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FIRST INTERIM TECHNICAL REPORT
For The
STUDY ON INTEGRATION OF SILVER-ZINC BATTERY IMPROVEMENTS

(19 June 1963 - 31 October 1968)

Contract No.: NAS 5-11579

Prepared By
HUGHES AIRCRAFT COMPANY
AEROSPACE GROUP
Space Systems Division
Propulsion And Power Systems Laboratory
El Segundo, California

For
GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland



FACILITY FORM 602

69-15718
(ACCESSION NUMBER)

(THRU)

48
(PAGES)

(CODE)

69-95758
(NASA CR OR TMX OR AD NUMBER)

3
(CATEGORY)

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ABSTRACT

This report covers the first 4-month period of Contract No. NAS 5-11579. The object of this program is to design a lightweight, experimental, five-cell, 12 amp-hr, silver-zinc battery for space application that incorporates many technology and design improvements for the purpose of achieving better cycle life and performance.

A study was completed during this period leading to the selection of Noryl thermoplastic for the main packaging material. Further, a process evaluation of adhesive bonding, solvent joining, ultrasonic welding, and hot gas welding was made to determine which method offered the best means for producing high reliability hermetic sealing of package parts. Although many of the joining processes looked attractive at first, adhesive bonding was selected.

The battery design developed during this reporting period offers the best tradeoff for lightweight, reliable performance, and the ability to integrate the desired technology improvements. The following list outlines the salient features of the battery to be built during the next reporting period:

- 1) Five-cell, monoblock, lightweight case
- 2) Noryl thermoplastic packaging with adhesively joined parts
- 3) Special technology improvements including:
 - Positive plates with densities specified for maximum cycle life
 - Teflonated negative plates
 - Improved separator system including RAI Permion 2290 separator, and for three of six batteries, in addition to the 2290 separator, calcium hydroxide electro-deposited coatings for the positive plates
 - Common gas manifold

- Microfuel cell assembly
- Permeable membrane cell ports to the common gas manifold
- Separator support frames to preclude the use of the U-fold
- Minimum interior draft angle case to achieve an improved plate-separator interface
- Lightweight cell interconnects of a new design

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1.0 INTRODUCTION

This report covers the first 4-month period of activity on this contract. In general, this program has three main objectives:

- 1) The integration of Government-sponsored silver-zinc battery improvements along with Hughes' aerospace packaging concepts to enhance the performance of the silver-zinc battery system for space applications.
- 2) The reduction of battery package weight by 20 to 30 percent compared to state-of-the-art batteries utilizing individual cells and associated hardware.
- 3) The design, fabrication, and delivery of six, five-cell 12 amp-hr, nonmagnetic, experimental silver-zinc batteries to NASA-GSFC.

Many Government-sponsored technology contracts over the last 3 to 4 years have led to specific improvements in the silver-zinc system. However, while improved components (i.e., plates, separators, seals) have been developed on independent programs, there has been little effort made to incorporate several of these improvements into one silver-zinc battery. The purpose of this program is to combine several independently developed improvements, along with lighter weight aerospace packaging, into one battery designed for optimum performance.

During this reporting period, the battery design was developed. An extensive materials and processes study was conducted leading to the selection of Noryl for the case material, and to the selection of adhesive bonding as the joining technique. Plate and battery case sizing has been completed, along with the selection of all electrochemical design points. In addition, the selection of specific technology improvements to be incorporated into the batteries for this program has been completed.

2.0 TECHNICAL DISCUSSION

2.1 BATTERY REQUIREMENTS

The latest modification of Contract No. NAS 5-11579 specifies a nonmagnetic, 12 amp-hr, five-cell, lightweight, silver-zinc battery. Several technology improvements have been included in the design of this battery, some new, some used previously, but all improvements have never been incorporated before in a single battery. Therefore, it is hoped that incorporation of improvements will achieve improved cycle life and calendar life for the silver-zinc battery with performance optimized for a 24-hour, or synchronous orbit. Cycle life equivalent to 3 years in synchronous orbit, 270 cycles, is a design goal, but certainly not a requirement. The battery must operate over a temperature range of 30 to 100°F, utilizing a two-step charge procedure developed by NASA-GSFC, combined with up to 60 percent depth of discharge within 1 hour.

Specifically, six, 12 amp-hr, five-cell, silver-zinc batteries are deliverable items to NASA-GSFC. Two of these batteries will be activated and tested by Hughes prior to their shipment to NASA. Originally, three, 16 amp-hr, ten-cell silver-zinc batteries were required. The change in configuration and in ampere-hour size will not affect the basic battery design nor the incorporation of technology improvements described later in this discussion.

A 25 percent minimum weight reduction over conventionally packaged, sealed, silver-zinc space batteries is desired. The battery design specified herein meets this goal when compared to similar ampere-hour size, conventionally packaged silver-zinc space batteries.

2.2 PACKAGING

Because a lightweight silver-zinc battery incorporating several special technological improvements is required, package design necessarily became a prime design consideration. The lightweight aspect of package design is important because of the design goal for a 25 percent weight reduction compared to conventionally packaged, sealed, silver-zinc space batteries. Battery manufacturers have reduced cell weights to the point that any

further weight reduction only can be achieved by a total battery design approach. Hermetically sealed space batteries produced by epoxy potting individual, vented, silver-zinc cells with appropriate mounting hardware, is uneconomical from a weight standpoint. Therefore, the package design described in the following subsection was arrived at through consideration of the required weight reduction, and to permit the incorporation of the special technological improvements.

2.2.1 Package Design

Several factors must be considered in designing space battery packages. Among these are: lightweight construction, reliable methods to achieve hermetic seals, long term package integrity, and the incorporation of special improvements, particularly minimum draft angle cell walls (explained later in subsection 2.4.6). After considering all pertinent factors, it has been concluded that monoblock battery construction using a low density thermoplastic for a package material will best meet the objectives of this program.

Monoblock battery construction is inherently lighter in weight than individual cell construction because contiguous cells share the same wall. Several manufacturing techniques were studied as possibilities for producing a monoblock design battery. Injection molding, profile extrusion, and machining techniques were investigated. Many thermoplastic resin manufacturers, injection molders, profile extruders, and machine shops were consulted concerning these techniques and their possible application in the fabrication of a space battery package. The results of this activity are summarized in Table I.

It was concluded that the best method for achieving the battery package design goals is to use an injection molded, five-cell monoblock incorporating minimum draft angle, thin-wall construction, as shown in Figure 1. Covers for the injection molded cases will be machined because of the limited number required. Machining the cases required, even a small quantity, is not compatible with obtaining the case quality required. It is uncertain, with the thin-wall construction and the height of the case, whether or not a stress-free case could be obtained by machining, even with a post-machining stress relief anneal.

Figure 2 shows the battery cover for the 12 amp-hr, five-cell monoblock. A common gas manifold and epoxy retaining channels for wiring and cell interconnects have been incorporated into the cover design, as well as holes for the fill plugs and slots for the plate tabs.

Filler plugs and the gas manifold lid will be bonded to the cover as shown in Figure 3. Grooves will be machined into the cover to interface with cell jar walls. These grooves will serve to increase joint strength and to self-locate the cover with respect to the case.

TABLE I. SUMMARY OF ADVANTAGES AND DISADVANTAGES OF POSSIBLE BATTERY CASE FABRICATION TECHNIQUES

Construction Technique	Comments
Injection molded, thin wall, five-cell case with bonded lid	<p><u>Advantages</u> Minimum draft angle of 0.2 degree Run cost per unit is low</p> <p><u>Disadvantages</u> High initial tooling costs</p>
Profile extruded, thin wall, five-cell case with bonded bottom and top	<p><u>Advantages</u> No draft angle Run cost per unit is low</p> <p><u>Disadvantages</u> It is doubtful that parallel, close tolerance walls could be obtained High initial tooling costs</p>
Building block approach – multiple four-sided injection molded cells joined together to form a five-cell monoblock	<p><u>Advantages</u> No draft angle along critical walls Moderate initial tooling costs</p> <p><u>Disadvantages</u> Requires extremely careful jiggling and alignment to ensure joint integrity</p>
Five-cell monoblock machined from solid block	<p><u>Advantages</u> No draft angle</p> <p><u>Disadvantages</u> Internal and machine induced stresses may cause stress cracking and/or distortion Exclusive of tool and mold costs, machined cases would be rather expensive on a cost per unit basis</p>

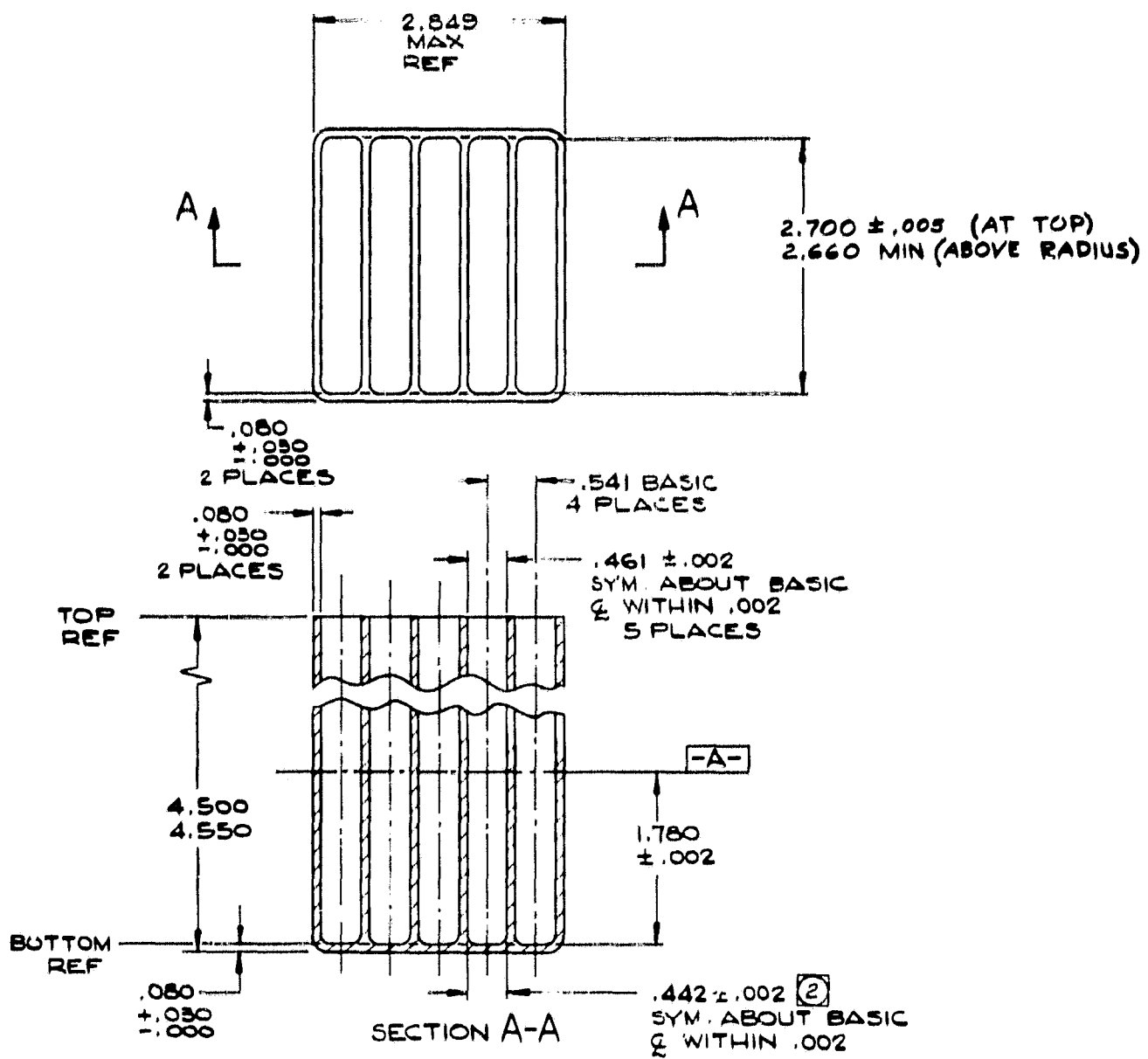


Figure 1. Injection Molded Battery Case

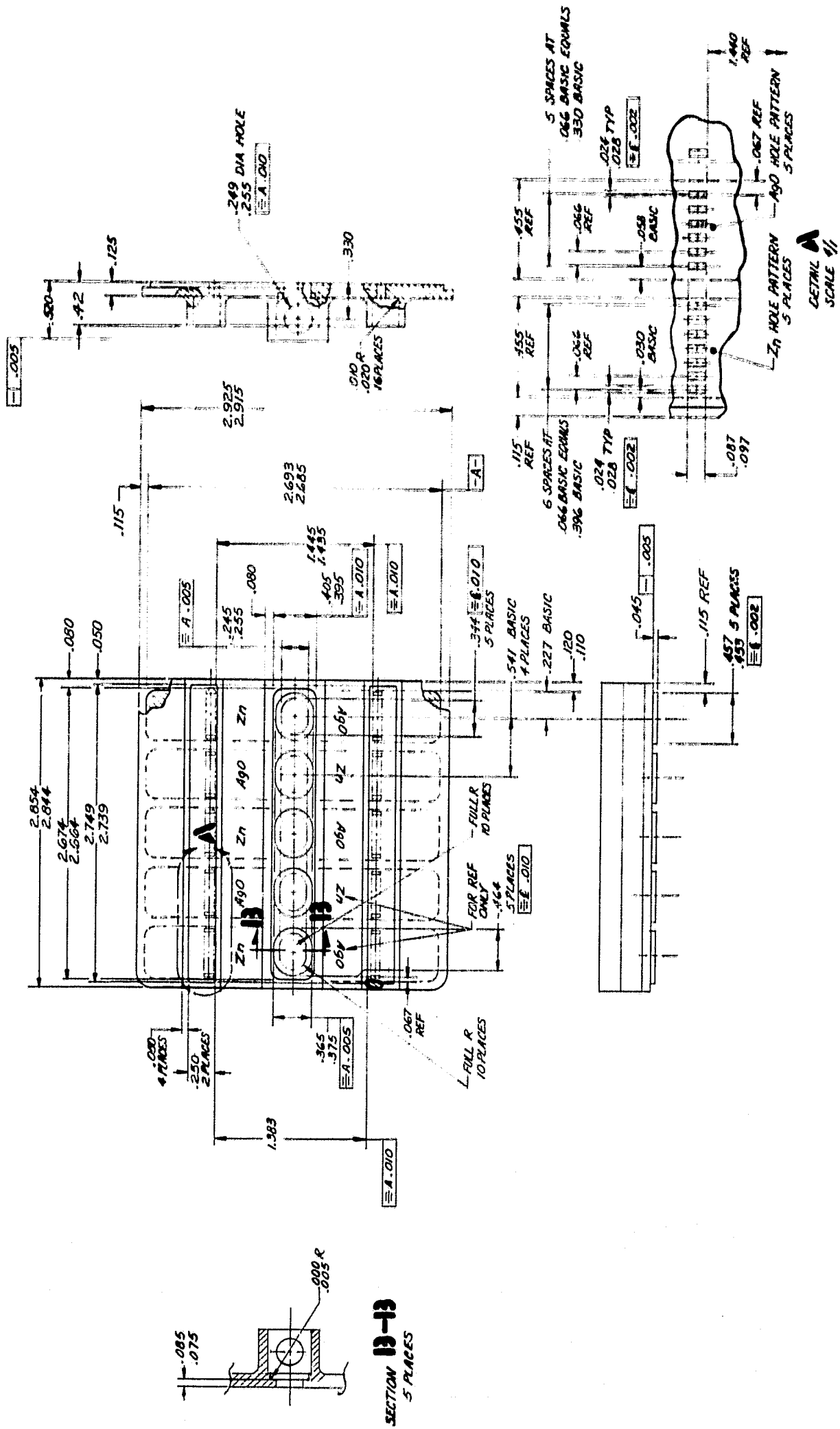


Figure 2. Battery Cover

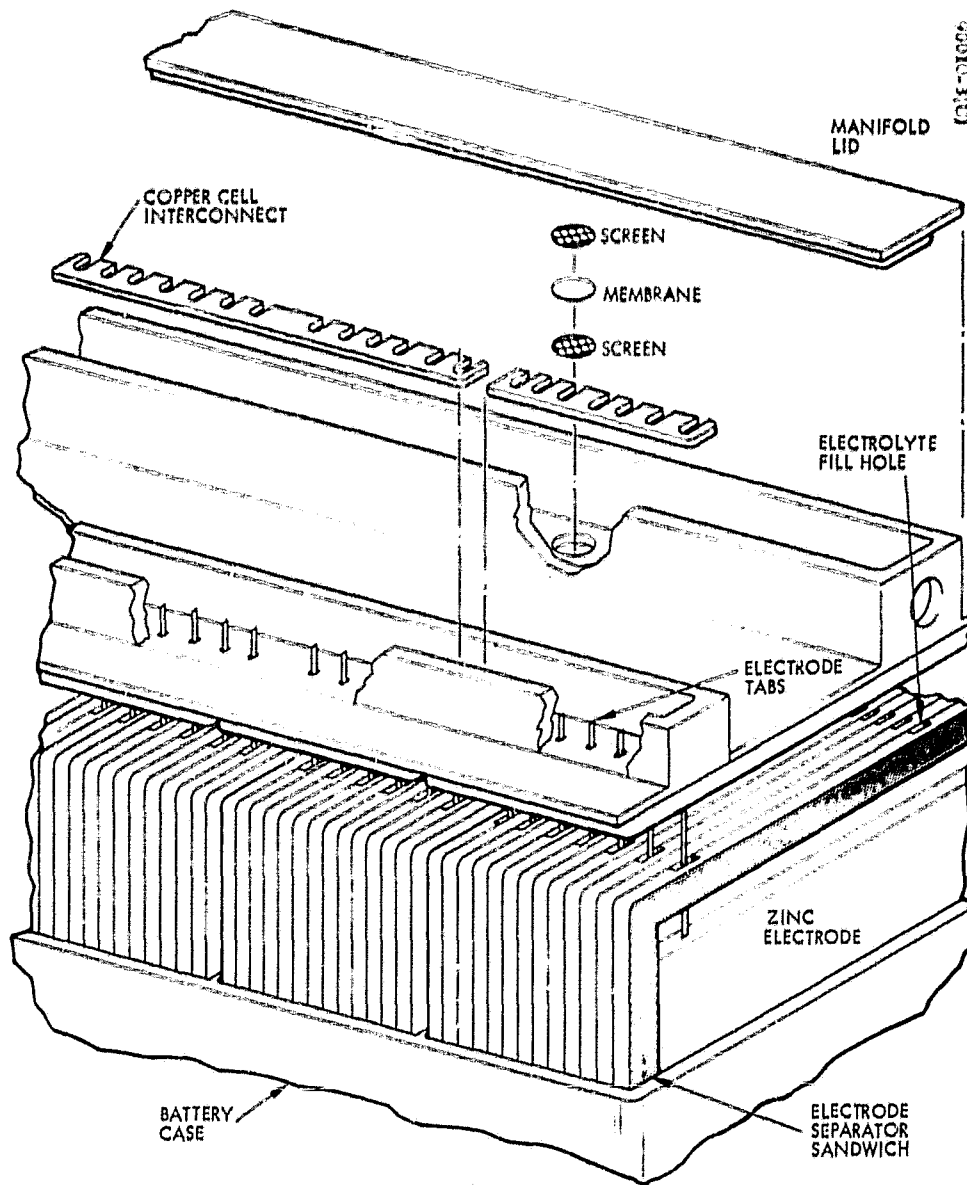


Figure 3. Battery Assembly

2.2.2 Material Selection

A study was conducted to evaluate suitable thermoplastics for use as battery case materials. The chemical resistance, moldability, joining characteristics, and solvent and stress cracking properties of all candidates were investigated. Noryl Grade 731-701 thermoplastic was selected as the best material for use on this program because of its good molding characteristics, low density, and resistance to KOH solution. Table II summarizes candidate thermoplastics and reasons for the material selection. Bonding characteristics of Noryl, polyphenylene oxide (PPO), and polysulfone are discussed in the following section. Data on the various thermoplastics was obtained by reviewing the literature, and consultation with Hughes Material Technology Laboratories and thermoplastic manufacturers.

2.2.3 Joining Techniques for Case Assembly

Manifold lid, filler caps, case lid, and case must be bonded together hermetically. The following criteria were used to evaluate the acceptability of candidate joining techniques:

- 1) Bond strength at least 50 percent of the virgin thermoplastic strength.
- 2) Bond integrity must not degrade during continual exposure to 40 percent KOH at 110°F for 3 years.
- 3) A hermetic seal, with a leak rate not greater than 1×10^{-4} cubic centimeters of helium per second per lineal inch at 15 pounds per square inch pressure differential, must be formed during bonding.
- 4) Impact and fatigue strength shall be sufficient to prevent damage during fabrication and subsequent handling.
- 5) Bonding processes and techniques must be simple, reliable, and produce consistent high quality results.
- 6) Room temperature bonding processes are preferred because battery active electrochemical components must not be exposed to excessively high temperatures (greater than 130°F).
- 7) Adhesives and solvents must not be allowed to contaminate battery separators and electrodes or harden in areas which would cause difficult assembly.

Four joining techniques listed below were selected for evaluation:

- 1) Adhesive joining
- 2) Solvent joining

TABLE II. BATTERY CASE CANDIDATE THERMOPLASTICS

Candidate Material	Disposition	Comments
Noryl	Selected	<p>General Electric proprietary PPO-based polymer alloy, probably: 50 percent PPO, 30 percent polystyrene, 5 percent inorganic including pigments, and 15 percent unaccounted content.</p> <p>The melting point viscosity index is lower than for unalloyed PPO, therefore, should injection mold more readily into thin wall monoblocks.</p> <p>Low density - 1.06 grams per cubic centimeter.</p> <p>Excellent resistance to 40 percent KOH solution.</p> <p>A lower temperature thermoplastic than PPO; it cannot be heat sterilized. However, this is not a requirement of this program.</p> <p>Can be joined by adhesive, solvent, ultrasonic, and hot gas weld techniques.</p> <p>Costs less than PPO.</p> <p>Good resistance to solvent and stress cracking.</p>
Polyphenylene oxide (PPO)	Back-up case material	<p>High injection mold temperatures required, making the time-temperature-viscosity consideration more severe than for Noryl.</p> <p>Thin wall sections (under 0.100 inch) may be difficult to mold.</p> <p>Can be heat sterilized.</p> <p>Yield strength slightly higher than that of Noryl.</p> <p>Costs more than Noryl.</p> <p>Good resistance to solvent and stress cracking.</p>
Polysulfone	Eliminated	<p>Doubts concerning polysulfone's ability to resist solvent and stress cracking could not be resolved. Molding stresses make this material susceptible to cracking in an environment of organic polar solvents (References 1 and 2).</p> <p>High temperature thermoplastic; can be considered for heat sterilization applications.</p> <p>Higher density material at 1.24 grams/cc compared to PPO and Noryl at 1.06.</p>
Polyolefin-type thermoplastics, i. e., polymethylpentene (TPX) and polypropylene	Eliminated	<p>High mold shrinkage of polyolefin type materials is a cause for concern where low draft angle battery case construction is desired.</p> <p>Cannot readily be joined by adhesive, ultrasonic, and solvent bonding techniques.</p>

- 3) Ultrasonic welding
- 4) Hot gas welding

Lap shear and butt tensile specimens were fabricated using the above techniques and three candidate materials: PPO, Noryl, and polysulfone.

Three epoxy adhesives were evaluated, as listed below:

- 1) Bondmaster M-611 (Pittsburg Plate Glass Company), a two-part paste adhesive consisting of a filled epoxy resin and an amine hardener TETA (triethylene tetramine), mixed 100 parts by weight resin to 10 parts hardener.
- 2) Epiphen 825A (Borden Chemical Company) a four-part modified paste epoxy system mixed as follows:

Resin	25 parts by weight
Modifier T	3 parts by weight
Filler	10 parts by weight
Converter	4 parts by weight

- 3) Armstrong A-12 (Armstrong Products Company), a two-part modified paste epoxy adhesive, mixed in equal parts by weight: resin component A and hardener-modifier component B.

Prior to adhesive bonding, samples were scuff sanded and solvent wiped with naphtha. The two modified epoxies have greater flexibility. Because the silver electrode tabs and copper cell interconnects have a lower thermal coefficient of expansion than the plastic case, some adhesive flexibility is required to avoid cracking during thermal cycling.

Polysulfone and Noryl were solvent bonded using a prebodied solution of the plastic dissolved in ethylene dichloride. PPO was solvent bonded using a cement made by dissolving plastic chips in a mixture of 95 volume percent chloroform and 5 volume percent carbon tetrachloride. Samples were scuff sanded and solvent wiped with naphtha prior to solvent joining.

The ultrasonic welding of machined specimens incorporating sonic energy directors was accomplished using Branson Sonic Power equipment. The ultrasonic bonding parameters used followed the equipment manufacturer's recommendations.

Hot gas welding (butt tensile specimens only) was performed using a 450 watt master model FMT-67-1 "flameless heat torch." Nitrogen gas was used as the heating media.

Appendix I lists results of lap shear and butt tensile tests. Prior to testing, some samples were exposed to 32 percent KOH solution at 250°F for 24 hours. Assuming that reaction rate doubles for each 10°C temperature increase, this exposure at 250°F for 24 hours simulates 80°F for 3 years.

Helium leak and pressure burst tests were run on Noryl cylindrical specimens. These samples were machined from 2-inch diameter rod to simulate as closely as possible joint length, wall thickness, and cover configuration of the actual monoblock battery case. Three samples were machined with energy directors and ultrasonically welded, three were solvent bonded, and three were adhesive bonded with Armstrong A-12 epoxy. Test results are presented in Table III.

Table IV summarizes the conclusions obtained from this study of joining techniques. Adhesive bonding was selected as the joining process to be used during battery fabrication.

2.3 ELECTROCHEMICAL

Six positive and seven negative plates per cell will be used. The positive plates each will contain 2.2 amp-hr silver capacity, and the negative plates will each contain 5.5 amp-hr of zinc oxide capacity. Therefore, this will produce a positive limited cell of 13.2 amp-hr capacity. The total negative capacity per cell is 33.0 amp-hr for six effective plates.

2.3.1 Plates

Positive Plate

The physical and chemical characteristics of the positive plates to be used in the batteries for this program are described in Table V.

An expanded silver substrate of 2/0 mesh size and 0.200 gram per square inch density will be used in the positive plate. The plate density of 69 grams silver per cubic inch has been established at the point for maximum cycle life, as reported in Sulkes' paper (Reference 3). The capacity requirement for the positive plates is determined by the ampere-hour battery capacity requirement of 12 amp-hr. Six positive plates per cell will be used, and the silver weight required per plate is calculated as follows:

$$\frac{[12 + 0.1 (12)] \text{ amp-hr} \times 1 \text{ gram silver}}{6 \text{ plates} \times 0.25 \text{ amp-hr}} = 8.80 \frac{\text{grams silver}}{\text{plate}}$$

TABLE III. HELIUM LEAK AND HYDROSTATIC BURST TEST RESULTS FOR BONDED NORYL SPECIMENS

Bonding	Specimen Number	Leak Test	Pressure to Failure, psig	Remarks
Ultrasonic	2	Passed	84	No. 6 leaked at end cap bond. No. 7 had a gross leak, unable to isolate. During burst testing, this specimen leaked pressure badly, invalidating the test results.
	6	Failed	45	
	7	Failed	90	
Solvent	1	All passed	70	No. 3 broke during burst test setup.
	3		-	
	4		82	
A-12	5	All passed	44	
	8		52	
	9		40	

These plates will be fabricated by Electric Storage Battery Company's (ESB) DP process, utilizing silver plastic sheets and expanded silver metal grid for the substrate. This manufacturing process is proprietary to ESB. Active silver weight in the final plate is better controlled by the DP process than with the use of a pressed powder or paste-up technique. However, in using the DP process, the ability to determine the actual active silver weight in each plate is lost because six individual plates are stamped from one DP biscuit. The average density for the grid material of the biscuit is used to estimate the active silver weight of each plate. An average grid density is measured for every six plates. The measurements shown in Figure 4 will be used to control the active silver weight of each plate.

Negative Plate

The negative plates will incorporate several features that should enhance the calendar and cycle life performance of this battery. First, these plates have been sized to establish a negative-to-positive ampere-hour capacity ratio of 1.7 ZnO:1.0 Ag. According to Lander (Reference 4), improved cycle life is achieved with increases in the negative-to-positive ampere-hour capacity ratio up to 2.0 ZnO:1.0 Ag. Lander pointed out two items that must be considered for this program:

- 1) Cycle life will be improved as the ZnO:Ag capacity ratio increases from 1.0:1.0 to 2.0:1.0, but because insufficient data are available above this point, it is uncertain whether or not cycle life will continue to improve above a ratio of 2.0:1.0. The range of 1:1 through 4:1 was studied.

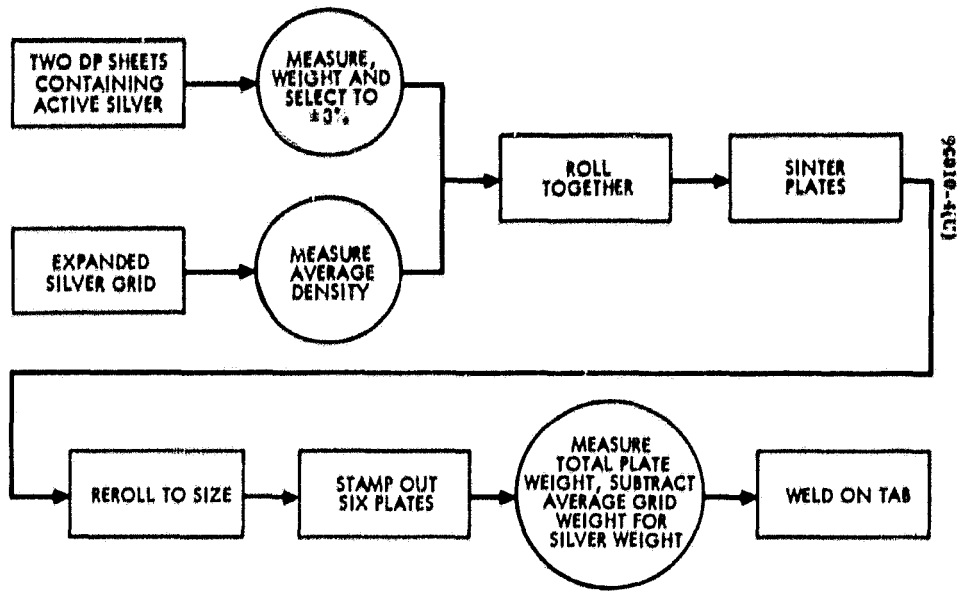


Figure 4. Measurements to Assure Control of Active Mix Weight in Positive Plates

TABLE IV. CONCLUSIONS CONCERNING JOINING TECHNIQUES

Process	Reason(s) for Selection or Elimination
Hot gas welding	<p>Eliminated</p> <p>May excessively heat active cell materials.</p> <p>Requires extensive process development to perfect.</p>
Solvent joining	<p>Eliminated</p> <p>Difficult to assure reliable joints with opaque thermoplastics.</p> <p>Can cause stress cracking.</p>
Ultrasonic welding	<p>Eliminated</p> <p>Simple geometry parts presented no problem. A complex part, such as a battery cover, would require further exploration of the technique.</p> <p>Hermetic seals were not consistently obtained with this technique.</p> <p>The ultrasonic energy cannot be confined to the cover and case alone. The main concern is that the silver and zinc plates are extremely fragile and may degrade (crumble) during exposure to ultrasonic energy. Short-term effects could be readily determined, but the long-term effects on cycle life and calendar life would be difficult to ascertain during battery fabrication.</p>
Adhesive bonding	<p>Selected</p> <p>This method was selected by the Hughes Design Review Board because it offers the best chance for success among all processes evaluated within the schedule and financial constraints of the program.</p>

TABLE V. PHYSICAL AND CHEMICAL CHARACTERISTICS OF POSITIVE PLATES

Characteristics	Amounts and Units	Tolerance
Dimensions		
Width	2,094 inches	+0,000 -0,030
Height	3,125 inches	+0,000 -0,030
Thickness	0,021 inch	±0,001
Corner radii, typical	0,25 inch	
Density	69 grams/ cubic inch	
Weight breakout		
Active material	3,80 grams	±0,21
Grid	1,29	
Subtotal	10,09 grams	±0,28*
Tab	0,22	
Total plate weight	10,34 grams	
Plate area (one side corrected tolerancing and corner radii)	6,453 square inches	
Grid effective thickness	1,16 × 10 ⁻³ inch	
Capacity	2,2 amp-hr	

*Primary weight control will be prior to the attachment of the silver tap electrical connection.

- 2) Apparently, it does not matter whether the zinc capacity is present in the charged or uncharged form for an improvement in cycle life to occur.

The negative-to-positive capacity ratio for this battery was computed as follows:

$$R \frac{\text{ZnO}}{\text{Ag}} = \frac{8.95 \text{ gm. ZnO} \times 0.659 \text{ A-H/gm ZnO} \times 6 \text{ plates}}{8.80 \text{ gm. Ag} \times 0.496 \text{ A-H/gm Ag} \times 0.80 \text{ silver percentage utilization} \times 6 \text{ plates}}$$

$$R \frac{\text{ZnO}}{\text{Ag}} = 1.7$$

Two configurations of negative plates have been considered. Both are teflonated to inhibit slumping. The difference would be that one of the negative plate designs would incorporate two expanded metal grids, one silver and one zinc, welded together for additional structure to retain the active mix. The second negative plate design has only one silver grid that is folded back upon itself at the edges for about one-quarter of an inch for added structural support of the active mix.

Zinc grids probably have not been used previously in a sealed, secondary silver-zinc battery. However, if one considers Lander's findings concerning improved calendar and cycle life attributed to a larger ZnO:Ag capacity ratio, along with the fact that it apparently does not matter whether the zinc capacity is in the form of ZnO or Zn, it becomes interesting to consider the use of a zinc grid. Further, from an electrochemical standpoint, zinc should plate and deplate more readily on a zinc substrate than on a silver substrate with some reduction of inherent corrosion problems associated with the use of a silver grid alone. Hughes has elected to use a single silver grid in the negative plate for the following reasons:

- 1) There is a greater experience factor established in both sealed, secondary silver-zinc batteries, and in the use of a single silver grid in teflonated zinc plates.
- 2) The zinc grid would convert to ZnO during cycling, therefore its mechanical support would be lost.
- 3) The maximum discharge rate of a plate containing a zinc grid would probably be limited to C/5.

Table VI summarizes the characteristics of the negative plate selected and sized for this program.

TABLE VI. PHYSICAL AND CHEMICAL CHARACTERISTICS OF
NEGATIVE PLATES

Description	Value and Units	Tolerance
Active material		
Composition, percent by weight		
ZnO	93	
HgO	2	
Teflon	5	
Total	<u>100</u>	
Plate weight breakout, grams		
Active mix	8.95	±0.05
(ZnO)	(8.33)	
2/0 silver grid with 0.25- inch fold back	1.58	
Subtotal	<u>10.53</u>	±0.10*
Tab	<u>0.22</u>	
Total	10.75	
Capacity		
ZnO	5.5 amp-hr	
Plate density	49.0 $\frac{\text{grams ZnO}}{\text{in}^3}$	
Dimensions, inches		
Width	2.094	±0.030
Height	3.125	±0.030
Thickness	0.029	±0.003

*Point of primary weight control.

2.3.2 Separator System

Separator

Permion 2290 is a polyethylene film, typically 0.0013-inch thick, which is grafted with acrylic acid. This membrane offers somewhat better properties for minimizing silver ion migration and blunting zinc dendrites, according to the current results of the separator study program at ESB Incorporated (Reference 5). Therefore, Hughes has been directed by NASA-GSFC to incorporate Permion 2290 separator into the batteries for this program. Five layers of 2290 separator will be used between the silver and zinc plates for the standard cell configuration for this battery. A second cell configuration is described in the next paragraph.

Calcium Hydroxide Coating

General Electric Company evaluated electrodeposited films of calcium and magnesium hydroxide for use in silver-zinc cells (References 6 and 7). As reported, magnesium hydroxide was ruled out because of poor adhesion of the coating to the plates. The main advantage to be gained by incorporating calcium hydroxide coatings is to achieve reduced rates of silver migration. By more efficiently retarding the silver migration, a reduction of separator thickness and improved cycle life can be realized. General Electric Company and ESB Incorporated test results (Reference 8) demonstrated that coating thicknesses of 1.2 to 2.0 mils show little evidence that capacity or cell voltage is significantly influenced. A coating thickness of 1.3 mils was selected as an optimum for this program because one layer of 2290 is 1.3 mils. Therefore, it is convenient for the three batteries that will incorporate Ca(OH)_2 to have 1.3 mils of Ca(OH)_2 and four layers of 2290 between each silver and zinc plate. The three batteries that do not contain Ca(OH)_2 will contain five layers of 2290. Therefore, the cell jar in both cases retains the same interior dimension.

2.3.3 Absorber

Kendall Webril Dynel EM470 is a candidate for an absorber material for this program. A single layer of absorber material (0.001 inch) between the positive plate and the 2290 separator will be used. This absorber will be suspended in the separator frames described later in subsection 2.4.5. The minimum thickness was selected so that only a minimum voltage drop is sustained across the absorber. The negative plate will be fabricated by a process that produces a mechanically stable plate that does not require a retainer. Further, the teflon fibers in the negative plate will act as an absorber. Also, the charge and discharge rates and durations required for a 24-hour orbit are such that an absorber would be required around the positive plate, but not necessarily around the negative plate.

2.4 SPECIAL IMPROVEMENTS

Many technology improvements in the silver-zinc system have been made over the past 3 to 4 years. Some of these improvements are the direct result of government technology contracts issued to battery and aerospace companies. The purpose of these contracts generally was to explore specific technology areas within the silver-zinc battery system such as positive and negative plates, separator systems, hermetic seals, and cell jar. Also, the purpose of other government technology contracts in the electrochemical field was to develop auxiliary devices, such as the microfuel cell, that could work in conjunction with a silver-zinc cell, or battery, to optimize overall performance. One of the main purposes of this contract is to make use of several of these specific technology improvements within one battery. The obvious goal is that if several independent improvements are all combined into one battery, that battery should offer superior performance characteristics. This, of course, assumes that there are no detrimental interactions between the individual technology improvements that have not been anticipated. The following paragraphs discuss the technology improvements that have been selected for incorporation into the batteries for this program.

2.4.1 Common Gas Manifold

The common gas manifold first was used on the Surveyor battery because the use of individually sealed cells required a close match of individual cell capacities within a battery. Available manufacturing techniques made attainment of a close match costly. Extended overcharge or cell reversal of a sealed cell in a battery can lead to buildup of significant gas pressure in the cell with eventual cell rupture. Individual sealed cells within a battery, unless very closely balanced, could not withstand overcharge successfully. Therefore, flight batteries were equipped with a common gas manifold into which all cells were vented. The manifold was designed to allow ample volume for expansion of gas generated during extended overcharge, and a pressure transducer was installed as an added safety measure. This permitted automatic charge termination when a predetermined pressure had been reached. Pressure during discharge was generally well below overcharge pressures. In the Hughes-designed battery, the common gas manifold will be utilized as in the Surveyor battery with one exception, the microfuel cell will replace the pressure transducer.

2.4.2 Microfuel Cell

During charge-discharge cycling of silver-zinc cells, oxygen and hydrogen gas are evolved. Unrecombined gas can cause pressure buildup within the cell. A two-step charge cycle and gas recombination microfuel cell, attached to the common gas manifold described in subsection 2.4.1, will be used to minimize pressure buildup within the battery designed for this program.

The NASA-GSFC 24-hour orbit, two-step charge cycle developed to minimize oxygen generation, in general, consists of the following:

- 1) Constant voltage charge at 1.98 volts per cell with a current limit of C/16 to C/24 until the current tapers to C/100. Then ...
- 2) Float charge at 1.87 volts per cell for the remainder of the 23-hour charge period.

This charge cycle is designed to return a state of full charge to a battery that had been discharged to a 60 percent depth of discharge within 1 hour.

A single microfuel cell assembly (References 9 and 10) will be mounted as shown in Figure 5. This microfuel cell will be wicked to a set of auxiliary silver and zinc electrodes. The purpose of the auxiliary electrodes is to provide a mechanism by which the microfuel can be charged without causing a cell imbalance in the five-cell silver-zinc battery.

A Yardney Model HR16(S)-1 silver-zinc cell with a McDonnell-Douglas microfuel cell assembly epoxy bonded to the vent was cycled through the above described two-step charge cycle to acquire information concerning hydrogen and oxygen gas generation rates for the silver-zinc cell and to correlate the microfuel cell's response to the gases generated. The charge voltage was set at 1.98 and 2.00 volts per cell to simulate average cell performance and the performance of a slightly imbalanced cell within a battery. The intent of these cycle tests was to develop data that would be useful in establishing battery design constraints. Table VII and Figures 6, 7, and 8 summarize the data obtained.

There are two points that must be considered when evaluating the results of these cycle tests. First, prior to cycle No. 1 the cell had been discharged to 1 volt and allowed to stand for several days. During this stand period at 1 volt, hydrogen probably was evolved, accounting for the greater amount of hydrogen recombination by the microfuel cell than was observed during subsequent cycles. Second, if the charge voltage is permitted to reach 2.00 volts per cell, simulating an imbalanced cell, considerably greater amounts of oxygen will be generated, as evidenced by the data for cycle No. 2.

2.4.3 Gas Permeable Membrane

A gas permeable membrane will be used between individual cells and the common gas manifold to transmit oxygen and hydrogen gas freely into the manifold, but to inhibit water, or potassium hydroxide solution, transmission. Various gas permeable membranes were evaluated and of the two still being considered, one will be selected for use in the battery. The two membranes are polyethylene film and RAI MPM (microporous plastic material). During preliminary test, the maximum oxygen gas generation rate of a 16 amp-hr silver-zinc cell in low gassing charge-discharge cycling was 1.0 cc/hr/cell. Assuming that silver-zinc cells evolve oxygen in proportion to their ampere-hour capacity, a 12 amp-hr cell could be expected to generate $12/16 \times 1$ cc O₂/hr/cell or 0.8 cc O₂/hr/cell. Hydrogen gas generation rate was negligible relative to the oxygen. The gas permeable membrane must allow oxygen transmission of at least the above rate in order to avoid cell pressure buildup.

TABLE VII. SUMMARY OF MICROFUEL CELL RESPONSE TO THE TWO-STEP CHARGE CYCLING OF A YARDNEY HR16(S)-1 CELL

Cycle Number	Charge Voltage, volts	Charge Current Limit, amperes	Float Voltage, volts	Discharge Current, amperes	End of Discharge Voltage, volts	Total Output of O ₂ Microfuel Cell		Maximum Rate of Recombination in O ₂ Microfuel Cell, cc/hr	Total Output of H ₂ Microfuel Cell		Maximum Rate of Recombination in H ₂ Microfuel Cell, cc/hr
						ma-hr	cc's of O ₂ recombined		ma-hr	cc's of H ₂ recombined	
1	1.98	1.00	1.87	9.6	1.43	5.7	7.7	0.21 ^B	1.7	0.71	0.115 ^{***}
2	2.00	1.00	1.89	9.6	1.42	22.0	46.0	0.89 ^{BB}	0.6	0.25	0.016 ^{***}
3	1.98	1.00	1.87	9.6	1.42	7.6	15.9	0.24 ^{BB}	0.4	0.16	0.012 [*]

^B Occurred at end of discharge

^{BB} Occurred at end of 1.98 volts portion of charge

^{***} Occurred at beginning of charge

2.4.4 Teflonated Negative Plates

Teflon and other polymer materials have been used by manufacturers of zinc and cadmium plates to act as a supportive matrix for the electrochemically active materials. This supportive matrix inhibits the slumping problem normally associated with this type of plate. Several government contracts have led to developments in this area (References 11 and 12). Hughes has elected to use the teflonation process developed by ESB on JPL Contract 951296.

2.4.5 Separator Frames

The separator frame design is shown in Figure 9. These frames will be fabricated of Noryl 731-701. Methods investigated for separator frame fabrication were machining from sheet material, injection molding, and stamping. The two fabrication methods still under consideration are injection molding and machining. Stamping was ruled out because of dimensional instability. Die cut separator laminate will be bonded with epoxy to the frame, thus eliminating the U-fold. The U-fold contributes to the problems listed below:

- 1) The bending of polymer materials causes stressed areas which are potential cell failure points.
- 2) The U-fold interacts with the draft angle present in the cell jar to over compress the separator-electrode core at the bottom of the cell. Further, this interaction causes inadequate compression of the separator-electrode core at the top of the cell. Therefore, a poor separator-plate interface is produced.

It is for the above reasons that this battery will make use of separator frames to eliminate the use of the U-fold.

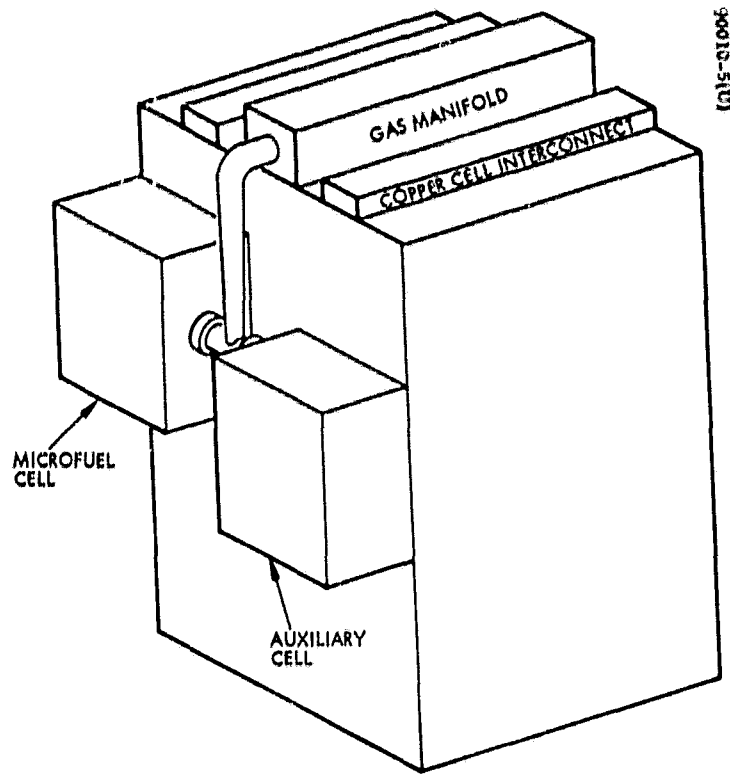


Figure 5. Silver-Zinc Battery Showing Location of Common Gas Manifold, Microfuel Cell Assembly, and Auxiliary Cell

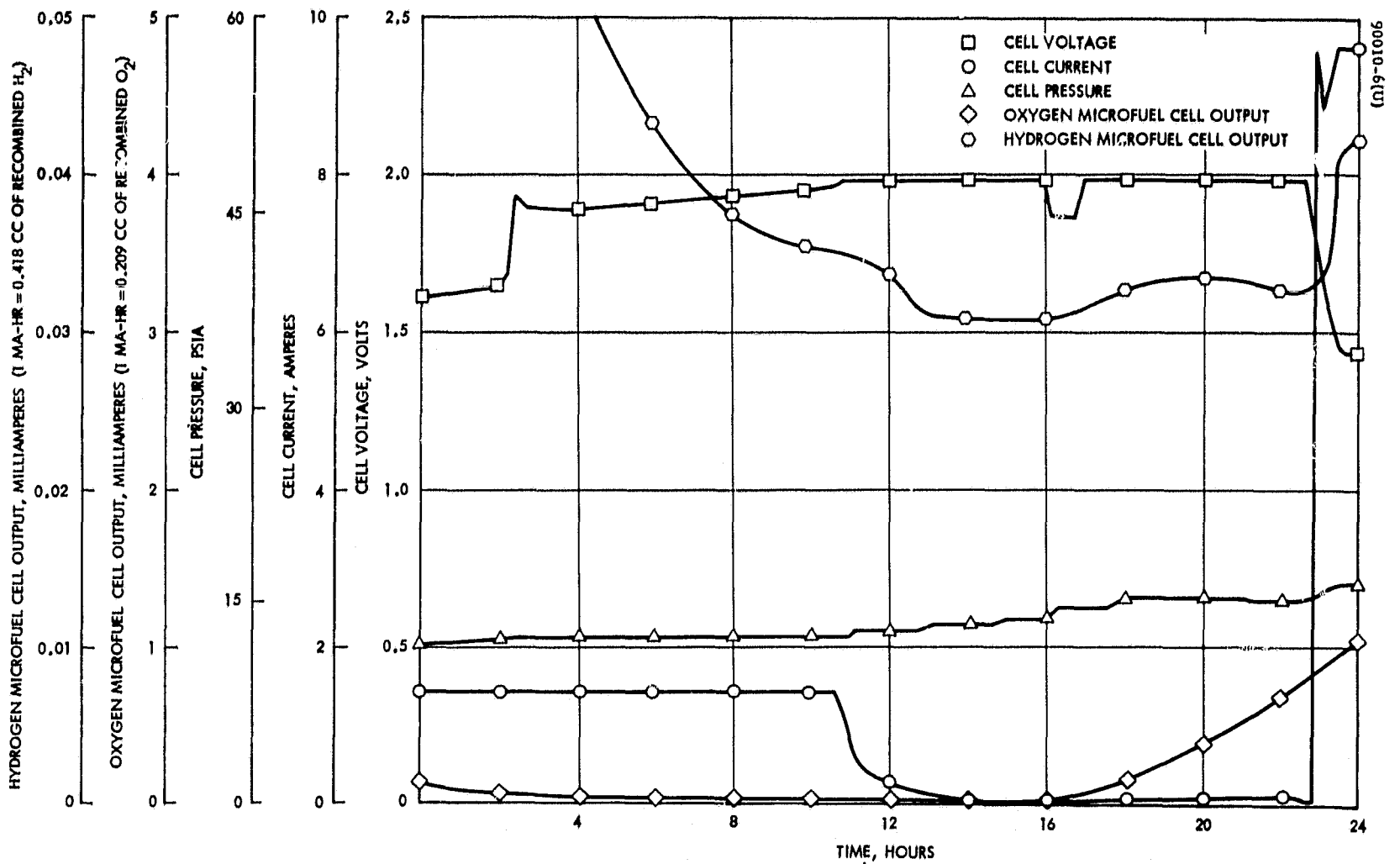


Figure 6. Charge-Discharge Cycle No. 1 of Yardney HR16(S)-1 Silver-Zinc Cell With Microfuel Cell Assembly

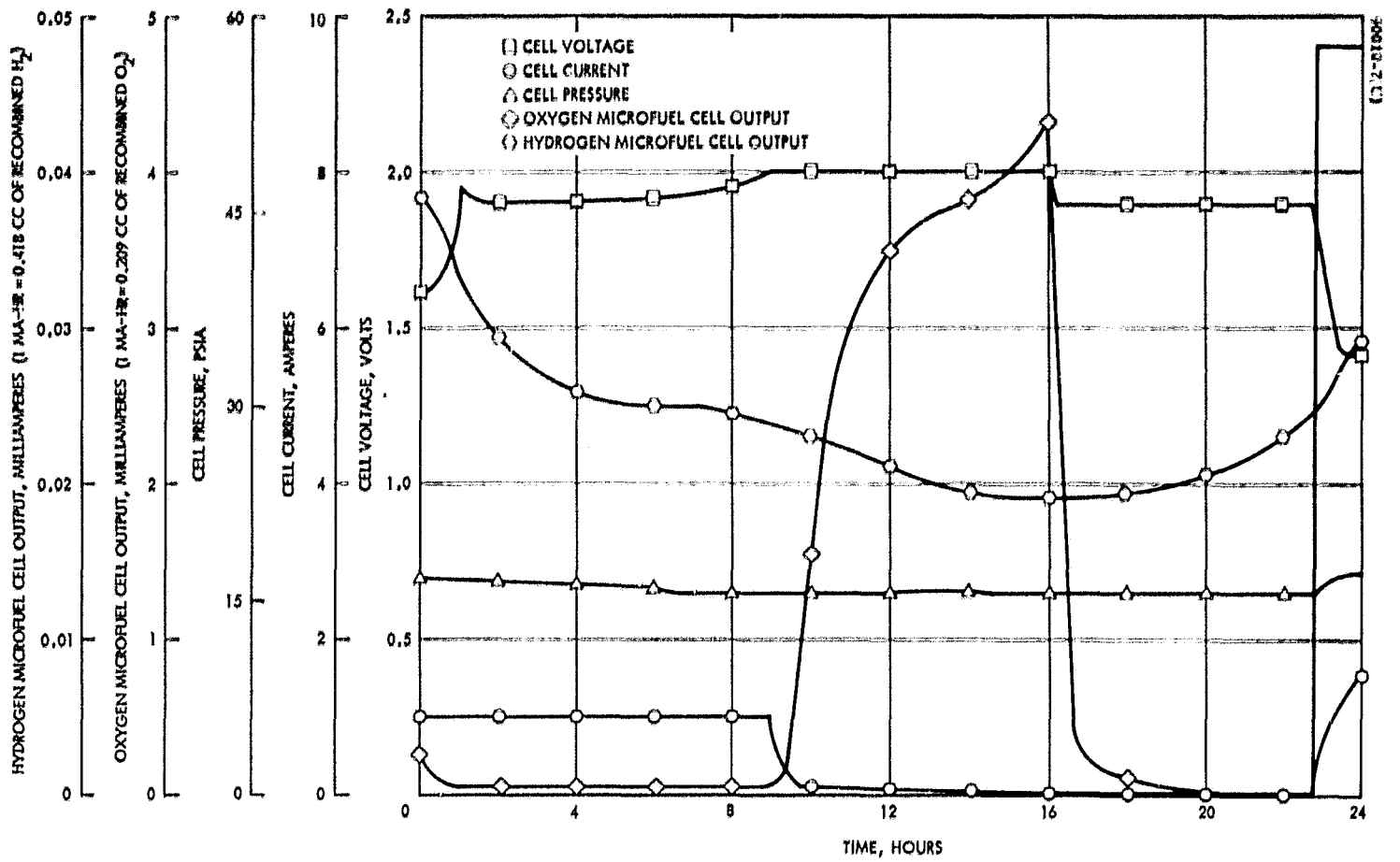


Figure 7. Charge-Discharge Cycle No. 2 of Yardney HR16(S)-1 Silver-Zinc Cell With Microfuel Cell Assembly

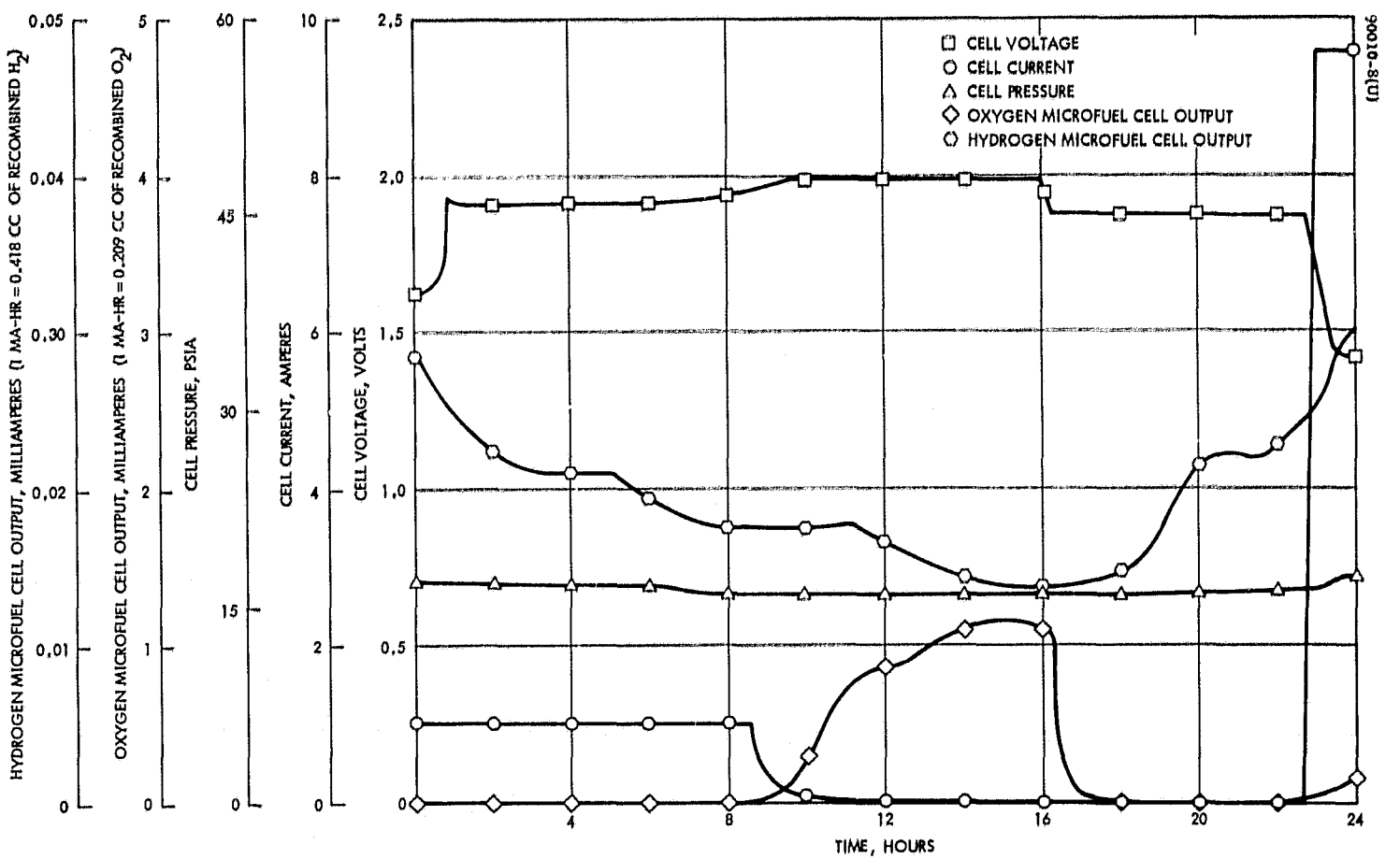


Figure 8. Charge-Discharge Cycle No. 3 of Yardney HR16(S)-1 Silver-Zinc Cell With Microfuel Cell Assembly

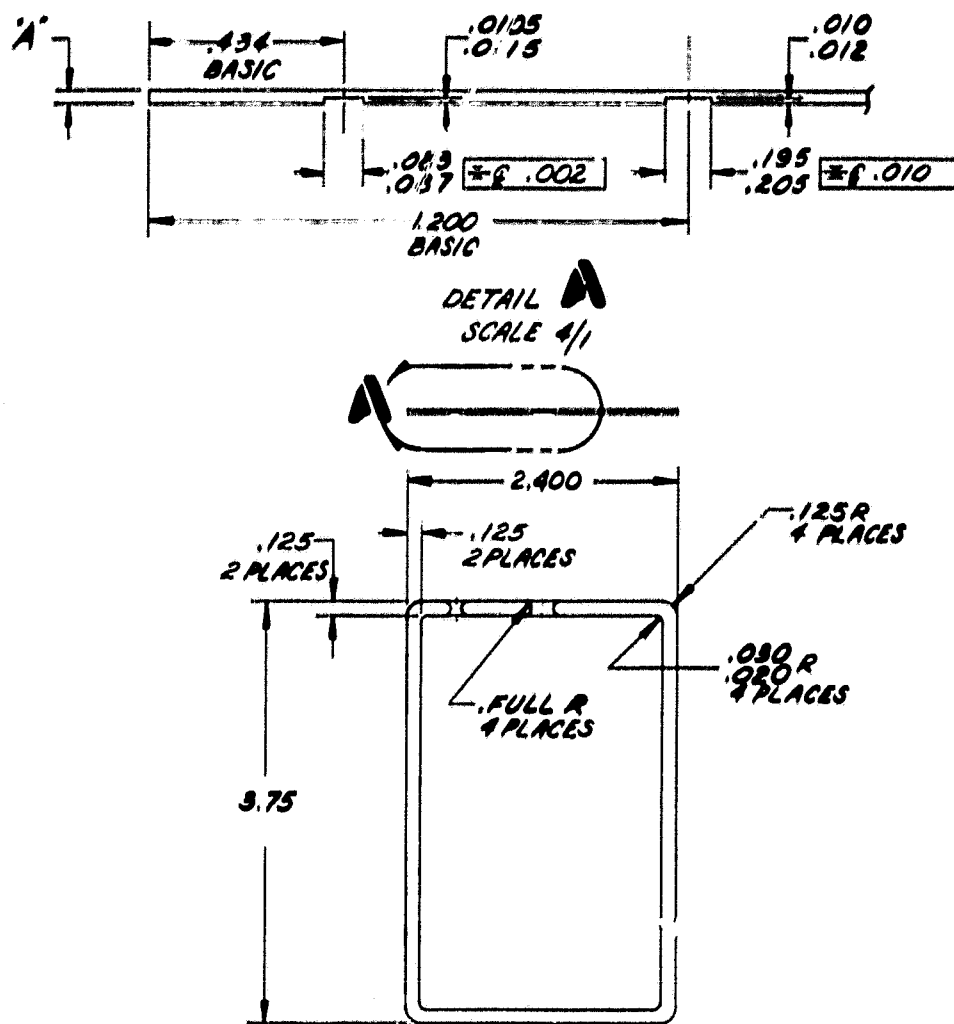


Figure 9. Separator Frame Design

2.4.6 Minimum Interior Draft Angle Case

The normal draft angle in an injection molded cylindrical or rectangular part is in the range of 0.5 to 1 degree. In terms of inches per inch, this amounts to 0.0087 to 0.0175 per side. This draft angle can change, depending upon the mold shrinkage rate of the thermoplastic material, tool design, degree of polish of the tool, the working temperature of the thermoplastic, and many other factors.

The plates to be used for this program are 3.125 inches high. This means that if the standard practice draft angle to facilitate part removal from the mold is used, the plates will be retained by the battery case 0.054 to 0.109 inch more at the bottom of the plate than at the top, considering both jar walls. This, combined with the U-fold separator configuration normally used in silver-zinc cells, causes an inefficient plate-separator interface.

The U-fold will not be used for this battery, as mentioned in subsection 2.4.5. The draft angle presently designed into the case is 0.2 degree, or 0.0035 inch per inch per side. This means that the nonuniformity of the case's interior dimension from the top to the bottom of the plate stack will not exceed:

$$0.0035 \frac{\text{inches}}{\text{inch}} \times 2 \times 3.125 \text{ inches} = 0.0219 \text{ inch}$$

Therefore, a much improved separator-plate interface is anticipated than is normal practice.

2.4.7 Hermetic Sealing

The most difficult type of hermetic seal to design and fabricate is one involving different materials with large differences in thermal expansion coefficients. Unfortunately, this type of seal is usually required in one form or another in any space battery. Glass-to-metal, ceramic-to-metal, and plastic-to-metal seals are the most frequently used types for space batteries. The reason is that one or more cell or battery terminals must be electrically isolated, and at the same time must provide hermetic sealing.

This battery will use plastic-to-metal sealing because of the Noryl thermoplastic package parts. Adhesive bonding of the Noryl case to Noryl cover has been described previously in subsection 2.2.3. Although formalized techniques have been worked out for plastic-to-metal seals (Reference 13), still the most reliable method for producing hermetic space seals (plastic-to-metal) appears to be multiple seals of flexible potting compounds, such as modified epoxies, followed by a massive dose of potting to seal up any pinholes not sealed the first time around. This technique has been used to produce space batteries from vented silver-zinc cells by completely encasing these cells in epoxy.

For this program, individual silver tabs from each silver and zinc plate will be brought up through the top of the battery cover. These tabs then will be locally epoxy potted into their respective cover slots, thus producing a first hermetic seal. Copper interconnects will be staked in place by epoxy at the same time the silver tabs are initially sealed.

All wiring and resistance soldering will be performed before the wiring channels are filled with epoxy to produce a second hermetic seal. The use of these interconnect-wiring channels greatly reduces battery weight without sacrificing seal integrity. Also, eliminating the usual cell terminals negates the need for a seal that would require accommodating the differential linear thermal expansion coefficients for silver metal, 10.9×10^{-6} per °F, and Noryl, 33×10^{-6} per °F.

2.4.8 Cell-Interconnects

The battery cell-interconnects will be slotted plates of OFHC¹ copper designed to match the plate tab holes in the battery cover. The material selection was based primarily on OFHC copper's high electrical conductivity and its compatibility with silver (plate tabs). Also, OFHC copper is readily machined to complex configurations. The battery cell-interconnect thickness was determined by the following computations:

- Assumptions:
- 1) Maximum voltage drop allowable between cells is 1 mv
 - 2) Maximum battery current not to exceed 10 amperes
 - 3) Average distance between cells is 0.5 inch

Symbolism: A = interconnect area
W = interconnect width
 δ = interconnect height

$$R = \frac{1 \text{ mv}}{10 \text{ amp}} = 0.1 \text{ m } \Omega$$

$$R_{\text{Cu}} = \frac{\Omega}{\text{foot}} = \frac{0.001 \Omega \times 12 \text{ inches}}{0.5 \text{ inch} \times \text{foot}} = \frac{0.0024 \Omega}{\text{foot}}$$

¹Oxygen-free high-conductivity copper produced by the U.S. Metals Refining Division of American Metal Climax, Inc.

$$\frac{2.4 \Omega}{10^3 \text{ foot}} \approx 14 \text{ gage}$$

$$A = 0.003225 \text{ in}^2$$

$$\delta = \frac{A}{W} = \frac{0.003225 \text{ in}^2}{0.200 \text{ in}}$$

$$\delta = 0.0161 \text{ inch}$$

Figure 10 illustrates the OFHC copper cell-interconnects and mating silver plate tabs prior to potting and resistance soldering of the assembly.

Several methods were evaluated for joining silver plate tabs to the copper intercell connecting bus. The joining techniques investigated were resistance welding, ultrasonic welding, laser welding, resistance brazing, and soldering. The evaluation of resistance welding of silver to copper indicated that this joining method was unsuitable. Because of the high thermal conductivity of both materials, it was difficult to obtain welds with the required reliability and strength. Ultrasonic welding gives satisfactory results, but additional work is needed because bond strength is less than ideal. Laser welding results have been unsatisfactory because of poor weld strength. Additional work could lead to improved results, but cannot be accommodated on this program. Resistance brazing with Sil-Fos brazing alloy is unacceptable because so far an acceptable braze of the two materials cannot be produced. Resistance soldering using Alpha Solder Cream #890-06 has given the best results. Hughes will use this method to join the silver plate tabs to the copper cell interconnects unless further study uncovers a superior technique within the schedule constraints of this program.

2.4.9 Lightweight Construction

The lightweight objectives of this program have been accomplished by the following three main design innovations:

- 1) The new method of utilizing cell interconnects that gather together all plate tabs directly, thus eliminating the usual heavy cell terminals.
- 2) The use of an injection molded monoblock battery case that provides only one wall thickness of plastic between contiguous cells.
- 3) The use of localized epoxy potting of major hermetic seal areas rather than the use of massive encapsulation.

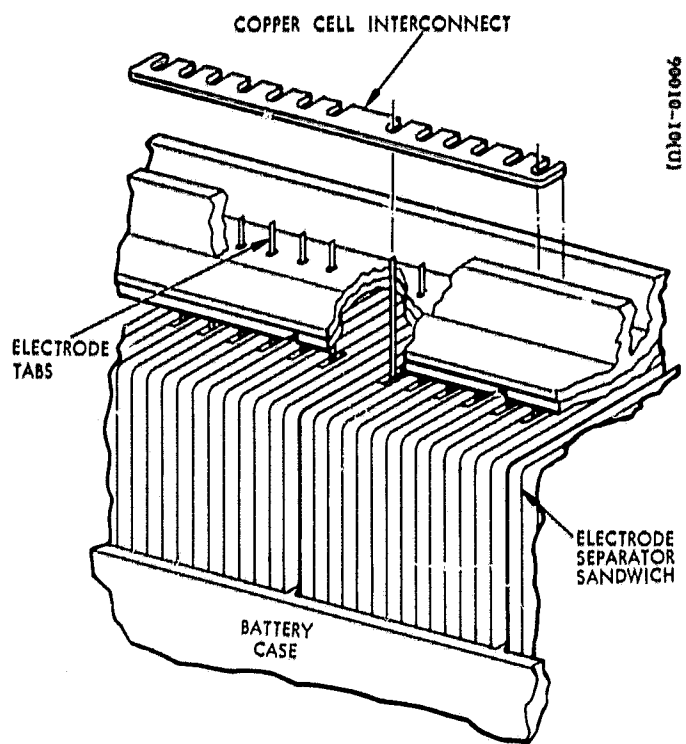


Figure 10. OFHC Copper Interconnects and Silver Plate Tabs

Computations comparing the Hughes designed battery with a model 12 amp-hr silver-zinc battery fabricated from vented cells and then encapsulated in epoxy indicate that a minimum weight savings of 25 percent is realized in this battery design.

2.5 BATTERY ASSEMBLY FABRICATION PROCESS

The major steps of the battery assembly fabrication sequence are:

- 1) Internal battery parts will be assembled into a cell unit. A cell unit will consist of six positive plates, seven negative plates, thirteen separator frames, four or five layers of 2290 separator and one layer of absorber material on each side of every positive plate as required, dependent upon configuration, and a layer of calcium hydroxide on all positive plates, dependent upon configuration. The cell unit will be built up sequentially, starting with a negative plate and a negative plate separator frame with its 2290 separator and absorber. Then, a positive plate with its separator frame, absorber, and separator will be appropriately jiggged for alignment with the negative parts. The positive and negative separator frames will be epoxied together. This sequence continues until the cell unit is complete.
- 2) The cell units will be weighed, checked for shorts, and then put into the battery case. Five cell units are required for each five-cell battery.
- 3) The individual silver tabs providing the electrical connection to individual positive and negative plates will be temporarily placed into comb-type jigs so that these tabs can be aligned with and placed into their respective slots in the battery cover. The cover then will be epoxied to the battery case.
- 4) Each silver tab will be epoxied into its respective slot, providing a first hermetic seal at this point. At the same time, the OFHC copper interconnects also will be epoxied into place.
- 5) Each silver tab will be resistance soldered to its specific location on a copper strip. All instrumentation and power lead wiring will be similarly soldered into place.
- 6) The trough containing the copper interconnects, instrumentation, and power wiring then will be completely filled with epoxy, providing a second hermetic seal.
- 7) The battery electrical connector, auxiliary silver-zinc cell for microfuel cell charging, and the microfuel cell itself, will be epoxied into place.

- 8) If the battery is to be activated, electrolyte will be introduced through the cell ports still accessible in the bottom of the common gas manifold. Formation cycling will be performed in this condition.
- 9) After formation cycling and initial battery cycling, the plugs containing the gas permeable membrane and the cover to the common gas manifold will be epoxied into place.

Two batteries, one of each configuration, will be cycle tested at Hughes according to the NASA-GSFC low gassing charge-discharge procedure. This procedure is briefly described in subsection 2.4.2.

3.0 NEW TECHNOLOGY

The design for connecting the individual plate tabs to the copper inter-connecting bus may be considered new technology. However, most other achievements during this period are either improved versions of existing technology, or the combined use of existing technology.

4.0 PROGRAM FOR NEXT REPORTING PERIOD

The program for the next 4 months is to fabricate six batteries of the design described in this report.

5.0 CONCLUSIONS AND RECOMMENDATIONS

All conclusions and recommendations will be deferred until the next report.

6.0 REFERENCES

1. G. W. Bodamer, Heat Sterilizable, Impact Resistant Cell Development, Jet Propulsion Laboratory Contract No. 951296, Interim Summary Report, 24 September 1965 to 30 September 1967, ESB Incorporated.
2. Personal Conversations with R. A. Dunaetz, Hughes Materials Technology Laboratory, July to October 1968.
3. M. Sulkes, Development of The Sealed Zinc-Silver Oxide Secondary Battery System, ECOM 02238-F, Contract DA 36-039-AMC-02238E, July 1966.
4. J. Lander, Unpublished Paper Presented at The Electrochemical Society Symposium on Silver-Zinc Batteries, Montreal, Canada, October 1968.
5. J. J. Kelley and J. Szymborski, Alkaline Battery Separator Characterization Studies, NAS 5-10418.
First Quarterly Report, May 1967 to August 1967.
Second Quarterly Report, August 1967 to November 1967.
Third Quarterly Report, November 1967 to February 1968.
Fourth Quarterly Report, March 1968 to June 1968.
6. W. N. Carson, Jr. and J. G. Consiglio, Electrodeposited Inorganic Separators, Final Report - August 1966, NAS 5-9168.
7. R. P. Hamlen, J. M. McQuade and E. G. Siwek, Silver-Zinc Cells with Electrolytically Deposited Calcium Hydroxide Separators, Electrochemical Technology, Volume 6, Pp. 1-2, January-February 1968.
8. E. K. Woomey, Performance of Cells Containing Plates Coated with Calcium Hydroxide Film, ESB Incorporated, Raleigh, N. C., Internal Report No. E-26-68, 6 August 1968.
9. H. Frank and M. P. Strier, Small Fuel Cell to Eliminate Pressure Caused by Gassing in High Energy Density Batteries, Final Report, 30 June 1965 to 30 June 1966, NAS 5-9594.

10. M. P. Strier, Sealing of Silver Oxide-Zinc Storage Cells, NAS 5-10409.
First Quarterly Report, June 1967 to September 1967.
Second Quarterly Report, September 1967 to December 1967.
Third Quarterly Report, December 1967 to March 1968.
11. J. Goodkin, Long Life Stable Zinc Electrode for Alkaline Secondary Battery, DAAB 07-67-C-0185, First through Fifth Quarterly Reports, 31 March 1967 through 31 September 1968.
12. A. Charkey and R. Seremji, Integration of Improvements in Silver-Cadmium Electrochemical Cells, August 1968, NAS 5-10238.
13. W. R. Scott, Jr., A Study of the State-of-the-Art of Hermetic Seals for Secondary Alkaline Spacecraft Cells, Final Report, 20 June 1967 to 20 March 1968, NAS 5-10432.

APPENDIX I, RESULTS OF LAP SHEAR AND BUTT TENSILE TESTS

TABLE I-1. LAP SHEAR STRENGTHS OF BONDED SPECIMENS
Approximately 0.5-inch Overlap

Plastic	Adhesive	Average Shear Strength, psi	Remarks
Noryl	Epiphen 825A	580	
	Armstrong A-12	264	
	Bondmaster M-611	431	
Polyphenylene oxide	825A	438	
	A-12	226	
	M-611	350	
Polysulfone	825A	726	Bonds intact; plastic broke in all specimens
	A-12	700	Bonds intact; plastic broke in all specimens
	M-611	373	

TABLE I-2. BUTT TENSILE STRENGTHS OF BONDED SPECIMEN

Plastic	Adhesive	Average Tensile Strength, psi	Remarks
Noryl	825A	1705	Large value scatter
	A-12	1460	
	M-611	1065	Large value scatter
Polyphenylene oxide	825A	1845	Large value scatter
	A-12	1635	
	M-611	1570	
Polysulfone	825A	2190	Large value scatter
	A-12	1570	Large value scatter
	M-611	1550	Large value scatter

TABLE I-3. LAP SHEAR STRENGTHS OF BONDED SPECIMENS
AFTER EXPOSURE TO KOH

Approximately 0.5-inch Overlap

Plastic	Adhesive	Average Shear Strength, psi	Remarks
Noryl	825A	677	All specimens broke in parent material. No visible signs of bond deterioration
	A-12	184	No visible signs of bond deterioration
	M-611	420	No visible signs of bond deterioration
Polyphenylene oxide	825A	370	No visible signs of bond deterioration
	A-12	315	No visible signs of bond deterioration
	M-611	420	No visible signs of bond deterioration
Polysulfone	825A	375	One specimen broke in parent material. No visible deterioration
	M-611	425	Two specimens broke in parent material. No visible deterioration
	A-12	1156	All specimens failed in parent material

TABLE I-4. BUTT TENSILE STRENGTHS OF BONDED SPECIMENS AFTER EXPOSURE TO KOH

Plastic	Adhesive	Average Tensile Strength, psi	Remarks
Noryl	825A	1190	No visible deterioration
	A-12	1150	No visible deterioration
	M-611	1900	No visible deterioration
Polyphenylene	825A	1570	Material was quite thick (~0.5 inch). One specimen failed in jaws of testing machine. No visible deterioration
	A-12	303	Evidence of poor adhesion
	M-611	1980	No visible deterioration
Polysulfone	825A	2320	No visible deterioration
	A-12	1700	One specimen broke in loading
	M-611	2640	

TABLE I-5. BUTT TENSILE STRENGTH OF HOT GAS WELDED SPECIMENS

Plastic	Average Tensile Strength, psi	Remarks
Noryl	1970	Broke in weld
Polyphenylene oxide	1090	Broke in weld
Polysulfone	730	Broke in weld

TABLE I-6. LAP SHEAR AND BUTT TENSILE STRENGTHS OF SOLVENT BONDED SPECIMENS

Plastic	Average Shear Strength, psi	Average Tensile Strength, psi	Remarks
Noryl	784	2164	
Polyphenylene oxide	711	1401	One shear specimen broke in parent material
Polysulfone	1242	2773	All shear specimens broke in parent material

TABLE I-7. LAP SHEAR AND BUTT TENSILE STRENGTHS OF SOLVENT BONDED SPECIMENS AFTER EXPOSURE TO KOH

Plastic	Average Shear Strength, psi	Average Tensile Strength, psi	Remarks
Noryl	669	2400	One shear specimen broke in parent material
Polyphenylene oxide	767	1227	
Polysulfone	977	1660	Two shear specimens broke in parent material

TABLE I-8. LAP SHEAR AND BUTT TENSILE STRENGTHS OF ULTRASONIC BONDED SPECIMENS

Plastic	Average Shear Strength, psi	Average Tensile Strength, psi	Remarks
Noryl	3180	1890	Large scatter in the tensile values
Polyphenylene oxide	5140	2520	
Polysulfone	2820	2420	

TABLE I-9. LAP SHEAR AND BUTT TENSILE STRENGTHS OF
ULTRASONIC BONDED SPECIMENS AFTER KOH EXPOSURE

Plastic	Average Shear Strength, psi	Average Tensile Strength, psi	Remarks
Noryl	1680	3330	All shear specimens broke in parent material
Polyphenylene oxide	2710	2400	All shear specimens broke in parent material
Polysulfone	1667	2490	All shear specimens broke in parent material