible that a more effective, specialized optimization algorithm can be used.

The printout of the C_i 's, currents, and E_i 's for each grid node will allow an estimation of equipotential lines, and the current lines which are orthogonal to the equipotential lines. In preparing a conceptual design from this information with grid lines following optimum current paths an appropriate area of the presumably finer grid pattern used to define the direction of the current lines would be allocated to the conceptual grid elements. The conductivity of the elements in the conceptual design would be calculated by vectorial addition of the x and y components of elements in the finer grid. At this point there is also an opportunity to use the computer graphics pointer technique to establish the grid points in the conceptual design followed by a computer program to do the vectorial addition and assign a conductivity to each element. This procedure may or may not be more cost and time effective than manual calculation, depending upon the number of designs considered, the number of grid elements involved, and so on.

It is likely that a grid pattern following optimum current paths will require less metal than an equivalent grid made with orthogonal horizontal and vertical grids. This is because vectorial rather than arithmetic addition of conductance is proper in deriving the current line design from the orthogonal mode. Therefore more than one trial may be necessary if the objective is to provide a predetermined amount of metal in a grid element. It would seem that a more reasonable way to approach the problem is to decrease the sum of conductances (and metal) to the point that the voltage drop or the mechanical strength of an optimized model are unsatisfactory. This amount of metal may turn out to be less than the maximum amount specified by ESB Incorporated for a satisfactory grid, however, other criteria, such as corrosion of the grid bars, may control the actual amount of metal used.

As before, ESB Incorporated will specify an overall size and thickness for rectangular grids having one tab located along its upper edge. Positive and negative plate grids are required for a lead-acid

battery cell, hence consideration must be given to maintaining a finite separation between these tabs so that plate groups may be successfully burned and joined with intercell connectors without increasing the likelihood of internal shorting. ESB Incorporated will also specify the lead casting alloy, hence its conductance, and also the maximum amount of material which can be used in each grid. Maximum pellet size (area) and minimum grid bar size will be further constraints. Conductance values for the electrolyte and the positive plate paste may be available from ESB Incorporated. The negative plate can be assumed to be an equipotential surface⁽⁶⁾, which permits the use of the BCL model. The conductance of the negative plate paste is available or may be readily determined.

PROGRAM ORGANIZATION

The proposed program will be carried out in the Corrosion and Electrochemical Technology (C&ET) Section within the Chemistry Department of Battelle's Columbus Laboratories. Mr. Walter K. Boyd is manager of the former, while Dr. Albert H. Adelman is manager of the latter. Mr. Boyd will have overall administrative responsibility for the program, and access to BCL line management will be through Mr. Boyd and Dr. Adelman.

Dr. Eric W. Brooman, Group Leader for electrochemical energy conversion and storage in the C&ET Section will be responsible for the day to day management of the proposed program, and will have technical responsibility for its effective implementation. However, Dr. Brooman will be assisted by Dr. Luther E. Vaaler and Dr. Ralph E. Thomas, as shown in Figure 2, in order to achieve the program's technical objectives. Dr. Vaaler is a Senior Researcher in the C&ET Section who was responsible for the initial development of the BCL computer modelling technique referred to earlier. Dr. Thomas is manager of the Statistical and Mathematical Modelling Section at BCL, and has worked with Dr. Brooman in the past on other battery modelling programs. Biographical sketches of these principal

(6) W. W. Smith, ESB Incorporated, private communication (1976).

FIGURE 2. PROPOSED MANAGEMENT ORGANIZATION
SHOWING PRINCIPAL PROGRAM PERSONNEL

program personnel are given in a later section of this proposal. Other staff members at BCL with specific capabilities pertinent to the proposed program will be consulted as the need arises. The interdisciplinary approach described is recognized as being the most effective for solving the needs of a sponsor.

LIAISON, MEETINGS, AND REPORTS

Battelle recognizes the importance of effective communication between the sponsor and the program staff. To ensure this, Dr. Brooman, as Program Manager, will be responsible for acting as liaison with Dr. George C. Kugler, or other authorized representatives of ESB Incorporated; arranging for any meetings; all reports, formal or informal, written or verbal; and negotiating any technical changes in the scope of the proposed research, in addition to his other duties mentioned earlier.

Representatives of ESB Incorporated will be most welcome to visit BCL to discuss progress on the program at mutually convenient times. A review meeting can be held towards the end of the proposed program at the ESB Technology Center, at which time the final report format and contents can be drafted. Alternatively, it may be more convenient for ESB personnel to visit BCL at this time for discussions with all the program personnel.

It is proposed that informal monthly letter reports be submitted by the tenth working day of the following month. These relatively short reports will include a description of progress made and plans for the next reporting period. A detailed final report will be submitted at the end of the proposed program. This final report will contain details of the experimental and modelling procedures, a description and interpretation and discussion of the results, and suggestions for implementing the improved grid designs(s).

ESTIMATED TIME AND COST

In order to meet the technical objectives of the proposed program, a six month period of performance is recommended with an estimated appro-

priation of \$40,000. The Task 1 effort will take approximately two months at a cost of about \$10,000. The Task 2 effort will take approximately four months to complete at a cost of about \$30,000.

Battelle agrees to provide a high standard of professional service, and will exert its best efforts toward achievement of the technical objectives within the time and funding provided. However, the results of the proposed program will be experimental and advisory in nature. Therefore, in no event shall Battelle, or its employees and agents, have any obligation or liability for damages, including but not limited to consequential damages, arising from or in connection with the sponsor's use or inability to use the information resulting from this program.

This proposal will be considered an open offer on the part of Battelle until March 31, 1977. Unless we extend this period, acceptance after that date will be subject to mutual agreement.

BIOGRAPHICAL DATA FOR PRINCIPAL PROJECT PERSONNELWALTER K. BOYD

Manager, Corrosion and Electrochemical
Technology Section

Bachelor in Metallurgical Engineering (1945)
The Ohio State University

Since joining Battelle in 1945, Mr. Boyd has conducted and supervised research on the metallurgical aspects of corrosion. He has contributed significantly to the development of high-temperature alloys and special chemical-resistant alloy systems, two of which have been patented. Mr. Boyd has studied a variety of corrosion mechanisms, such as stress-corrosion cracking for austenitic stainless steels, aluminum alloys, titanium alloys, nickel- and copper-base alloys, and low-alloy steels. His broad experience in corrosion research also includes a variety of problems associated with high-temperature fluid systems (e.g., water, liquid metals, and fused salts).

Mr. Boyd has had extensive experience in corrosion problems associated with various types of water, including marine environments and the high-purity, high-temperature water used in fossil fuel and nuclear power plants. His experience has encompassed a wide variety of problems associated with both the leaching of uranium bearing ores and the recovery of nickel and copper values by chemical metallurgical techniques from low-grade ores.

He has been very active in the field of marine corrosion and has participated in the selection of a number of materials for deep ocean mining and offshore drilling facilities.

Mr. Boyd is a past National Director of the National Association of Corrosion Engineers. He serves on numerous committees for the NACE; for example, he is Chairman of the Publications Committee, the Definitions and Terminology Committee, and a member of the Finance Committee. He is also a member of the ASM.

Mr. Boyd is internationally recognized in the corrosion field and in recent years has been invited to lecture on corrosion in Korea, Mexico, Canada, Russia, Italy, England, as well as in the United States.

In May, 1973, he received the citation of recognition for outstanding contributions from the NACE. He is a registered engineer in Ohio and a NACE registered corrosion specialist.

ERIC W. BROOMAN

Group Leader, Corrosion and Electrochemical
Technology Section

Diploma in Technology, Metallurgy (1963) Battersea
College of Advanced Technology, England

Ph.D., Electrochemistry (1966) University of
Cambridge, England

Dr. Brooman was educated in England, and worked for the United Kingdom Atomic Energy Authority before joining Battelle's Columbus Laboratories in 1966. Since that time, he has competently worked in many areas of electrochemical engineering, but principally in the areas of battery technology, fuel cells, and hydrogen technology. He currently is a Group Leader responsible for electrochemical energy conversion and storage.

He has developed new alloys for primary cell electrodes, and helped design new electrode structures to accommodate the volume changes which occur when secondary cell electrodes are cycled. He is an expert on the thermophysical properties of aerospace batteries, cells and their components, and has firmly established the use of thermal resistance-capacitance network analogs for predicting cell and component conductivities. This work had led to the publication of his results, and some results of his work were presented at a National Meeting of the Electrochemical Society.

His recent interest include two programs on energy storage using secondary battery or fuel cell systems. He was a member of the team of experts at BCL directed by ERDA to review the development status of U.S. technology in energy storage, and he was responsible for two subject areas, namely, battery technology and hydrogen technology. In the latter context, he has been involved with programs to assess the technical and economic feasibility of using metal hydrides for bulk energy storage, and for storage on hydrogen-fueled ground vehicles.

In an intermittent effort over the last 13 years Dr. Brooman has investigated the use of alloys as electrocatalysts with increased activity for fuel cell reactions (oxygen, hydrogen, and methanol half-cell reactions). This activity is reflected in the list of publications at the end of this capabilities statement. As an example, from 1972 to 1973 he studied the use of ion-implantation techniques to incorporate small amounts of transition metals in base metals to produce inexpensive electrocatalysts.

Dr. Brooman has published over 10 technical papers, the latest including "Electric Vehicle Batteries: Opportunities for Materials Improvement," which appeared in the SAMPE Journal, 12 (1976) 4; and "Correlations Between the Rate of the Hydrogen Electrode Reaction and the Properties of Alloys", J. Electroanalyt. Chem., 49 (1974) 325.

Dr. Brooman is a Member of the Institution of Metallurgists, the professional qualifying body in the United Kingdom. He is also an active member of the Electrochemical Society, and served on the Personal Membership Committee from 1968-1971. He was Membership Chairman of the Columbus Local Section from 1968-1971, Secretary/Treasurer from 1971-1972, and for 1974-1975; Vice-Chairman for 1975-1976, and is presently serving as Chairman. He is currently also Secretary of the Council of Local Sections of the Electrochemical Society.

LUTHER E. VAALER

Senior Researcher, Corrosion and Electrochemical
Technology Section

A.B., Chemistry, Mathematics, Luther College,
Decorah, Iowa

Ph.D., General and Physical Chemistry (1947)
University of Wisconsin

Dr. Vaaler has had extensive experience in applied electrochemistry, particularly with large scale processes such as the production of chlorine-caustic and chlorate, electrometallurgy and metal finishing. His work includes the application of insoluble anodes of metal or graphite to such processes. He is also well versed in the application of carbon and graphite to the chemical process industries and nuclear power plants. He has managed diverse industrial and government R&D programs.

Some of Dr. Vaaler's specific accomplishments are as follows:

- In a series of laboratory investigations he established some of the basic parameters involved in electrolyte production of chlorine on a sound technological base. These parameters include anolyte pH and anode current density as they affect current efficiency and anode corrosion.
- He devised methods for field testing electrodes in large-scale electrolytic cells using applied statistics to design experiments and analyze results. He also wrote computer programs to calculate the effect of electrode specific resistance and design on the voltage required to operate the cells. Such calculations allowed optimization of the electrode design.
- He supervised the development of and the pilot-scale production of a special moderator graphite for the Molten Salt Reaction Experiment at Oak Ridge. Sophisticated processing and quality control techniques were required.

- He obtained and supervised a government project on development of an improved activated carbon to absorb chemical agents. He was instrumental in obtaining contracts with the Office of Saline Water to develop porous heat exchanger tubes that would inhibit scale formation, and supervised the work itself. He also supervised development work on arc carbons used in solar simulators to test out the Appollo Spacecraft.
- He discovered a hydrometallurgical method of removing selenium from ores and refinery sludges and a method of electropolishing zinc die casting.
- He supervised a broad survey of the metal finishing industry to aid in establishing effluent limitations guidelines.
- He is presently involved in project development in several areas of applied electrochemistry including organic synthesis and metal deposition.

Dr. Vaaler has published 11 papers and has three patents issued. He is a member of the Electrochemical Society, American Chemical Society, and American Institute of Chemists.

RALPH E. THOMAS

Manager, Statistical and Mathematical Modeling Section

B.A., Mathematics (1948) Ohio Wesleyan University

M.A., Mathematics (1950) The Ohio State University

Ph.D., Operations Research (1966) Case Institute of Technology

Since joining Battelle-Columbus in 1952, Dr. Thomas has made significant contributions in applications of statistics and mathematical models to problems in research.

As Section Manager, Dr. Thomas has been the administrative supervisor of approximately five professional statisticians since 1967. He is responsible for the technical quality of the statistical research performed by his Section.

The statistical and mathematical aspects of the following recent programs were under his technical supervision:

- A computer-based data-processing methodology was developed by Dr. Thomas to analyze simultaneous combinations of environmental variables. The combinations include climatic variables (temperature, relative humidity, wind speed, etc.), weather events (fog, rain, hail, etc.), and air pollution variables

SO₂, O₃, etc.). The method generates answers to the following kinds of questions: How often does a particular environmental condition occur in a specified time period? How long does it last? What condition is likely to occur next? The methodology was applied to data for the 1965-1974 time period at nine climatically diverse geographic locations.

- An innovative modeling approach to the analysis of accelerated test data by Dr. Thomas was awarded a citation by the National Aeronautics and Space Administration (NASA). The approach involves a blend of empirical methods, statistical methods, and methods based on physical laws. This approach has been used by both NASA and the United States Air Force as a basis for the design and analysis of test programs for spacecraft batteries.
- A computer program was written by Dr. Thomas for the United States Air Force to obtain estimates of the reliability of electro-mechanical systems. As input the program uses reliability information on the subsystems together with structural information obtained from engineering diagrams of the system. This program forms the basis of the Tabular System Reliability Analysis (TASRA) which is operational and being further extended by the Air Force.
- A statistical assessment was made of the effectiveness of a career screening method for Bio-Digital Science, Inc. The assessment was made by modifying the Automatic Interaction Detector (AID) computer program; applying the modified program to the data; and then comparing the results obtained with those obtained using conventional linear discriminant analysis.
- In a program for the Office of Economic Opportunity, Dr. Thomas applied statistical concepts to obtain valid assessments of the impact of compensatory education. The analyses were based primarily on achievement scores and supplementary questionnaire data. Technical problems associated with nonrandomization, instrument unreliability, etc., were given critical attention in order to attain evaluations that were fully objective.

Experience in addition to that at Battelle includes mathematical research in military operations analysis from 1955 to 1957 at North American Aviation, Inc., and lecturing in mathematical statistics at The Ohio State University.

In addition to four years of teaching undergraduate courses before joining Battelle-Columbus, Dr. Thomas has taught the following courses:

Design of Experiments (noncredit course given at North American Aviation, Inc., 1956-1957). Topics included randomized blocks, Latin squares, factorial designs, and response-surface analysis.

Mathematical Statistics (graduate-level course, Mathematics Department, The Ohio State University, 1958-1959). Topics included estimation theory, hypothesis testing, multivariate normal theory, and nonparametric statistics.

Engineering Statistics (noncredit course given at Battelle's Columbus Laboratories, 1961-1962). Topics included analysis of variance, regression analysis, and statistical inference.

Interpretation of Biological Data (graduate-level course, Zoology Department, The Ohio State University, 1962-1963). Topics included t-tests, F-tests, analysis of variance, and nonparametric tests of hypotheses.

Scientific Method (graduate-level course, Case Institute of Technology, 1964-1965). Topics included philosophy of science, scientific inference, development of models, and validity testing.

Calculus Refresher (noncredit course, Battelle's Columbus Laboratories, 1967-1968). Topics included differential and integral calculus with an introduction to FORTRAN programming.

Dr. Thomas is a member of Pi Mu Epsilon, Phi Beta Kappa, Sigma Xi, Mathematical Associations of America, New York Academy of Sciences, Member of Board of Elections of the Ohio State Chapter of Sigma Xi (1963-1971), and President of the Operations Research Club of Central Ohio (1970-1971).

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RELATING TO BATTERY AND FUEL CELL TECHNOLOGY

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- (2) McGraw, L. D., "Advances in Battery Power Systems", Battelle Technical Review, 7 (1958) 12.
- (3) Schaer, G. R., U.S. Patent No. 2,870,068, "Electroformed Screens" (January 20, 1959).
- (4) McCallum, J., Clifford, J. E., and Semones, D. E., U.S. Patent No. 2,929,860, "Primary Cell" (March 22, 1960).
- (5) McGraw, L. D., "Fuel Cells: Introduction", SAE Preprint 179A presented at SAE Summer Meeting (June 5-10, 1960).
- (6) Clifford, J. E., and Gates, J. T., "Oxygen From Water", Battelle Technical Review, 10 (1961) 23.
- (7) Clifford, J. E., McCallum, J., and Semones, D. E., U.S. Patent No. 2,992,143, "Acid Primary Cell" (July 11, 1961).
- (8) Hardy, R. W., and McCallum, J., "Research Requirements for High-Temperature Fuel Cells", "Fuel Cells", a CEP Technical Manual (1963) p 45.
- (9) McCallum, J., "Electrolytic Reaction Zone Inside a Pore", paper presented at Journees Internationales D'Etude des Piles A Combustible, June 21-24, 1965.
- (10) Brooman, E. W., and Hoar, T. P., "Platinum Metal Alloys in Electrocatalysis", Platinum Metals Review, 9 (1965) 122.
- (11) Clifford, J. E., Kolic, E. S., and Faust, C. L., "Water Electrolysis Using a H₂-Diffusion Cathode", AIChE Preprint No. 478 (1965).
- (12) Hardy, R. W., Chase, W. E., and McCallum, J., "The Double-Duty Anode for Molten Carbonate Fuel Cells", in "Hydrocarbon Fuel Technology", Academic Press Inc., New York, New York (1965) p 213.
- (13) Brooman, E. W., and Hoar, T. P., "Platinum Metal Alloys in Electrocatalysis: A Further Evaluation of Relative Activities", Platinum Metals Review, 10 (1966) 135.
- (14) Brooman, E. W., and Hoar, T. P., "Electroreduction of Oxygen on Pt-Ru and Pt-Rh Alloys", Electrochimica Acta, 11 (1966) 545.
- (15) Brooman, E. W., "Surface States of Platinum Electrodes", Platinum Metals Review, 10 (1966) 86.

- (16) Clifford, J. E., and Kim, B. C., "Carbon Dioxide Reduction and Water Vapor Electrolysis System", SAE Preprint No. 680719 (1968).
- (17) Clifford, J. E., "Phosphoric Acid Electrolysis Cell Generates O₂ from Water Vapor", SAE Journal, 76 (1968) 62.
- (18) Clifford, J. E., "Water Vapor Electrolysis Cell with Phosphoric Acid Electrolyte", SAE Trans., 76 (1968) 2607.
- (19) Schaer, G. R., "Electroformed Screens With Controlled Hole Size for Battery Plaques", Plating, 55 (1968) 130.
- (20) Reed, A. H., Cover, P. W., and McCallum, J., "Failure Analyses of Sealed Ni-Cd Batteries", Extended Abstr., Fall Meeting, The Electrochem. Soc. (1969), Abstr. No. 11, p 29.
- (21) Semones, D. E., and McCallum, J., "Physical Changes of Lithium Electrodes During Charge-Discharge Cycling", Proc. 24th Power Sources Symp. (1970) p 16.
- (22) Brooman, E. W., and McCallum, J., "Thermal Conductivity Measurements of Ni-Cd Aerospace Cells, Part I: Cell Conductivities", J. Electrochem. Soc., 118 (1971) 1518.
- (23) Semones, D. E., and Faust, C. L., Canadian Patent No. 798,930, "Electrodes and Preparation Thereof".
- (24) Semones, D. E., and Cross, W. E., U.S. Patent No. 3,355,326, "Method of Preparing Electrodes".
- (25) Clifford, J. E., U.S. Patent No. 3,620,843, "Rechargeable Cell Having Moving Tape and Rotating Electrodes", (November 16, 1971).
- (26) Brooman, E. W., and McCallum, J., "Thermal Conductivity Measurements of Ni-Cd Aerospace Cells, Part II: Component Conductivities", J. Electrochem. Soc., 119 (1972) 1137.
- (27) Clifford, J. E., "An Electrically Rechargeable Zinc-Air Tape Battery", Proc. Symp. on "Batteries for Traction and Propulsion", Columbus Section, Electrochemical Soc. (1972), p 150.
- (28) Semones, D. E., Kerr, R. L., and McCallum, J., Editors, Proc. Symp. on Batteries for Traction and Propulsion, Columbus Section, The Electrochemical Society (1972).
- (29) Brooman, E. W. and Kuhn, A. T., "Correlations Between the Rate of the Hydrogen Electrode Reaction and the Properties of Alloys", J. Electroanal. Chem, 49 (1974) 325.
- (30) Semones, D. E., Brooman, E. W., and Clifford, J. E., "Scorecard on Battery and Fuel Cell Development for Electric Vehicle Propulsion", paper presented at ASME Design Engineering Conference, April, 1974.

- (31) Brooman, E. W., Semones, D. E., and Clifford, J. E., "The Development Status of Batteries for Electric Vehicles", paper presented at the Dana Electric Vehicle Symp., June, 1974.
- (32) Cover, P. W., Brooman, E. W., and Clifford, J. E., "Materials for Electrochemical Energy/Conversion and Storage", paper presented at ASM Materials/Design Forum, June, 1974.
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- (34) Cover, P. W., "Batteries and Fuel Cells as Energy Sources", paper presented to the Columbus Section, The Electrochemical Society, September, 1974.
- (35) Brooman, E. W., and Clifford, J. E., "Materials Problems Associated With Electric Vehicle Batteries", Proc. 6th National SAMPE Conference (October, 1974), p 273.
- (36) Cover, P. W., "Batteries or Fuel Cells: Alternatives to Petroleum Fuels", paper presented at the 2nd National Energy and Environmental Conference (November, 1974).
- (37) Brooman, E. W., Clifford, J. E., and Semones, D. E., "Batteries: Prospects for Electric Vehicles", Automotive Engineering, 83 (1975), p 30.
- (38) Brooman, E. W. and Clifford, J. E., "Better Batteries for Electric Vehicles", Machine Design, May 15, 1975, p 89.
- (39) Clifford, J. E., and Brooman, E. W., "A Water Battery Concept for Electric Utility Energy Storage", Proc. Symp, on Energy Storage, The Electrochemical Society, October, 1975.
- (40) Brooman, E. W., and Clifford, J. E., "Electric Vehicle Batteries: Opportunities for Materials Improvement", SAMPE Journal, 12 (1976)4.

Appendix 2

Battelle Columbus Laboratories' Proposed Research
Program for Computer Battery Performance Modeling

PROPOSED RESEARCH PROGRAM

on

ELECTRIC VEHICLE BATTERY MODELING STUDIES

to

ESB INCORPORATED
Technology Center

January 31, 1977

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

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PROPOSED RESEARCH PROGRAM
on
ELECTRIC VEHICLE BATTERY MODELING STUDIES
to

ESB INCORPORATED
Technology Center

from

BATTELLE
Columbus Laboratories

January 31, 1977

INTRODUCTION

Battelle's Columbus Laboratories (BCL) is pleased to have this opportunity to respond to a request from Dr. George C. Kugler of ESB Incorporated to assist his company in another of its activities to advance the state of the art for battery-powered electric vehicles. Earlier BCL submitted a proposal entitled "Electric Vehicle Battery Development Studies" wherein it was proposed that computer-assisted analytical methodology be applied to the design of lead-acid battery grids. In the project proposed herein, after model definition, computer-assisted modeling techniques will be used to describe the important electrical characteristics of lead-acid batteries. Once the model is established it will be used to predict battery performance for a given load (driving) profile.

The proposed research project will be performed in the Corrosion and Electrochemical Technology Section of the Chemistry Department at BCL. Researchers familiar with battery development within this section will be supported in their activities by personnel experienced in modeling from the Statistical and Mathematical Modeling Section familiar with battery technology, having worked on interdisciplinary projects before. BCL is confident that these talents applied to the proposed project will enhance the potential for the eventual development of lead-acid batteries for electric vehicle applications.

TECHNICAL BACKGROUND

Attempts have been made in the past to model batteries for a variety of reasons. The ability to predict voltage and/or temperature behavior during charge discharge cycling has always been important^(1,2) along with the need to be able to calculate the practical capacity for stationary applications having relatively simple load profiles.⁽³⁾ In the 1960's, the need for battery models coupled with models for various energy/power sources and sinks for predicting spacecraft requirements became evident, and methods were developed⁽⁴⁾ for selecting qualified batteries with the requisite electrical performance characteristics. As a corollary, the models were often used to predict battery performance characteristics when subjected to various hypothetical and simulated load profiles.

More recently, emphasis has shifted from the space program to the development of pure electric, and electric hybrid vehicles with the result that battery requirements and performance must be projected for these applications. Models of varying degrees of sophistication and applicability have been described in the literature. Gelb, et al⁽⁵⁾, modeled both lead-acid and nickel-cadmium batteries in conjunction with

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- (1) M. G. Jayne, "The Behavior of Lead-Acid Batteries Under Pulsed Discharge Conditions", Paper No. 4 presented at the 10th Int. Power Sources Symp. Brighton, U.K. (September, 1976).
 - (2) C. E. Wright and V. M. Halsall, "Thermal/Voltage Response Characteristics of Automotive Nonantimonial Lead-Acid Batteries", Paper No. 750471 presented at the Auto. Eng. Congr. and Expo., Detroit, MI (February, 1975).
 - (3) E. A. Hoxie, "Some Discharge Characteristics of Lead-Acid Batteries", Paper No. 54-177 presented at the AIEE Winter General Meeting, New York, NY (January, 1954).
 - (4) P. Bauer, "Computer Simulation of Satellite Electric Power Systems", IEEE Trans. Aerospace and Electronics Systems, AES-5 (1969) 934.
 - (5) G. H. Gelb, et al, "Hybrid Power Trains", The Battery Man, 11 (1969) 4, No. 7.

an analog model of an engine, generator, and traction motor. These simulated vehicles were "driven" over the Los Angeles, LA-4 (urban) driving route. Regeneration of the vehicle's kinetic energy through the traction motor acting as a generator was included in this simulation because the electrical energy supplied to the battery affected its state of charge. The phenomenon of increased polarization losses at higher rates of charge and discharge was briefly alluded to because of the need to "dump" excess energy during charging above a preselected voltage level. Battery or fuel cell/conventional power source interactions on hybrid vehicles have also been described elsewhere.^(6,7) The emphasis in Reference (7) was on maintaining "battery balance", that is no net energy was drained from the battery during each driving cycle.

Open circuit voltage and specific gravity measurements were used as indicators of state of charge during some EPA tests in order to determine whether the battery was in a similar condition at the end of a cycle to that at the beginning of the cycle.

Kleckner has proposed a lead-acid battery model⁽⁸⁾ in order to predict the operating range of an electric vehicle under an urban driving cycle such as SAE-J227. The model is developed for a single constant current discharge, then the useful battery discharge time under a wide range of fluctuating current demands is approximated by stepwise changes in constant current discharges using the Gaussian error function. The model is said to keep track of battery terminal voltage, and also state of charge by taking into account charging and discharging efficiencies. Constant current discharges (capacity tests) were also used in Reference (9) to

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- (6) L. D. Gaddy, Jr., "Application of Fuel Cell Power Plants for Electrical Drive Systems", Proc. 20th Power Sources Conf., (May, 1966) p. 52.
 - (7) V. Wouk, "An Experimental ICE/Battery-Electric Hybrid With Low Emissions and Low Fuel Consumption Capability", Paper No. 760123 presented at the Auto. Eng. Congr. and Expo., Detroit, MI (February, 1976).
 - (8) K. R. Kleckner, "Modeling and Testing of Storage Batteries", Paper No. 730251 presented at the Int. Auto. Eng. Congr., Detroit, MI (January, 1973).

construct plots of ampere-hours and voltages versus discharge times. From these plots for each type of battery is as stated that all battery characteristics could be approximated provided time to voltage cut-off and voltage versus time for any discharge rate curves could also be generated. Agruss describes⁽⁹⁾ log-log plots for obtaining these data and the assumptions made by him. Range, voltage at any discharge level, number of acceleration pulses and power at any discharge level were said to be estimable within "tolerable" engineering limits using manufacturers test data, or a minimum of three constant current capacity tests. Others have used a similar approach, for example in Reference (10) a battery is modeled in terms of variations in specific power versus specific energy, charger efficiency as a function of rate of charge, and an efficiency value to account for internal battery losses on charge and discharge. Energy (watt-hour) additivity was used to estimate range, as opposed to charge (ampere-hour) additivity which has been more commonly used. Energy additivity was said⁽¹⁰⁾ to affect (increase) the underestimation of range by less than 5 percent. Reference (11) discusses why range is underestimated with the charge additivity method.

Thus, various authors have contributed to the solution of the problem of predicting battery performance under complex discharging regimes which will be encountered in electric vehicle duty schedules (see Figure 1). However, there are shortcomings with each approach, and a more widely applicable modeling technique would be desirable. As Kleckner says⁽⁸⁾, "in the final analysis, the designer must subject batteries in the laboratory to actual vehicle-type loads in order to obtain good vehicle range projections", because "no elementary model can incorporate all of the idiosyncracies of a real storage battery".

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- (9) B. Agruss, "Characterizing Batteries for Vehicular Applications", Abstract No. 64, Extended Abstracts, the Electrochem. Soc. Fall Meeting, Las Vegas, NV (October, 1976).
 - (10) D. C. Sheridan, J. J. Bush, and W. R. Kuziak, Jr., "A Study of the Energy Utilization of Gasoline and Battery-Electric Powered Special Purpose Vehicles", Paper No. 760119 presented at the Auto. Eng. Congr. and Expo., Detroit, MI (February, 1976).
 - (11) A. R. Cook, "The Data and Performances Required of the Lead-Acid Battery by the Electric Vehicle Designer", Proc. Sym. "Batteries for Traction and Propulsion", Columbus, OH (March, 1972).

FIGURE 1. EXAMPLE OF AN ELECTRIC VEHICLE DUTY SCHEDULE WITH MULTIPLE STOPS AND STARTS

PROPOSED RESEARCH PROJECT

Project Objective

The technical objective of the proposed project is to develop a computer modeling technique which will describe lead-acid battery performance under a complex discharge regime. The modeling technique should be able to predict the dynamic performance of a given battery, in terms of current versus voltage output and total energy delivered, under various repetitive discharge (load) profiles at different ambient temperatures. The load profiles may be specified as a function of time versus current or time versus power, and the profile may be repeated until a maximum current or minimum terminal voltage is reached. Thus, it is important that the model permits the calculation of battery discharge voltage at any selected time during loading.

Because a computer modeling program based upon strictly theoretical design parameters of a battery, and yielding dynamic performance data, would be complex and beyond the scope of the program foreseen by ESB Incorporated⁽¹²⁾, it is proposed that BCL's modeling activities use as inputs actual battery test data. The technical objective of the project, therefore, includes recommending the nature and number of battery tests to be performed in order to establish an adequate data base.

Method of Attacking the Problem

The easiest approach to structuring a battery model based upon practical engineering or experimental data would be to consider simple current versus time plots, and supply these as input to the model, with a modifying term to account for changes with number of cycles and/or calendar time. Equations do exist⁽⁸⁻¹³⁾ which adequately describe the constant current

(12) Private communication, G. C. Kugler to E. W. Brooman (October, 1976).

(13) C. M. Shepherd, "Design of Primary and Secondary Cells", J. Electrochem. Soc., 112 (1965) 657.

discharge curves of lead-acid batteries. However, such an approach does not permit a charge balance to be obtained for the battery unless ampere-hours are measured or computed by determining mathematically the area under each discharge curve. Also, the charging efficiency of the battery, and the electrical efficiency of the battery charger needs to be known. Charge balances calculated for batteries, with a knowledge of the appropriate discharging voltages to assure the voltage cut-off is not exceeded, have been used to predict electric vehicle range⁽⁹⁾. The disadvantage with this method is that ampere-hour capacity recovery (due to decrease in concentration and ohmic polarizations) during stand or idle periods of duty cycle can increase the actual driving range. Also, as the discharge rate (current) increases the available capacity (number of ampere-hours which can be withdrawn) decreases. Taking simple voltage versus capacity or state of charge data from constant current discharges is thus not sufficient for a realistic projection of driving range, and taking the average of the actual current and "effective" current will not be adequate. Here "effective" refers to the value of the discharge current modified to take into account the rate of discharge⁽¹¹⁾.

For electric vehicles, power requirements will be critical but energy requirements will be relatively less demanding. Constant power discharges probably will be more prevalent than constant current discharges, while recharges will likely end in the constant voltage mode. Energy transferred to and from the battery during use can be used to calculate an energy balance for the purposes of predicting driving range. However, for similar reasons given for the charge balance method, the range is usually underestimated, often to a larger extent than for the charge balance method⁽¹¹⁾. For example, Sheridan et al.⁽¹⁰⁾, used energy density (whr/lb) versus power density (W/lb) data and assumed that the energy available from the battery corresponded to that obtaining at the maximum power drain demanded by the motor. The number of cycles of operation was then calculated by dividing the total energy available by the energy withdrawn at this maximum power rate in a single duty cycle. The value which resulted was 5 percent more of an underestimation than if the charge balance method had been used. They pointed out that after the predicted number of cycles, 40 to 50 percent of the energy originally available was left in the battery. Operating at reduced power

demands to the same voltage and current cut-off limits would increase the range traveled.

It is apparent that the type of duty schedule and the number and frequency of on-off periods, affects the number of ampere-hours and watt-hours which are withdrawn, hence will affect the driving range. Any realistic battery model, therefore, must take into account the rate of charge (capacity) or energy withdrawal as a minimum requirement. In terms of the pulse-like nature of the battery discharges in some duty cycles, there is some experimental evidence⁽¹⁴⁾ to suggest that if the time integrated product of voltage and current (true power) is equal to the product of the average voltage and average current, then battery capacity and voltage associated with the average current of the pulses are identical to those produced by a "true dc battery current". Such an approximation would greatly simplify a battery model.

With the above considerations in mind, BCL proposes to use the following method for attacking the problem of devising an acceptable battery model.

After a specific duty (load) schedule has been imposed on a fully charged battery, it will be assumed that the charge remaining in the battery is specific to the duty schedule used. Therefore, even though many different schedules may be used in an experimental program to obtain corresponding charge (capacity) data, it is not possible to predict from the results obtained how much charge would remain if the battery were subjected to another schedule which had not previously been described. However, the types of duty schedules, as well as the measured residual charge, can be treated statistically to predict probable values for remaining charge as well as the probable distribution (error) of the values for arbitrary duty schedules. It should also be possible to determine a relationship, (whether analytical or graphical) between the most probable remaining charge and measurable aspects of the duty schedule such as rms deviations around the mean current or power.

(14) J. J. Gumbleton, D. L. Frank, et al., "Special Purpose Urban Cars", Paper No. 690461 presented at the SAE Mid-Year Meeting, Chicago, IL (May, 1969).

The conditions for partial discharge are the input variables in this system. Some conditions would be constant throughout a discharge experiment, such as temperature, number of times the battery had been discharged previously, and depth of discharge used. However, variations of load with time would be imposed during the discharge. It seems probable that such load variations would consist of related relatively short cycles such as the SAE advocated residential and metropolitan area driving cycles⁽¹⁵⁾ which have a cumulative time for each cycle of 150 seconds. Several such cycles should be considered that represent the anticipated variations in load and time at each load expected to be encountered in the practical use of electric vehicle batteries.

Output variables would be the voltage measured continuously during the discharge and the remaining charge (capacity) after imposing a specific discharge schedule. Remaining capacity may be measured experimentally by discharging under a steady (or fluctuating) load, depending on the duty cycle, and monitoring voltage continuously until the cut-off value is reached.

Discharge under the fluctuating load would be continued to estimated depths of discharge such as 25 percent, 50 percent, 75 percent, followed by constant load discharge to 100 percent. Alternatively, recharging at constant load may be desirable in some cases to bring the battery back to a common state of charge.

Such experimental data can be analyzed to determine the relationship between fluctuating and constant-load discharge in terms of capacity. Furthermore, data for several types of load cycles can be analyzed simultaneously to provide a relationship between load and capacity so that probability limits for the capacity of an arbitrary load cycle can be predicted. These data are treated by stochastic methods, particularly that of covariance

(15) SHE Recommended Practice SAE J227, "Electric Vehicle Test Procedure", Society of Automotive Engineer's Handbook, Part 2, (1976), p 27.1.

analysis between load and capacity. The other finite variables such as temperature, number of discharge cycles, etc., are of course, additional inputs to the analysis. If the load-time plot can be approximated with reasonable accuracy by a polynomial function, the technique of regression integral analysis can be applied.

Analytical Procedures Proposed for Modeling
Electric Vehicle Batteries

Thus, in order to analyze the effect on battery capacity of different load cycles, in different sequences, and under different conditions, BCL will employ the statistical method of analysis of covariance, or some modification thereof. This method can be used to analyze a dependent variable in terms of independent variables which may be either discrete or continuous in nature. The discrete independent variables may be qualitative variables, so that differing values of these variables indicate different categories of a qualitative factor. The result of applying analysis of covariance procedures is to obtain least squares fits to values of the dependent variable against the continuous independent variables, after these values have been partitioned into groups based on the different combinations of categories obtained from the qualitative factors.

Because of the dynamic nature of the relationship between load and capacity, it may prove fruitful to incorporate a statistical technique known as regression integral analysis into the analysis of covariance scheme. This procedure enables the prediction of a single value of a dependent variable (such as capacity) from a distribution of values over time of an independent variable (such as load). Further, the techniques can also be used to predict what will be the effect on the dependent variable of changes in the independent variable at a given time or over a given period of time. The regression integral analysis is accomplished by fitting the time distribution of the independent variable by k orthogonal polynomial. This procedure forms k variables whose values are the coefficients of the fitting polynomials of degree $0, 1, \dots, k-1$. These independent variables may then be incorporated as continuous variables in the analysis of covariance model.

The results of such analyses will enable BCL to predict capacity under different combinations of conditions with the associated statistical limits of error of such forecasts. It will also provide an estimate of a function which will relate capacity to the previous input parameters and distributions.

For the model to be developed, temperature will refer to ambient conditions (measured at the battery terminals) and the battery will be assumed to have negligible thermal inertia, with immediate response to ambient temperature changes.

For the purposes of this model, the battery thus will be considered to resemble a homogeneous "black box" with each cell or battery subcomponent in the battery having identical electrochemical behavior. All cells will be considered matched initially, and remain matched during simulated cycling. If it is desirable to consider the effect of battery size, in terms of terminal voltage and capacity, because of design changes, then it may be possible to normalize the battery data to permit interpolations and extrapolations to be made. For example, current densities (A/ft^2) can be used instead of currents (A) and the scaling factor then depends on the total electrode area available for reaction. Battery voltages can be reduced to individual cell voltages for the homogenous model suggested, and the scaling factor is simply the ratio of the number of cells in series in the batteries. When electrode areas are unknown, it can be assumed that capacity is proportional to electrode area, hence a normalized current can be represented by the quotient amperes/ampere-hours, provided electrodes of similar construction are used or assumed.

Having identified the input data requirements for the battery model, specific experimental data will be obtained from the literature or requested from ESB Incorporated. It is anticipated that ESB Incorporated will want to conduct themselves those experiments identified as being necessary on representative battery systems, and supply the information to BCL. Factorial or partial factorial experiments will probably be necessary to obtain the input data required. Similarly, ESB Incorporated will supply duty schedules to exercise the model once it has been completed.

The technical objective of the proposed project will be met when it can be demonstrated that the battery model constructed can be used to simulate, with an acceptable accuracy, actual batteries subjected to selected duty schedules. First, BCL will exercise the model under hypothetical loading conditions to assure that it functions in the desired manner. Second, the battery model will be subjected to a duty schedule selected by ESB Incorporated, and mutually agreed upon output parameters will be monitored and recorded. The output obtained will be compared to data experimentally obtained by ESB Incorporated on a lead-acid battery having similar characteristics to those simulated in the model, and subjected to the same duty schedule. Correspondence between the simulated and experimental data will mean the technical objective has been met.

Project Organization

The proposed program will be carried out in the Corrosion and Electrochemical Technology (C&ET) Section within the Chemistry Department of Battelle's Columbus Laboratories. Mr. Walter K. Boyd is manager of the former, while Dr. Albert H. Adelman is manager of the latter. Mr. Boyd will have overall administrative responsibility for the program, and access to BCL line management will be through Mr. Boyd and Dr. Adelman.

Dr. Eric W. Brooman, Group Leader for electrochemical energy conversion and storage in the C&ET Section will be responsible for the day to day management of the proposed program, and will have technical responsibility for its effective implementation. However, Dr. Brooman will be assisted by Luther E. Vaaler and Dr. James L. Gemma, as shown in Figure 2. Dr. Vaaler is a Senior Research Scientist in the C&ET Section who has successfully used computer modeling techniques to simulate electrochemical systems. Dr. Gemma is a member of the Statistical and Mathematical Modeling Section at BCL. Biographical sketches of these principal program personnel are given in a later section of this proposal. Other staff members at BCL with specific capabilities pertinent to the proposed program will be consulted as the need arises. The interdisciplinary approach described is recognized as being the most effective for solving the needs of a sponsor.

FIGURE 2. PROPOSED MANAGEMENT ORGANIZATION SHOWING PRINCIPAL PROJECT PERSONNEL

LIAISON, MEETINGS, AND REPORTS

Battelle recognizes the importance of effective communication between the sponsor and the program staff. To assure this, Dr. Brooman, as Program Manager, will be responsible for acting as liaison with Dr. George C. Kugler, or other authorized representatives of ESB Incorporated; arranging for any meetings; all reports, formal or informal, written or verbal; and negotiating any technical changes in the scope of the proposed research, in addition to his other duties mentioned earlier.

Representatives of ESB Incorporated will be most welcome to visit BCL to discuss progress on the program at mutually convenient times. A review meeting can be held towards the end of the proposed program at the ESB Technology Center, at which time the final report format and contents can be drafted. Alternatively, it may be more convenient for ESB personnel to visit BCL at this time for discussions with all the program personnel.

It is proposed that informal monthly letter reports be submitted by the tenth working day of the following month. These relatively short reports will include a description of progress made and plans for the next reporting period. A detailed final report will be submitted at the end of the proposed program. This final report will contain details of the modeling procedures, a description and interpretation of the results, and a discussion of the applicability of the battery model for electric vehicle usage.

ESTIMATED TIME AND COST

A twelve-month period of performance is recommended with an estimated appropriation of \$50,000, including the fixed fee of \$3,270, as established by Contract W-7405-Eng 92. A breakdown of the estimate cost is attached.

Battelle agrees to provide a high standard of professional service, and will exert its best efforts toward achievement of the technical objectives within the time and funding provided. However, the results of the proposed program will be experimental and/or advisory in nature. Therefore, in no event shall Battelle, or its employees and agents, have any obligation or liability for damages, including but not limited to consequential damages, arising from or in connection with the sponsor's use or inability to use the information resulting from this program.

This proposal will be considered an open offer on the part of Battelle until April 30, 1977. Unless we extend this period, acceptance after that date will be subject to mutual agreement.

BIOGRAPHICAL DATA FOR PRINCIPAL PROJECT PERSONNELWALTER R. BOYD

Manager, Corrosion and Electrochemical
Technology Section

Bachelor in Metallurgical Engineering (1945)
The Ohio State University

Since joining Battelle in 1945, Mr. Boyd has conducted and supervised research on the metallurgical aspects of corrosion. He has contributed significantly to the development of high-temperature alloys and special chemical-resistant alloy systems, two of which have been patented. Mr. Boyd has studied a variety of corrosion mechanisms, such as stress-corrosion cracking for austenitic stainless steels, aluminum alloys, titanium alloys, nickel- and copper-base alloys, and low-alloy steels. His broad experience in corrosion research also includes a variety of problems associated with high-temperature fluid systems (e.g., water, liquid metals, and fused salts).

Mr. Boyd has had extensive experience in corrosion problems associated with various types of water, including marine environments and the high-purity, high-temperature water used in fossil fuel and nuclear power plants. His experience has encompassed a wide variety of problems associated with both the leaching of uranium bearing ores and the recovery of nickel and copper values by chemical metallurgical techniques from low-grade ores.

He has been very active in the field of marine corrosion and has participated in the selection of a number of materials for deep ocean mining and offshore drilling facilities.

Mr. Boyd is a past National Director of the National Association of Corrosion Engineers. He serves on numerous committees for the NACE; for example, he is Chairman of the Publications Committee, the Definitions and Terminology Committee, and a member of the Finance Committee. He is also a member of the ASM.

Mr. Boyd is internationally recognized in the corrosion field and in recent years has been invited to lecture on corrosion in Korea, Mexico, Canada, Russia, Italy, England, as well as in the United States.

In May, 1973, he received the citation of recognition for outstanding contributions from the NACE. He is a registered engineer in Ohio and a NACE registered corrosion specialist.

ERIC W. BROOMAN

Group Leader, Corrosion and Electrochemical Technology Section

Diploma in Technology, Metallurgy (1963) Battersea College of Advanced Technology, England

Ph.D., Electrochemistry (1966) University of Cambridge, England

Dr. Brooman was educated in England, and worked for the United Kingdom Atomic Energy Authority before joining BCL in 1966. Since that time, he has competently worked in many areas of electrochemical engineering, but principally in the areas of battery technology, fuel cell technology, and electrochemical energy storage.

He has developed new alloys for primary cell electrodes, and helped design new electrode structures to accommodate the volume changes which occur when secondary cell electrodes are cycled. On a recent program for an industrial sponsor he designed a production facility for electric watch batteries and performed an analysis of production costs. He is an expert on the thermophysical properties of aerospace batteries, cells, and their components, and has firmly established the use of thermal resistance-capacitance network analogs for predicting cell and component conductivities. This work has led to the publication of his results, and some results of this work were presented at a National Meeting of the Electrochemical Society.

Dr. Brooman has helped to develop failure analysis techniques for aerospace cells, and he developed a classification of failure modes, determinants, and mechanisms for NASA and the U.S. Air Force. He has also helped to advance the state of the art of the accelerated life testing of cells and batteries. This work for NASA and the Air Force has led to a long-term testing program at NAD, Crane, based upon these findings and recommendations.

Recently for 1-1/2 years Dr. Brooman was on leave of absence as a Sponsored Research Fellow at the University of Salford, England, investigating new methods of developing low cost electrocatalysts. In addition to this research, Dr. Brooman served as a consultant to a State Government in Western Africa which wanted to set up an indigenous lead-acid battery industry. He is familiar with most aspects of the industry from factory design to selection of materials and equipment for monolid, multilid, and plastic-case SLI battery types. He has toured battery factories in the U.K. in connection with training the staff for this battery factory.

Current interests include the use of electrochemical devices, such as batteries and fuel cells, for bulk energy storage and vehicular use. On three recent programs for federal agencies he has been responsible for reviewing the state of the art of such devices for these applications which include peak-shaving, load levelling, and load following for electric utility companies.

ERIC W. BROOMAN (Continued)

Dr. Brooman has published numerous technical papers which include: "A Water Battery Concept for Electric Utility Energy Storage", Proc. Symp. on Energy Storage, The Electrochemical Society (October, 1975); and "Electric Vehicle Batteries: Opportunities for Materials Improvement", SAMPE Journal, 12 (1976) 4.

Dr. Brooman is a Member of the Institution of Metallurgists, the professional qualifying body in the U.K. He is also an Active Member of the Electrochemical Society, serving on the Personal Membership Committee from 1968-1971. He was Membership Chairman of the Columbus Local Section from 1968-1971, and Secretary/Treasurer for 1971-1972 and 1974-1975. He served as Vice-Chairman of this Section in 1975-1976, and is currently Chairman. For 1976-1977 he was elected Secretary of the Council of Local Sections.

LUTHER E. VAALER

Senior Researcher, Corrosion and Electrochemical
Technology Section

A.B., Chemistry, Mathematics, Luther College,
Decorah, Iowa

Ph.D., General and Physical Chemistry (1947)
University of Wisconsin

Dr. Vaaler has had extensive experience in applied electro-chemistry, particularly with large scale processes such as the production of chlorine-caustic and chlorate, electrometallurgy and metal finishing. His work includes the application of insoluble anodes of metal or graphite to such processes. He is also well versed in the application of carbon and graphite to the chemical process industries and nuclear power plants. He has managed diverse industrial and government R&D programs.

Some of Dr. Vaaler's specific accomplishments are as follows:

- In a series of laboratory investigations he established some of the basic parameters involved in electrolytic production of chlorine on a sound technological base. These parameters include anolyte pH and anode current density as they affect current efficiency and anode corrosion.
- He devised methods for field testing electrodes in large-scale electrolytic cells using applied statistics to design experiments and analyze results. He also wrote computer programs to calculate the effect of electrode specific resistance and design on the voltage required to operate the cells. Such calculations allowed optimization of the electrode design.
- He supervised the development of and the pilot-scale production of a special moderator graphite for the Molten Salt Reaction Experiment at Oak Ridge. Sophisticated processing and quality control techniques were required.
- He obtained and supervised a government project on development of an improved activated carbon to absorb chemical agents. He was instrumental in obtaining contracts with the Office of Saline Water to develop porous heat exchanger tubes that would inhibit scale formation, and supervised the work itself. He also supervised development work on arc carbons used in solar simulators to test out the Appollo Spacecraft.

LUTHER E. VAALER (Continued)

- He discovered a hydrometallurgical method of removing selenium from ores and refinery sludges and a method of electropolishing zinc die casting.
- He supervised a broad survey of the metal finishing industry to aid in establishing effluent limitations guidelines.
- He is presently involved in project development in several areas of applied electrochemistry including organic synthesis and metal deposition.

Dr. Vaaler has published 11 papers and has three patents issued. He is a member of the Electrochemical Society, American Chemical Society, and American Institute of Chemists.

RALPH E. THOMAS

Manager, Statistical and Mathematical Modeling Section

B.A., Mathematics (1948) Ohio Wesleyan University

M.A., Mathematics (1950) The Ohio State University

Ph.D., Operations Research (1966) Case Institute of
Technology

Since joining Battelle-Columbus in 1952, Dr. Thomas has made significant contributions in applications of statistics and mathematical models to problems in research.

As Section Manager, Dr. Thomas has been the administrative supervisor of approximately five professional statisticians since 1967. He is responsible for the technical quality of the statistical research performed by his Section.

The statistical and mathematical aspects of the following recent programs were under his technical supervision:

- A computer-based data-processing methodology was developed by Dr. Thomas to analyze simultaneous combinations of environmental variables. The combinations include climatic variables (temperature, relative humidity, wind speed, etc.), weather events (fog, rain, hail, etc.), and air pollution variables SO_2 , O_3 , etc.). The method generates answers to the following kinds of questions: How often does a particular environmental condition occur in a specified time period? How long does it last? What condition is likely to occur next? The methodology was applied to data for the 1965-1974 time period at nine climatically diverse geographic locations.
- An innovative modeling approach to the analysis of accelerated test data by Dr. Thomas was awarded a citation by the National Aeronautics and Space Administration (NASA). The approach has been used by both NASA and the United States Air Force as a basis for the design and analysis of test programs for spacecraft batteries.
- A computer program was written by Dr. Thomas for the United States Air Force to obtain estimates of the reliability of electromechanical systems. As input the program uses reliability information on the subsystems together with structural information obtained from engineering diagrams of the system. This program forms the basis of the Tabular System Reliability Analysis (TASRA) which is operational and being further extended by the Air Force.

RALPH E. THOMAS (Continued)

- A statistical assessment was made of the effectiveness of a career screening method for Bio-Digital Science, Inc. The assessment was made by modifying the Automatic Interaction Detector (AID) computer program; applying the modified program to the data; and then comparing the results obtained with those obtained using conventional linear discriminant analysis.
- In a program for the Office of Economic Opportunity, Dr. Thomas applied statistical concepts to obtain valid assessments of the impact of compensatory education. The analyses were based primarily on achievement scores and supplementary questionnaire data. Technical problems associated with non-randomization, instrument unreliability, etc., were given critical attention in order to attain evaluations that were fully objective.

Experience in addition to that at Battelle includes mathematical research in military operations analysis from 1955 to 1957 at North American Aviation, Inc., and lecturing in mathematical statistics at The Ohio State University.

In addition to 4 years of teaching undergraduate courses before joining Battelle-Columbus, Dr. Thomas has taught the following courses:

Design of Experiments (noncredit course given at North American Aviation, Inc., 1956-1957). Topics included randomized blocks, Latin squares, factorial designs, and response-surface analysis.

Mathematical Statistics (graduate-level course, Mathematics Department, The Ohio State University, 1958-1959). Topics included estimation theory, hypothesis testing, multivariate normal theory, and nonparametric statistics.

Engineering Statistics (noncredit course given at Battelle's Columbus Laboratories, 1961-1962). Topics included analysis of variance, regression analysis, and statistical inference.

Interpretation of Biological Data (graduate-level course, Zoology Department, The Ohio State University, 1962-1963). Topics included t-tests, F-tests, analysis of variance, and nonparametric tests of hypotheses.

Scientific Method (graduate-level course, Case Institute of Technology, 1964-1965). Topics included philosophy of science, scientific inference, development of models, and validity testing.

RALPH E. THOMAS (Continued)

Calculus Refresher (noncredit course, Battelle's Columbus Laboratories, 1967-1978). Topics included differential and integral calculus with an introduction of FORTRAN programming.

Dr. Thomas is a member of Pi Mu Epsilon, Phi Beta Kappa, Sigma Xi, Mathematical Association of America, New York Academy of Sciences, Member of Board of Elections of The Ohio State Chapter of Sigma Xi (1968-1971), and President of the Operations Research Club of Central Ohio (1970-1971).

JAMES L. GEMMA

Research Scientist, Statistical and Mathematical
Modeling Section

B.S., Mathematics, magna cum laude (1962) University
of Detroit

M.S., Mathematics (1965), The Ohio State University

Ph.D., Mathematics (1970), The Ohio State University

Dr. Gemma is expert in applications of mathematics, probability, and statistics to problems in research. His involvement in statistical data analysis and model development often involves the use of computer methods such as scientific programming and computer graphics, and the utilization of mathematical/statistical software packages. Areas of research experience include regression analysis theory and methods, analysis of variance and covariance, multivariate statistical theory and methods, statistical inference forecasting, and design. In addition, he is experienced at the highest levels in the theory of mathematics, probability, and statistics. He has made wide application of theory and methods in diverse research areas such as environmental studies, climatology, energy, human interactions, and information sciences.

Some specific examples of Dr. Gemma's research are:

- He applied the technique of regression integrals, developed by R. A. Fisher for analysis of weather-yield problems to an analysis of maximum ozone concentrations in terms of distributions of various meteorological and pollutant predictors.
- He helped prepare a management information system to aid in evaluating fuel allocation procedures and in preparing new procedures.
- He applied the Box-Jenkins method of time-series analysis to develop a model for haze formation in terms of air quality and meteorological data.
- He is using multivariate statistical techniques including multidimensional scaling in order to analyze interactions between nurse and patient as transcribed from videotape.

From fall, 1971, through summer, 1973, Dr. Gemma was Assistant Professor of Mathematics at Wichita State University. Among the courses he taught were probability, statistics, and graduate courses in real

JAMES L. GEMMA (Continued)

analysis. He served on the Graduate Committees of five master's degree candidates, and was a member of the Committee for the Development of an Urban Studies Program.

From 1969 to 1972, Dr. Gemma was a Research Mathematician in Battelle's Information Systems Section. He did research in probabilistic coding theory and in automatic document classification.

Prior in joining Battelle in 1969, Dr. Gemma was a member of the technical staff in the Traffic Studies Center at the Bell Telephone Laboratories, Incorporated, from 1965 to 1966. His work consisted of analyzing existing and proposed communications systems by probabilistic models and computer simulation. From 1966 until joining Battelle, Dr. Gemma was a Graduate Teaching Assistant, and later, Graduate Teaching Associate, in the Mathematics Department of The Ohio State University while working towards his Ph.D. in Mathematics.

In the summers of 1962 and 1963, between academic years in graduate school, Dr. Gemma was a summer employee in the Operations Research and Applied Mathematics Group at the Youngstown Sheet and Tube Company. He worked with engineers on general problems in operations research, and developed a computer program for forecasting by exponential smoothing.

Journal Publications

Gemma, J., and Ahlswede, R., "Bounds on Algebraic Code Capacities for Noisy Channels, I", Information and Control, Vol. 19, No. 2, pp 124-245, September, 1971.

Gemma, J., and Ahlswede, R., "Bounds on Algebraic Code Capacities for Noisy Channels, II", Information and Control, Vol. 19, No. 2, pp 146-148, September, 1971.

Gemma, J., and Spicer, C. et al., "The Fate of Nitrogen Oxides in Urban Atmospheres", Removal of Trace Contaminants from the Air, ACS Symposium Series 17, Victor R. Dietz, Ed., pp 159-173, Washington, D.C., 1975.

Degree Publications

Gemma, J. L., "Coding Theorems for Systems of Channels:", Ph.D. Thesis, The Ohio State University, 1970.

Gemma, J. L., "On the Matingale Convergence Theorem", Master's Thesis, The Ohio State University, 1965.

CAPABILITIES AND EXPERIENCE IN BATTERY TECHNOLOGY

Introduction

BCL has extensive experience in (1) secondary batteries both of the aerospace and non-aerospace types, and (2) primary batteries for many applications. Their broad experience in electrochemical energy conversion in general has also encompassed studies of the feasibility of using battery systems for electric propulsion, off-peak energy storage, and life support systems. These areas of competence are briefly outlined in the following sections.

Battery Research

For more than 20 years, electrochemists in the Corrosion and Electrochemical Technology Section have performed research on many kinds of batteries. This work was done for industry or for the United States Government. Most of the past work for industry is proprietary but includes work on the following battery systems or components:

- Separators and lead alloy grids for lead-acid batteries
- Circulating electrolyte for lead-acid batteries
- A lead-phosphoric acid battery
- Compounds for water-activated lead-acid batteries
- A rectifying grid for lead-acid batteries
- Corrugated lead-foil electrode
- Titanium and titanium alloys for primary cells
- A rechargeable iron battery
- A design study for a rechargeable zinc-air battery
- Alloys for magnesium-seawater batteries
- Electrode structures for rechargeable nickel-zinc batteries
- Fast activation of magnesium-silver chloride batteries
- Determination of failure mechanisms for commercial silver-zinc batteries

- A lead dioxide-copper secondary battery
- Zinc and cadmium alloys for commercial primary batteries
- Fuel-cell electrodes and mechanism studies for fuel-cell reactions using hydrogen or hydrocarbon as fuels and oxygen or air as oxidants
- Electroformed zinc cups for primary cells
- Electrophoretic formation of manganese dioxide bobbins
- Improved zinc-chlorine batteries.

A major portion of the capabilities in secondary battery development over the past years relates to failure mechanisms and accelerated testing techniques, lithium/organic battery development, and development of improved electrodes based on nickel plaques. Broad experience in secondary batteries covers lead-acid, zinc-oxygen, regenerative hydrogen-oxygen batteries, and advanced systems. Major experience relates to secondary batteries for space applications (nickel-cadmium, silver-zinc). A 3-year program for the Air Force was completed on "Failure Mechanisms and Accelerated Life Tests of Nickel-Cadmium Batteries". Improved nickel cadmium cells have been developed from concept through fabrication and assembly. Work has entailed the design and installation of plaque-fabrication machinery, plate impregnation, and formation facilities for producing Ni, Cd, Ag, and Zn electrodes in a variety of sizes. Cells assembled from components have exhibited longer cycle life than cells fabricated from commercially available plates (documented in Air Force Report AFAPL-TR-70-44). Life-cycle tests on commercial cells, recording, and evaluation of data have been accomplished to characterize batteries and develop accelerated testing techniques.

A research project for the Air Force resulted in the identification of new compounds as positive electrode materials for use with lithium in organic electrolyte batteries. The objective of this earlier project was to develop rechargeable positive electrodes for use in secondary lithium batteries at high rates.

The following is a list of several important battery project conducted for the U.S. Government:

- "Failure Mechanisms in Sealed Batteries", Wright-Patterson Air Force Base Contract No. AF 33(615)-3701; Funding \$602,180 for 3 years.
- "Failure Mechanisms and Accelerated Life Tests of Nickel-Cadmium Batteries", Wright-Patterson Air Force Base Contract No. F-33615-69-C-1537; Funding \$630,072 for 3 years.
- "Study of Space Battery Accelerated Testing Techniques", NASA Goodard Space Flight Center Contract No. NAS 5-11594; Funding \$99,000 for 1 year.
- "Development of Improved Plaque Material for Aerospace Nickel-Cadmium Cells", NASA Goddard Space Flight Center Contract No. NAS 5-2110; Funding \$49,840 for 1 year.
- "Development of Large-Internal-Surface-Area Nickel Metal Plaques", NASA Lewis Research Center Contract No. NAS 3-6003; Funding \$99,730 for 1 year.
- "Lithium Battery Research", Air Force Aero Propulsion Laboratory Contract No. P33615-68-C-1282; Funding \$284,667 for 3 years.
- "Investigation of Porous Lithium Battery Electrodes", Air Force Aero Propulsion Laboratory Contract No. AF 33(615)-2619; Funding \$105,000 for 1 year.

The programs for NASA and the Air Force on accelerated life tests involved as part of the effort the modelling of secondary batteries. Analogies with physical systems were drawn in some instances in order that cell performance could be described mathematically. Details may be found in the NASA Special Publication No. 323 (1973) entitled "Accelerated Testing of Space Batteries", and authored by J. McCallum, R. E. Thomas, and J. H. Waite.

SELECTED LIST OF PUBLICATIONS AND PATENTS
RELATING TO BATTERY AND FUEL CELL TECHNOLOGY

- (1) Tripler, A. B., Jr., and McGraw, L. D., "An Investigation of Some New Cathode Depolarizer Materials", J. Electrochem. Soc. 105 (1958) 179.
- (2) McGraw, L. D., "Advances in Battery Power Systems", Battelle Technical Review, 7 (1958) 12.
- (3) Schaer, G. R., U.S. Patent No. 2,870,068, "Electroformed Screens" (January 20, 1959).
- (4) McCallum, J., Clifford, J. E., and Semones, D. E., U.S. Patent No. 2,929,860, "Primary Cell" (March 22, 1960).
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Appendix 3

Quality Assurance Manual

ESB INCORPORATED
TECHNOLOGY CENTER
YARDLEY, PA.

QUALITY ASSURANCE PROCEDURES
MANUAL

October 1, 1976
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QUALITY ASSURANCE PROCEDURES

INTRODUCTION

- I. SCOPE This document delineates the Quality Assurance procedures written for ANL Contract No. 31-109-38-3621.
- II. PURPOSE The procedures in this document are to assure the reproducibility of the research and development effort by measuring, accounting and auditing the significant characteristics in materials, processes and tests used.
- III. AREAS OF ACTIVITY TO BE CONTROLLED
- a Written Procedures and Instructions Written procedures and instructions shall be prepared to cover all phases of inspection, test, and control of all items used in the assembly and fabrication of batteries. The procedures shall be kept current by examination of new and revised drawings, customer and/or Government specifications with revisions or additions made accordingly.
 - b Inspection and Test Instructions shall be prepared to cover in detail all functions of inspection and test. Gage control shall be accomplished in order to assure the validity of tests and inspections. A system of records shall be established which shall be adequate to be used as references if investigations are required.
 - c Corrective Action Corrective action shall be initiated on those items where recurring discrepancies adversely affect ESB quality, costs, or customer service. The corrective action is not necessarily performed by the Quality Assurance group, but it is the responsibility of Q.A. to implement the required action.
 - d Defect Prevention Effective inspection and control procedures shall be performed to prevent the use of defective material. Process inspection shall be performed to minimize rejection.
 - e Purchased Materials Procedures shall be provided for vendor evaluation, certification of purchased materials, and acceptance of incoming material. Receiving inspection instructions shall be established. Provision shall be made for spot checking of incoming certified materials to verify vendor's certification.

f Design Review - Provision will be made for design reviews to be performed at designated check points during the research and development program.

IV. QA in other ESB Locations

Work performed on this contract in ESB locations other than the Technology Center shall conform to the requirements specified in this manual.

Section 1

GENERAL

1.1 ORGANIZATION

The organization for the development of Lead-Acid Batteries for Electric Vehicle Propulsion will be as shown in the accompanying chart.

1.2 AUTHORITY

- 1.2.1 The Quality Assurance Engineer has the authority to affect the quality of the product by injecting into the system the controls necessary to achieve the objectives of the program.
- 1.2.2 The Quality Assurance Engineer has the authority to halt any process or movement of parts when quality analysis indicates that the process controls, documentation, operator skills, equipment or inspection standards are not adequate for the purpose intended.
- 1.2.3 The Quality Assurance Engineer or his designate shall serve as Chairman of the Material Review Board and shall have the authority to convene the board at regularly scheduled intervals or at his discretion in critical situations.

1.3 RESPONSIBILITY - The Quality Assurance Engineer shall provide for the performance of the following tasks:

- (1) Review all purchase orders to vendors supplying components and raw materials in order to assure proper quality information to vendors.
- (2) Inspect incoming components and raw materials to the extent necessary to determine conformance to specification requirements.
- (3) Maintain records of inspection and lot control designation on components and raw materials.
- (4) Initiate Corrective Action reports to vendors when discrepant items or lots adversely affect delivery schedules or quality.
- (5) Investigate vendor capability to produce critical or special process items to the desired quality levels and report on findings.
- (6) Review all discrepant materials and components and provide for disposition thereof in cooperation with Engineering, Manufacturing, and Government Inspection personnel.

- (7) Maintain records and dispose of all scrap generated during the manufacturing process.
- (8) Maintain complete and current files of all engineering drawings and revisions or additions thereto.
- (9) Prepare written procedures on the inspection of materials and components.
- (10) Inspect and calibrate gages and maintain records of such inspections, calibrations and corrective action.
- (11) Maintain a set of primary measurement standards that are traceable to the National Bureau of Standards and maintain orderly and current records of such traceability.
- (12) Maintain all gages to assure dependability and availability.
- (13) Inspect all assemblies, subassemblies, and components to the extent necessary to assure conformance to applicable specifications.
- (14) Maintain records of all inspections and lot control designations on assemblies and subassemblies.
- (15) Initiate corrective action whenever recurring discrepancies are experienced or anticipated.
- (16) Monitor processes and provide for statistical controls where such controls can provide assurance of quality levels.
- (17) Inspect packaging and preservation of all outgoing materials and determine conformance to applicable packing specifications.

JAC:K
2/21/77

SECTION 2

PURCHASED MATERIAL CONTROL

2.1 SCOPE - This section specifies the procedures and controls used in the procurement of materials.

2.2 DEFINITIONS

2.2.1 Approved Vendor - Any supplier of material who has demonstrated capability of meeting specification requirements either through satisfactory quality history or through a quality survey.

2.2.2 Test Record - A document supplied by the vendor indicating the actual test performed on the procured materials and the results of the tests.

2.2.3 Critical Item - Any raw material, assembly, part or component whose physical or chemical characteristics have a significant effect on the basic design objectives of the end item.

2.2.4 Procurement Document - Any purchase order, subcontract or amendments and additions thereto, including all referenced product and quality specifications.

2.3 SOURCE CONTROL

2.3.1 Vendor Classification List - The Vendor Classification List shall contain the following information:

2.3.1.1 Vendor's Name - This is the full corporate name and division, as applicable. The vendor's factory location shall be identified if only a portion of a multi-plant operation is classified.

2.3.1.2 Products - The products supplied by the vendor to ESB shall be listed.

2.3.1.3 Processes - Special Processes by vendor shall be listed.

2.3.1.4 Classification - The vendor may be classified into one of three categories - Approved, Conditional Approved and Not Approved.

2.3.1.5 Basis for Classification - The vendor may be classified on the basis of a formal survey, or historical quality data.

2.3.2 Vendor Quality Capability Survey

2.3.2.1 The Quality Assurance Department shall survey vendors as required to assure that their capabilities and facilities are adequate to produce the products and services conforming

to ESB or contractor specifications. A survey is required when one or more of the following conditions exist:

- (1) The purchased items have a critical characteristic which cannot be detected and adequately screened at incoming inspection.
- (2) No quality history exists for the vendor and failure to meet quality requirements will adversely affect delivery schedules and program planing.
- (3) Tests for compliance to specification requirements are destructive and prohibitive in cost or time.
- (4) Reliability or life are dependent upon internal quality characteristics which can be observed only at the time of manufacture.
- (5) Vendor quality history is poor and it is desired to aid the vendor in improving his record.
- (6) Change of vendor location or ownership indicates possible failure to meet specification requirements.

2.3.2.3 Survey Performance - The vendor shall be surveyed to determine the adequacy of his staff, equipment and quality procedures to produce acceptable products or services. While conducting the survey at the vendor's facility, discussions with the vendor's personnel shall be limited to information pertaining to their quality control system. The report shall reflect only existing conditions, not plans for future improvement. The final evaluation shall be completed after the surveyor leaves the vendor's facility. Included in this Q.A. survey shall be:

- (1) A description of the vendor's organization and facilities.
- (2) A description of their quality control and inspection system as applicable to the specific products or services being supplied.
- (3) A listing of the companies for which the vendor has provided products or services.

2.3.3 Vendor Rating

2.3.3.1 Survey Rating - As a result of the survey a vendor may be rated as follows:

- (1) Approved - The vendor's quality control system and facilities are adequate to produce products and services conforming to contract requirements.
- (2) Conditional Approval - Conditions exist which may cause poor quality performance but the nature of the condition

is such that corrective action can be taken within a reasonable amount of time consistent with manufacturing and delivery schedules.

- (3) Not approved - The vendor's quality control system or facilities have deficiencies which will not adequately control the product or services and corrective action is improbable within the time limits imposed by schedules.

2.3.3.2 Vendor Quality History - A record shall be maintained by the Q.A. Department on all vendors supplying items for use in battery fabrication.

2.4 PROCUREMENT DOCUMENT CONTROL

2.4.1 Purchase Order Requirements - Each order issued for raw materials, services, parts, components or other items used in battery fabrication or research shall contain the following Quality information, as applicable:

2.4.1.1 Item Configuration Control Documents

- (1) Engineering Drawing
- (2) Material Specification or applicable portions thereof.
- (3) Special instructions specified on Purchase Requisition.

2.4.1.2 Preservation and Packaging Requirements of Other Than Commercial

- (1) Military Specifications - Type and Class.
- (2) Prime Contractor Specifications.
- (3) ESB Packaging Specifications as referenced on Engineering Drawing or in Material Specification.

2.4.1.3 Control of Lot-Sensitive or Age-Sensitive Items

- (1) Maximum allowable age at time of shipment.
- (2) Identification of calendar life or cycle life.
- (3) Lot Numbering Requirements.
- (4) Lot Homogeneity Requirements.

2.4.1.4 Test, Inspection or Process Control Data Requirements

- (1) Chemical analysis and/or physical test report.
- (2) Special process certification.
- (3) Inspection and/or function test data.
- (4) Lot homogeneity certification.

2.4.2 Distribution of Purchase Orders - Each Purchase Order shall be distributed as follows:

Copy Number	1	-	To Vendor for his use and record.
"	"	2	- Purchasing Department Follow-Up.
"	"	3	- Accounting Department.
"	"	4	- Receiving Department.
"	"	5	- Originator
"	"	6	- Quality Assurance

2.4.3 Review of Purchase Orders

2.4.3.1 Each order issued for materials in battery fabrication or research shall be reviewed by personnel of the Q.A. Department to verify that latest drawing, specification, or quality standard is noted. The Q.A.E. shall initial acceptable Purchase Orders on the reverse side.

2.5 VENDOR INFORMATION PROCEDURE

Vendors shall be informed of potential or experienced problems as a result of vendor plant surveys, recurring discrepancies, or MRB action. The Q.A.E. shall see that the necessary information data is submitted to the vendor.

The vendor, however, shall be required to furnish a description of the action taken to correct the discrepancy and avoid any recurrence.

SECTION 3

INSPECTION OPERATION

3.1 SCOPE - This section specifies the procedures used to assure quality conformance through examination and control of product characteristics.

3.2 DOCUMENTATION - All inspection records will be kept in the inspector's notebook.

3.3 SEGREGATION OF MATERIAL BY INSPECTION STATUS

3.3.1 All incoming materials shall be physically segregated into:

- (1) Material awaiting inspection - these items will be segregated and identified.
- (2) Material inspected and accepted - this material shall be entered into inventory (Sec. 3.7.3) and may be used directly or put in storage to await usage by the cognizant project leader.
- (3) Material rejected and designated for rework or completion - these items will be identified and processed as per Q.A.P. section 4.
- (4) Material rejected and designated as "Scrap".
Scrap items shall be stored in containers that are prominently marked "Scrap" and dispositioned as per Q.A.P. section 4.

3.4 INCOMING MATERIAL INSPECTION

3.4.1 All items received by the requisitioner shall be recorded in his notebook. He then shall notify the Q.A. Department for inspection, as applicable. The inspector shall obtain the Quality Assurance copy of Purchase Order, all referenced drawings and specifications, and a Q.A. copy of the vendor's packing slip.

3.4.2 Each item shall be examined for the following as applicable:

3.4.2.1 Documentation

- (1) Vendor certification conforms to Purchase Order requirements as described in Section 2.
- (2) Data contained in vendor certification conforms to the tolerance limits of the applicable Material Specifications.
- (3) Vendor is in "Approved" or "Conditional Approval" category.

3.4.2.2. Material Conformance

- (1) Inspect all attributes as required. Where specific sampling plans are not referenced, all non-destructive test characteristics shall be inspected when necessary.
- (2) Verify that the specified age limits have been applied to the items or item containers and that the items are within the specification age limits.

3.4.3 When the lot or item has been inspected as specified, the inspector shall initial the reverse side of Quality Assurance Copy of P.O. and/or packing slip.

3.5 IN-PROCESS INSPECTION AND CONTROL

3.5.1 Product Inspection

Items inspected shall be recorded in the Inspector's Notebook. Nature of inspection and item identification shall be clearly indicated in this record. Non-conforming items shall be identified, segregated and processed as specified in Q.A.P. section 4.

3.5.2 Process Inspection

Where applicable depending on nature of process and volume of production, Shewhart Process Control Charts shall be established and maintained to determine process capability and to detect process changes.

3.6 SPECIAL PROCESS CONTROL

3.6.1 Special control procedures shall be required when one or more of the following conditions exist:

- (1) The process is of a nature that uniform high quality cannot be assured by inspection of the processed items alone.
- (2) Tests for conformance are destructive and/or extremely expensive.
- (3) The process is an acceptance function itself and requires a high level of personal skill and/or equipment control in order to obtain reliable and repeatable results.

3.6.2 Elements of Process Control

3.6.2.1 Process Specifications - For each special process, the cognizant laboratory department shall prepare a specification containing the following information:

- (1) Description of process
- (2) Method of control
 - (a) Materials
 - (b) Input energies
 - (c) Methods and/or operating sequence
 - (d) Environment
- (3) Equipment requirements
 - (a) Capacity
 - (b) Accuracy
 - (c) Stability
- (4) Acceptance Criteria
 - (a) Process parameter control limits.
 - (b) Finished product test and/or inspection requirements

3.6.2.2 Process Control - see #3.5.2

3.7 CONTROL OF MATERIAL IN STOCK

3.7.1 Method of Storage

Accepted materials shall be stored in a manner designed to prevent deterioration in stock due to corrosion, aging, fungus damage or handling damage.

3.7.2 Inspection

Periodic inspections for corrosion, damage due to storage, and obsolescence shall be performed.

3.7.3 Inventory & Transfers

A current inventory shall be maintained of material in storage. This will show data and quantity of each accepted incoming material and date, quantity, and recipient of material transferred out of storage.

SECTION 4

NON-CONFORMING MATERIAL CONTROL

4.1 SCOPE This section specifies the procedures to be followed in the designation, review, judgement, disposition and correction of discrepancies in any purchased item, detail part, raw material, assembly or final product.

4.2 DEFINITIONS

4.2.1 Deviation A specific authorization, granted by the Technical Program Manager or Q.A.E. before the fact, to depart from a particular requirement of specifications or related documents.

4.2.2 Discrepancy Nonconformance to a particular specification requirement. Degree of nonconformance or importance of the nonconforming characteristic are not factors in the designation of a characteristic as discrepant.

4.2.3 Rework An action taken to restore a discrepant article to the specified requirements. Rework shall include only those operations normal to the construction of the article.

4.2.4 Repair An action taken to convert a discrepant item to the specified functional requirements by means of an operation not normal to the construction of the article.

4.2.5 Waiver Granted use or acceptance of an article which does not meet specified requirements.

4.3 MATERIAL REVIEW BOARD

4.3.1 Authority - The Material Review Board has the authority to decide on the disposition of any discrepant item as defined above to prescribe the action necessary to correct, if possible, the item and the basic condition which produced the discrepancy. In addition, the MRB has the authority to require corrective action on any process which in their judgement produces an excessive number or frequency of discrepant items.

4.3.2 Qualifications - Members of the MRB are appointed by the Technical Program Manager on the basis of technical knowledge of ESB products and contract requirements, and decision-making ability.

4.3.3 Responsibilities - Responsibilities of the MRB are as follows:

- (1) Judge the severity and effect of the discrepancy on the basic requirements of the product and prescribe action to eliminate any adverse effects.

- (2) Provide for quality verification on items that are processed as a result of MRB decision.
- (3) Provide for specific corrective action to eliminate or minimize the effect of the basic cause of the discrepancy.
- (4) Followup to assure effectiveness of the corrective action.
- (5) Maintain records in a manner that will allow detection of recurring discrepancies and permit periodic summaries to be prepared.
- (6) Utilize the advice of specialists in cases where decisions require talents and knowledge beyond the scope of the MRB.
- (7) Notify the Quality Assurance Engineer of any conditions that prevent or inhibit the performance of the MRB.

4.3.4 Composition The MRB shall be composed of:

- (1) A representative of the Quality Assurance Department.
- (2) A representative of the Laboratory Project Group
- (3) The Technical Program Manager
- (4) A representative of the Purchasing Department,
- (5) and a representative of ANL when deemed necessary by the Technical Program Manager.

Additional personnel may be consulted when specialized knowledge or abilities are required to arrive at a sound decision. Such personnel may serve only in a consulting capacity and shall have no vote in the final decision. Each of the MRB members above may appoint an alternate to serve on the MRB with full authority to carry out the requirements of this document. The alternates shall not be permitted to delegate MRB authority.

4.4 REVIEW OF DISCREPANT ITEMS

4.4.1 Preliminary Material Review

4.4.1.1 Rework - Items that can be reworked per the definition of paragraph 4.2.3 do not require formal Material Review Board (MRB) action. The Laboratory Head, cognizant Project Leader, or Quality Assurance Engineer has the authority to approve rework, route the items for the required rework and submit the reworked items for inspection. A record of the discrepancy and subsequent approval after rework and inspection shall be entered in the Inspector's Notebook.

4.4.1.2 Scrap - Parts such as plates, spearators, cell cases, nuts and bolts may be scrapped without recourse to MRB action provided:

- (1) The quantity scrapped is within the normal day-to-day scrap rate for processes where the process capability is known to produce a certain percentage of scrap. In no case may an entire lot be scrapped without MRB action.
- (2) The parts are remnants of destructive test specimens and have no useful function.
- (3) Records of the scrapped quantities and reasons are recorded in the laboratory notebook.

4.4.1.3 Incomplete Part - Items that are discrepant because of missing operations may be routed to the function responsible for completion of the item provided that completion of the item conforms to the proper sequence of operations. Where an altered sequence of operations has a significant effect on the quality or reliability of the item, or on the ability to inspect the item, MRB action is required.

4.4.2 Formal Material Review

4.4.2.1 Rework - Where there is doubt as to the applicability of the "Rework" designation, the Laboratory Head or Quality Assurance Engineer may elect to submit the discrepant items to MRB for disposition.

4.4.2.2 Repair - Items repairable per the definition of paragraph 4.2.4 shall be submitted to MRB for approval of the method of repair and the method of quality verification.

4.4.2.3 Incomplete Part - Items that must be completed by methods or sequences of operations not normal to the item as originally planned shall be submitted to MRB for approval of the fabricating sequence and the method of quality verification.

4.4.2.4 Scrap - Major items such as cells, molds, process equipment and other similar items shall be submitted to MRB for disposition. This procedure is applicable regardless of the condition of the item except where personnel safety will be affected by time delay in convening the MRB. The quality assurance engineer shall be responsible for submitting scrap items to MRB.

4.5 MATERIAL REVIEW

4.5.1 Material Review Records - The following Material Review information shall be recorded in all MBR members' notebooks.

- (1) Part Number.
- (2) Serial Number, if applicable.

- (3) Lot Number, if applicable.
- (4) Part Name as shown on drawing or specification.
- (5) Type of item discrepant - vendor item, in-process, etc.
- (6) Purchase Order Number for vendor items.
- (7) Source of items - Vendor name or ESB department where discrepancy was discovered. This is not necessarily the department that caused the discrepancy.
- (8) Number Rejected - This is the total quantity affected by the material review.
- (9) Quantity Inspected - This is the total number inspected in the lot or random sample.
- (10) Quantity Discrepant - This is the total number of defective items found in the sample or lot.
- (11) Specification - The specified drawing tolerance, attribute, or other characteristic that is discrepant.
- (12) Observed Characteristic - The actual values or range of values of the discrepant characteristic.
- (13) Inspected By - include names of all inspectors.
- (14) Date Inspected.
- (15) Comments - The inspector (if other than MRB member) may add any additional information that may be helpful to the MRB. Or, in cases of multiple serial numbers or lot numbers, the additional lot or serial numbers may be entered here.

4.5.2 MRB Data Responsibility - After examining the items and above data the Material Review Board members shall record the following information:

- (16) MRB Action - Description of action on each discrepancy, including any special instructions to effect repair, rework, completion and inspection.
- (17) Laboratory Head signature indicating approval of MRB action.
- (18) Quality Assurance signature indicating approval of MRB action.
- (19) Date of MRB meeting.

4.5.3 MRB Quality Assurance Data Responsibility - The Quality Assurance Member of MRB shall be responsible for recording the following information in his notebook.

- (20) Responsibility for discrepancy - The function which was the originator of the condition which caused the discrepancy (Vendor, Customer or specific ESB Department.)
- (21) Verification of disposition - Parts that have been reworked, repaired or completed, inspected and given final acceptance shall have the acceptance indicated.
- (22) Corrective Action - Description of the action taken to eliminate or minimize the effect of basic cause of discrepancy.

4.5.4 Scrap Verification - Items that are designated scrap shall have the actual scrapping operation witnessed by the Q.A. inspector.

4.6 MRB ACTION AND DECISIONS

4.6.1 Data Examination - The Material Review Board shall examine the discrepant material and all supporting data which shall include, as a minimum, the following:

- (1) All pertinent specifications and supporting documents.
- (2) Previous historical data on similar rejections, MRB action and corrective action.
- (3) Quality data which can indicate a recurrence pattern of the discrepant condition.

4.6.2 MRB Disposition - After careful review of the items and supporting data the MRB shall dispose of the material by one of the following methods.

- (1) Accept and Use as Is - If the discrepancy will not affect basic objectives of the end item, the material may be accepted as is and thereafter shall be handled as normal material.
- (2) Rework - Items that can be reworked economically shall have the rework and subsequent inspection specified.
- (3) Repair - Items that cannot be accepted as is or reworked may be repaired provided the repair action does not create new discrepant conditions or prevent quality verification of the item. The MRB shall specify the necessary details of the repair method and the details of inspection if the inspection requires special techniques or tooling. The repair method shall be so selected as to have no affect on basic objectives of the end item.

- (4) Scrap Parts that are unfit for use and cannot be re-worked or repaired economically shall be scrapped. All such material shall be conspicuously and permanently identified either by marking the items or the container. The MRB shall enter the word "Scrap" in their notebooks and also enter the reason for scrap.
- (5) Return to Vendor Discrepant vendor items that cannot be used as is shall be returned to the vendor for replacement. If the nature of the discrepancy is such that correction will involve repair or out of sequence completion, the vendor must be notified to submit his proposed correction method for ESB MRB approval prior to performing any work on the items. The procedure for control and verification shall be as specified in section 2 of the ESB Quality Assurance Procedures.

4.6.3 MRB Vote Requirements - All MRB decisions shall be unanimous. Failure to arrive at unanimous agreement on product acceptance shall require that the items in question be scrapped. The MRB may elect to submit the problem to higher authority instead of making a "Scrap" decision. The higher authority shall be bound to the same constraints and procedures as the regular MRB as delineated in this document.

4.6.4 Historical Data - Previous MRB decisions shall not be used as routine justification for acceptance of subsequent similar discrepancies.

4.6.5 Waiver Procedure - Discrepancies that affect the basic objectives and cannot be corrected through rework, repair or completion may be submitted by MRB to ANL for waiver.

4.7 MRB AREA

4.7.1 Access Restrictions - One or more locked areas shall be allocated solely for Material Review. The area shall be locked at all times except when authorized personnel are in the area. Authorized personnel are as follows:

- (1) All members of the MRB and their alternates.
- (2) All inspectors who have business in the area such as moving discrepant parts in or processing or reinspecting parts in the area.
- (3) The Quality Assurance Engineer.

4.7.2 Non-Movable Items - Items that cannot be moved to the MRB area because of size, environmental constraints, safety or other technical considerations shall be conspicuously marked as discrepant by means of a Rejection Tag.

4.7.3 Unauthorized Removal - Unauthorized removal of any items in the MRB area shall be brought to the attention of the offender's supervisor. The supervisor will submit a written report within 48 hours to the Quality Assurance Engineer stating the action to prevent recurrence of the offense.

4.8 MRB SUMMARY

4.8.1 Preparation Responsibility - The Quality Assurance Member of the MRB shall prepare a monthly summary of MRB action and decisions.

4.8.2 Summary Requirements - The MRB summary shall report all MRB meetings and decisions indicating attendees, description of discrepant items, the disposition of these items, and nature of corrective action taken, if any.

4.8.3 Distribution - The MRB Summary shall be distributed as follows:

- (1) Technology Center Department/Program Management
- (2) Technical Program Manager
- (3) Purchasing, and
- (4) ANL in the Monthly Reports.

4.9 Corrective Action - The Quality Assurance Member of the MRB shall be responsible for corrective action.

SECTION 5

CONTRACT DATA CONTROL

5.1 SCOPE This section specifies the preparation and distribution of research documentation.

5.2 LABORATORY NOTEBOOKS

5.2.1 Contents The following items are to be recorded in bound notebooks assigned to all ESB personnel on the ANL contract.

5.2.1.1 Records of purchase requisitions.

5.2.1.2 Inspections

- (a) incoming material (Sec. 3.4)
- (b) inprocess material (Sec. 3.5.1)
- (c) stored material (Sec. 3.7)

5.2.1.3 MRB Action (Sec. 4.4.1 and 4.4.3)

5.2.1.4 Laboratory Experiments These shall be entered into the notebook using the following format: (Note - items (a) through (e) may be covered by reference to a test specification).

- (a) Description A description of the type of experiment that is intended.
- (b) Purpose A reason for designing and preparing the experiment.
- (c) Background Reference to literature or previous work if any.
- (d) Procedure Describe the approach to be pursued in carrying out the experiment.
- (e) Equipment Indicate all of the equipment to be used in the experiment (gages, power supplies, etc.) by their ESB Serial No. and when necessary, a brief description.
- (f) Data and Calculations Record, in detail, all data and calculations from experiment directly into notebook.
- (g) Conclusions Summarize the experimental results and compare to any previous experiments and to the desired or expected results. Note any recommendations (design changes, etc) for future work in this area.

5.2.2 Use - For any additional information on the use of notebooks, follow the procedure described in "Instruction for using this notebook".

5.3 ENGINEERING DRAWINGS

Copies of drawings which are used to define the configuration of any article in terms of dimensional, visual, functional or other features shall be maintained in a Q.A. file.

5.4 DISTRIBUTION

Reports, drawings, etc. will be prepared and distributed as specified in the contract.

SECTION 6

EQUIPMENT AND GAGE CONTROL

6.1 SCOPE - This section establishes requirements for control of inspection gages, jigs, fixtures and instruments used in the acceptance of process of product.

6.2 DEFINITIONS

6.2.1 Tools - Any drill jig, die, oven, etc., where dimensions of the finished part are dependent on form of the manufacturing equipment.

6.2.2 Working Gages - Any item that is used to pass judgement on the acceptability of the product or the process producing the product. Examples are: micrometers, voltmeters, scales, timers, thermometers, hydrometers, ammeters, and tensile testers.

6.2.3 Reference Standards - Any cell, instrument, resistor or other piece of equipment for which there exists a long term history of stability and repeatability. They shall be of rugged construction and purchased from manufacturers of high reputation and of long experience in producing instruments and apparatus of demonstrated performance. Reference standards are the most accurate instruments maintained at ESB Technology Center. All Reference Standards shall have a periodic calibration by or directly traceable to the National Bureau of Standards through an acceptable source.

6.2.4 Working Standards - Equipment similar in design and principle to any production, inspection or test equipment except there exists long and short term records of precision, accuracy and stability. Working standards are periodically calibrated against reference standards and reserved for use in the calibration of production, inspection or test equipment. Working standards are never used directly for measurements in the plant or laboratory.

6.3 TOOL CONTROL

6.3.1 Initial Inspection - Jigs, fixtures, dies or other tools shall be processed through the Quality Assurance Department for inspection and identification before they are used. Any tool that is reworked because of wear or engineering change either by ESB or a vendor must be re-inspected.

6.3.2 Accuracy - All tools shall be inspected to the limits of accuracy required by drawings or other applicable specifications by the Q.A.E. or his designate.

6.3.3 Identification - All accepted tools shall be identified with a serial number and inspection acceptance tag. Under no conditions are tools to be released for use without the acceptance tag unless approval is obtained from the Quality Assurance Engineer.

6.3.4 Records - A detailed inspection acceptance record shall be initiated by the tool and gage inspector detailing all the dimensions inspected and the results of the inspection. Dimensional discrepancies shall be noted. These shall be discussed by the Quality Assurance Engineer and the Technical Program Manager. The inspection acceptance record shall be filed in the Quality Assurance Department.

6.4 GAGE AND INSTRUMENT CONTROL INSTRUCTIONS

6.4.1 New or Modified Gages - Prior to the initial use of any new or modified gage, the device shall be processed through the Quality Assurance Department where it shall be completely inspected to specification requirements. New gages shall be entered into inventory.

6.4.2 Tolerances - A unilateral system of tolerances shall apply wherein gage wear shall not exceed product tolerances.

6.4.3 Record and Identification - All gages shall be identified with gage serial number which is clearly marked, in a location that will not impair the accuracy or usability of the gage. An instrument calibration record shall be initiated containing the following information.

- (1) Name of Gage.
- (2) Manufacturer's name and catalog number.
- (3) Location of gage.
- (4) Frequency of check.
- (5) Rated accuracy.
- (6) Results of periodic inspection and initial inspection.
- (7) General remarks, if any.
- (8) The reverse side of the card shall be used to record information on repair or modification.

6.4.4 Storage - All gages shall be stored in such a manner as to prevent damage due to corrosion or improper handling.

6.4.5 Date Identification - All gages shall be identified with a tag containing the date of the most recent check, the date of the next scheduled check and the initials or stamp of the person performing the check.

In cases where gage adjustments are exposed such as the mechanical zero on the direct current voltmeters, the inspection label shall be placed over the adjustment to prevent accidental change of calibration.

Each employee - prior to use - shall verify that the gage re-calibration date has not passed. If the re-calibration date has passed, the laboratory supervisor shall notify the calibration technician and the gage shall not be used until the recalibration is performed.

6.4.6 Inventory of Gages - An up-to-date inventory shall be maintained on all inspection gages and instruments, and frequency of calibration required on each item.

6.4.7 Inactive or Obsolete Gages - These shall be removed from normal laboratory areas and stored until needed.

6.5 STANDARDS AND INSPECTION GAGES

6.5.1 Instrument and Gage Code Designation

- (1) Reference Standards (Electrical) - RSE
- (2) Reference Standards (Mechanical) - RSM
- (3) Working Standards (Electrical) - WSE
- (4) Working Standards (Mechanical) - WSM
- (5) Working Gages (Electrical) - WGE
- (6) Working Gages (Mechanical) - WGM
- (7) Tools (Electrical) - TE
- (8) Tools (Mechanical) - TM

6.5.2 Frequency of Calibration - Gages and instruments shall be checked at least as often as required in the inventory charts. Inactive gages need not be checked until used. Gages used intermittently shall be checked prior to each use where the time between usage is greater than the time allowed between checks.

6.5.3 Accuracy of Calibration Any standard used to calibrate any gage or any gage to measure any component or assembly must be at least four times more accurate than that being calibrated or measured.

6.5.4 Standards Control

- (1) Reference Standards - All reference standards shall remain in the calibration area at all times except for periodic re-certification.

The reference standards shall be handled with care and stored in an area free from dust, dirt, vibration, shock, or any corrosive atmosphere.

No one shall be allowed the use of the reference standards without authorization from the Quality Assurance Engineer except Quality Assurance Department personnel.

Under no circumstances shall the reference standards be used as an inspection or production gage.

Reference standards in some instances may be used directly to calibrate a working gage.

- (2) Working Standards - Working standards shall be maintained in the gage calibration area but may be removed for the purpose of calibrating inspection gages where it becomes impractical to bring the inspection gage to the calibration area.

Working standards shall be handled with care and stored in an area free from dust, dirt, vibration, shock, or any corrosive atmosphere.

No one shall be allowed the use of the working standards except the Quality Assurance Engineer.

Under no circumstances shall the working standards be used as an inspection or production gage.

Complete records of the history of all working standards shall be available for examination by the contractor representatives.

SECTION 7

DESIGN REVIEW

7.1 SCOPE This section specifies the procedures to be followed in the review of designs to meet contract objectives.

7.2 PURPOSE The design review shall question the practicality of engineering designs and proposed production and inspection procedures by examining the form, fit, and function of each material, part, process, subassembly, product, and package where applicable.

Safety in end use, abuse, or misuse shall be questioned at each step of the design review.

7.3 DESIGN REVIEW COMMITTEE A design review committee (DRC) shall be established by the Technical Program Manager to execute the function of this section.

7.3.1 Committee Composition The DRC shall consist of:

- Representative of Department/Program Management
- Technical Program Manager
- A QA Representative
- Manufacturing Specialist (may be from Divisions)
- Materials Specialist (may be from Divisions)
- Others who, in the opinion of the Technical Program Manager, can contribute to the design review.

7.3.2 Meetings DRC meetings shall be held:

- prior to the large scale commitment of funds for development,
- prior to release of product to manufacturing facility,
- prior to release of product to customer, and
- at any time convened by the Technical Program Manager.

7.4 DOCUMENTATION

7.4.1 Design Review Checklist A design review checklist shall be prepared by the QAE to aid the DRC in performing its duties. The Principal Investigator shall supply the checklist along with copies of all documents and drawings pertinent to the design to the DRC members prior to meetings so that each member may become familiar with the subjects to be discussed. The review will not be limited by the items on the checklist.

7.4.2 DRC Minutes - The QAE or his representative shall note all suggested design changes with reasons and will submit meeting minutes to the members within seven working days of the meeting. The Technical Manager shall have the responsibility for follow-up on suggested changes.