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DEVELOPMENT OF CALORIMETER FOR SPACECRAFT BATTERIES

W. V. Johnston

Rocketdyne
A Division of North American Rockwell
6633 Canoga Avenue
Canoga Park, California 91304

April 1971

FINAL REPORT

Prepared For

GODDARD SPACE FLIGHT CENTER
Greenbelt, Maryland 20771

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16. Abstract

A conduction heat flow calorimeter for use in measuring the thermal output of 100 ampere-hour and 20 ampere-hour sealed nickel-cadmium cell has been designed and constructed. The unit has been installed and calibrated at NASA-Goddard Space Flight Center.

The heat flow calorimeter is composed essentially of a pressurized vessel, thermally isolated from its surroundings in all directions but one, a heat sink maintained at a constant temperature considerably lower than that of the calorimeter, and a copper conductor connecting the two. A heater winding in the calorimeter near the junction with the conductor is supplied with sufficient power to automatically maintain the calorimeter at a constant temperature. Thermal effects taking place in the calorimeter are equal to the adjustments in power required to maintain the thermal head. A wattmeter, accurate and precise to 0.2%, measures the power changes. The calorimeter will measure a heat flow of 30 watts with a resolution of 0.01 watts. The calorimeter operates over a temperature of -10 C to 40 C. The results of cycling 20 A-H and 100 A-H nickel-cadmium cells are included.

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PREFACE

This report describes a seven-month program sponsored by NASA-Goddard Space Flight Center to design, construct, and test a calorimeter capable of measuring the thermal output of 20 ampere hour and 100 ampere hour sealed nickel-cadmium cells while experiencing simulated spacecraft load cycling. The design objectives were met and the calorimeter has been installed at NASA-Goddard. The Contract No. was NAS5-21514. The technical monitor for this contract was Mr. William H. Webster, Jr.

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FIGURES

INTRODUCTION

Several anticipated satellite launching programs require a knowledge of the heat generated by different types of nickel-cadmium batteries during charge-discharge cycles. The information will be used to help optimize radiator and heat exchanger designs in the satellites. Since the mechanisms of the reactions in nickel-cadmium cells during charge and discharge are not well defined, it is impossible to make theoretical predictions of heat effects resulting therefrom, and it is necessary to determine the values experimentally. However, the nature of the calorimetry required to obtain the information that is required is somewhat unusual in that it is necessary to measure the heats over a succession of charge-discharge cycles, and the heat generation is expected to be relatively large. Conventional calorimetric techniques, adiabatic or isoperibolic, cannot be applied, and apparatus unique to the needs of the satellite program was designed and constructed. This program is concerned with the design, construction, and delivery of the appropriate calorimetric apparatus.

The specific objectives of this program are the design of a calorimeter capable of measuring the thermal output of sealed nickel-cadmium cells of 20 and 100 ampere-hour (A-H) capacity. The calorimeter must be capable of measuring thermal effects of at least 25 watts when used with the 100 A-H cell and at least 5 watts when used with the 20 A-H cell. The calorimeter must measure the thermal output of each cell with 3% accuracy and 1% resolution over a temperature range between -10 C and +40 C. The response to a change of thermal output must not exceed five minutes and the instrument must remain stable to at least 1% of the thermal capacity of the calorimeter over a 24-hour period. The calorimeter must also permit currents of at least 50 amperes to flow through the cells being measured.

These objectives were met and the calorimeter has been installed and accepted at NASA-Goddard Space Flight Center.

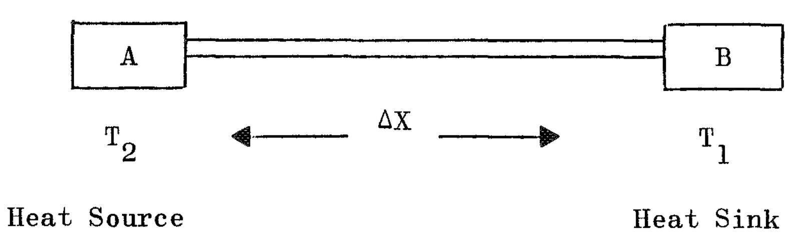
THEORY

After consideration of a number of types of calorimeters, the design which appeared to be most suitable, based on the criteria of sensitivity, versatility, ease and rapidity of construction, and cost, was a conduction heat flow calorimeter.

A heat flow calorimeter is designed so that the thermal leakage modulus is as high as possible. It may be operated totally isothermally or under conditions very close to isothermicity. In our design, a constant thermal head is established between an electrically heated calorimeter and an isothermal heat sink; the change in heater power needed to maintain this head gives a direct measure of the heat evolved or absorbed within the calorimeter. This approach is similar in principle to the substitution method used on modern analytical balances.

The heat flow calorimeter constructed is composed essentially of a calorimeter vessel, thermally isolated from its surroundings in all directions but one, a heat sink maintained at a constant temperature considerably lower than that of the calorimeter, and a copper conductor connecting the two. A heater winding in the calorimeter near the junction with the conductor and the calorimeter is supplied with sufficient power automatically to maintain the calorimeter at a constant temperature. Thermal effects taking place in the calorimeter will result in an adjustment in power required to maintain the thermal head. These changes in power level are equal to the heat liberated or absorbed in the calorimeter.

Schematically, the method can be analyzed as follows:



The equation (Ref. 1) for steady state heat flow (W_T) in a rod of constant cross sectional area between two bodies, A and B, one acting as a heat source at T_2 and the other as a heat sink at T_1, and with no heat exchange along ΔX, is

$$W_T = k A \frac{T_2 - T_1}{\Delta X} \tag{1}$$

where A is the cross sectional area normal to the direction of heat flow, and k is the mean thermal conductivity between T_2 and T_1, and ΔX is the distance between the heat source and the heat sink. At any location along the rod connecting the source and sink, the law of heat exchange (heat in = heat out) must be obeyed. This principle may be applied in a heat flow calorimeter in the following manner: Let A be a calorimeter, surrounded by an adiabatic jacket so that no heat is exchanged with the surroundings except through the solid conductor, and W_A be the amount of heat which must be supplied to maintain the temperature T_2. The heat sink (T_1) might be a liquid at its boiling point where its heat vaporization serves to hold temperature constant.

$$\text{At steady state } W_A = W_T \tag{2}$$

The total input power (W_A) can be considered to be made up of a number of components, W_E, W_B, W_L, and W_C (all of which may not be applicable at one time).

where:

W_E = head added electrically to maintain T_2 constant

W_B = heat evolved (or absorbed) by the cell being studied

W_L = heat input or loss due to heat leakage with the surroundings

W_C = heat introduced by a calibration heater

Since W_A is a constant as long as the thermal head is maintained, heat evolved or absorbed by the battery is compensated by changes in the electrical input (W_E). It is not necessary that W_L be known as long as it is constant.

DESCRIPTION OF THE CALORIMETER

GENERAL DESCRIPTION

The calorimeter comprises three main units: an upper portion which surrounds the calorimetric unit with an adiabatic shield and vacuum jacket; the calorimetric unit consisting principally of a pressurized shell, a cell support structure, and a copper rod, which conducts the heat from the calorimetric unit to a finned surface immersed in boiling liquid nitrogen; and a lower unit which surrounds the copper rod and minimizes its heat exchange with the surroundings.

CALORIMETER VESSEL

Physical Description

The calorimeter is sized to contain cells whose maximum body dimensions are 7.56 inches square by 2.25 inches thick. If the terminals are both on the same side, the total length may be 8.125 inches. Cells with opposing terminals may be a maximum of 8.75 inches end to end. Sealed nickel-cadmium cells generate gas during charging which requires that the sides of the cell be restrained in some manner to prevent their bowing out. The normal precedure is to clamp the cell between heavy steel or aluminum plates during charging operations. During the design phase of this program, it was determined that the mass of the constraining plates might seriously reduce the sensitivity of the calorimeter, and alternative methods for restraining the cell were sought. The solution was found in making the calorimeter a pressure vessel and pressurizing it to 60 psi. This pressure is sufficient to exceed the pressure buildup within the cell and keep the sides of the cell from bowing out.

Pressure Vessel

The outer shell of the calorimetric unit serves as the pressure vessel and is in the form of an oblate spheroid formed from two aluminum alloy dishes joined at the equator by a flange containing an "O" ring seal. Figure 1 is a photograph of the outer shell. The diameter of the dish is 12 inches and the height of each half is 3 inches. The diameter of the flange is thirteen and 1/8 inches. A groove for a Parker No. 2-278 "O" ring is machined in the flange of the lower half shell. The shell is made of 0.050 inch 6061-T6 aluminum alloy and is designed to operate under a five atmosphere pressure differential. The wall thickness required, as calculated by the Boiler and Pressure Vessel Code of the ASME assuming a 20 KSI yield strength, is only 0.022 inches. The "O" ring flanges are also made of 6061-T6 aluminum alloy. Thirty-six 10-32 machine screws on a 12-11/16 inch bolt circle join the two halves. The external surfaces of the

Figure 1. Photograph of Pressure Shell

shell were polished and electroplated with gold over a nickel undercoat. A 3/4 inch diameter opening in the bottom half shell, provided for the heat conducting rod and electrical leads to pass out of the pressure vessel. The opening is sealed with an "O" ring compression seal and fastened with 8-32 machine screws on a 1-3/32 inch bolt circle. Details of the passthrough are contained in a later section. A stainless steel needle valve used for filling and pressurizing the vessel is located on the flange. See Fig. 2 for details.

Calorimetric Unit

Inside the shell is a calorimetric unit consisting of a square tray of silver which contains the cell under test, a cell support platform, and an electrode which is separated electrically from the tray by a sheet of 0.0025 inch thick MYLAR. Below the cell support platform, and silver soldered to it, is a silver casting. This casting is silver soldered to the copper rod which conducts the heat to the heat sink in the liquid nitrogen bath at the bottom of the calorimeter.

Each of the components described, except the tray, is formed from two halves which are joined together at the center line with epoxy, with a piece of

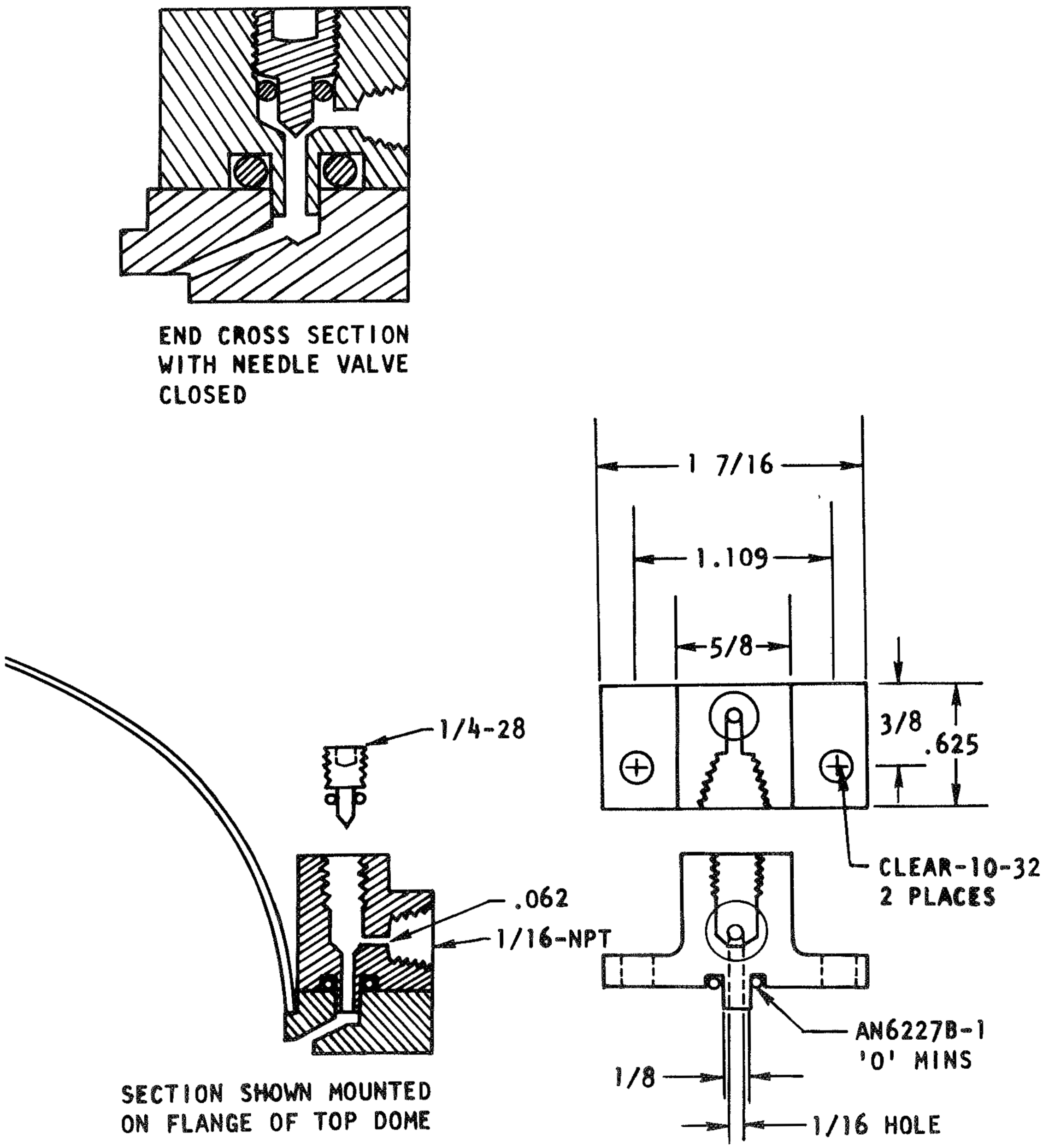
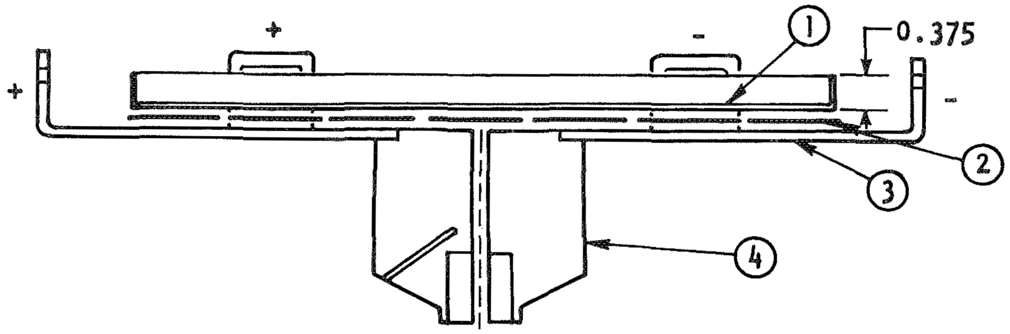


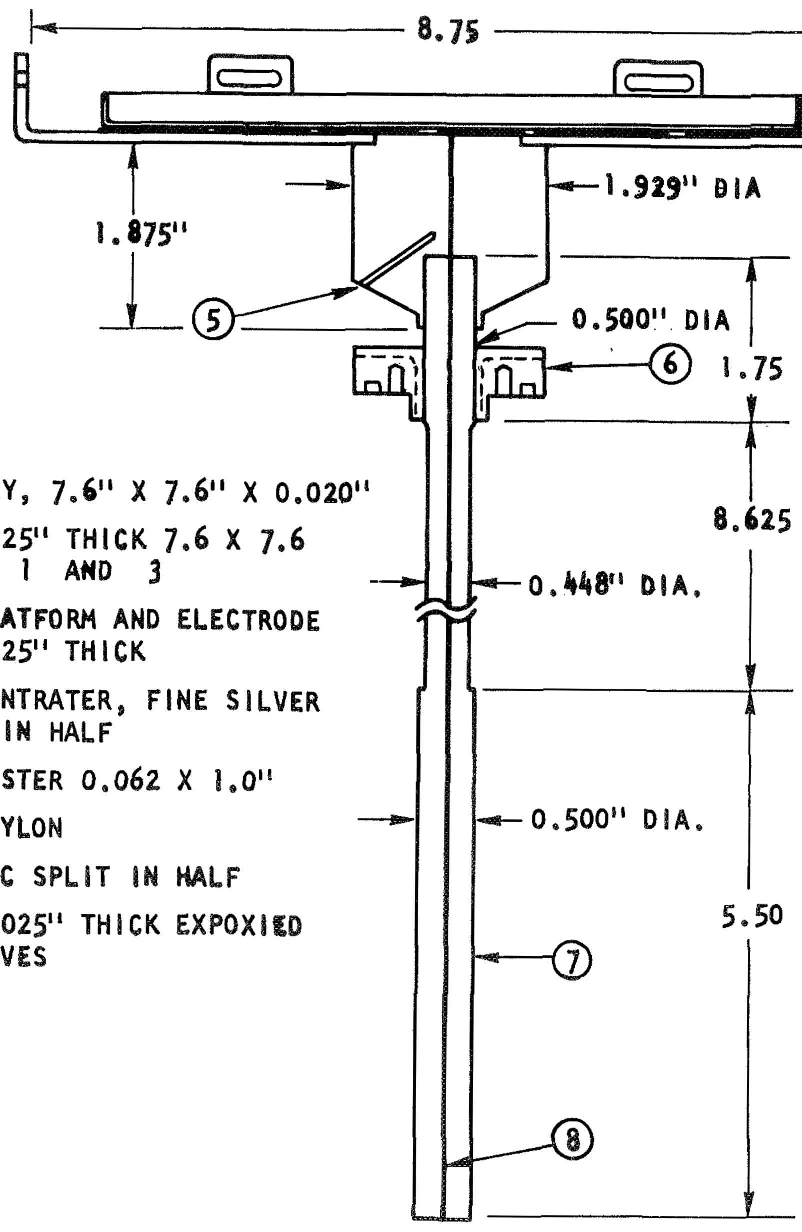
Figure 2. Design of Pressurization Valve

MYLAR in between. This was done so that the copper rod-support platform can be used to carry the current for cycling the cells. One half serves as the positive conductor and the other half is the negative conductor. Figure 3 is a cross section of the calorimetric unit showing the pertinent dimensions. Figure 4 is a quarter section cutaway view of the calorimeter which shows the calorimetric unit in perspective with the remainder of the calorimeter.

The cell support platform measures 7.212 inches on a side and is made in two halves from fine silver plate 0.125 inches thick. The cell platform halves serve as electrical conductors and have tabs to bring the battery charging current to the cell electrodes. The tabs 0.875 inches wide are formed from the same sheet of silver by extending the sheet out one inch and bending upward to 0.875 inch. A slot is milled into the tab to accept a No. 10 bolt for attachment to the cell electrode. Two such slots are located 4.25 inches in centers at one end of the platform for use with cells having both electrodes at the same end. Tabs are located in the centerline of the opposite sides of the platform to be used with cells having opposing electrodes. One tab of each type is located on each half of the platform.



DETAIL OF ELECTRODE INSULATION



1. FINE SILVER TRAY, 7.6" X 7.6" X 0.020"
2. MYLAR FILM 0.0025" THICK 7.6 X 7.6 EPOXIED BETWEEN 1 AND 3
3. CELL SUPPORT PLATFORM AND ELECTRODE FINE SILVER 0.125" THICK
4. HEAT FLOW CONCENTRATER, FINE SILVER CASTING, SPLIT IN HALF
5. WELL FOR THERMISTER 0.062 X 1.0"
6. PASS THROUGH, NYLON
7. COPPER ROD, OFHC SPLIT IN HALF
8. MYLAR FILM 0.00025" THICK EXPOXIED BETWEEN ROD HALVES

Figure 3. Calorimetric Unit

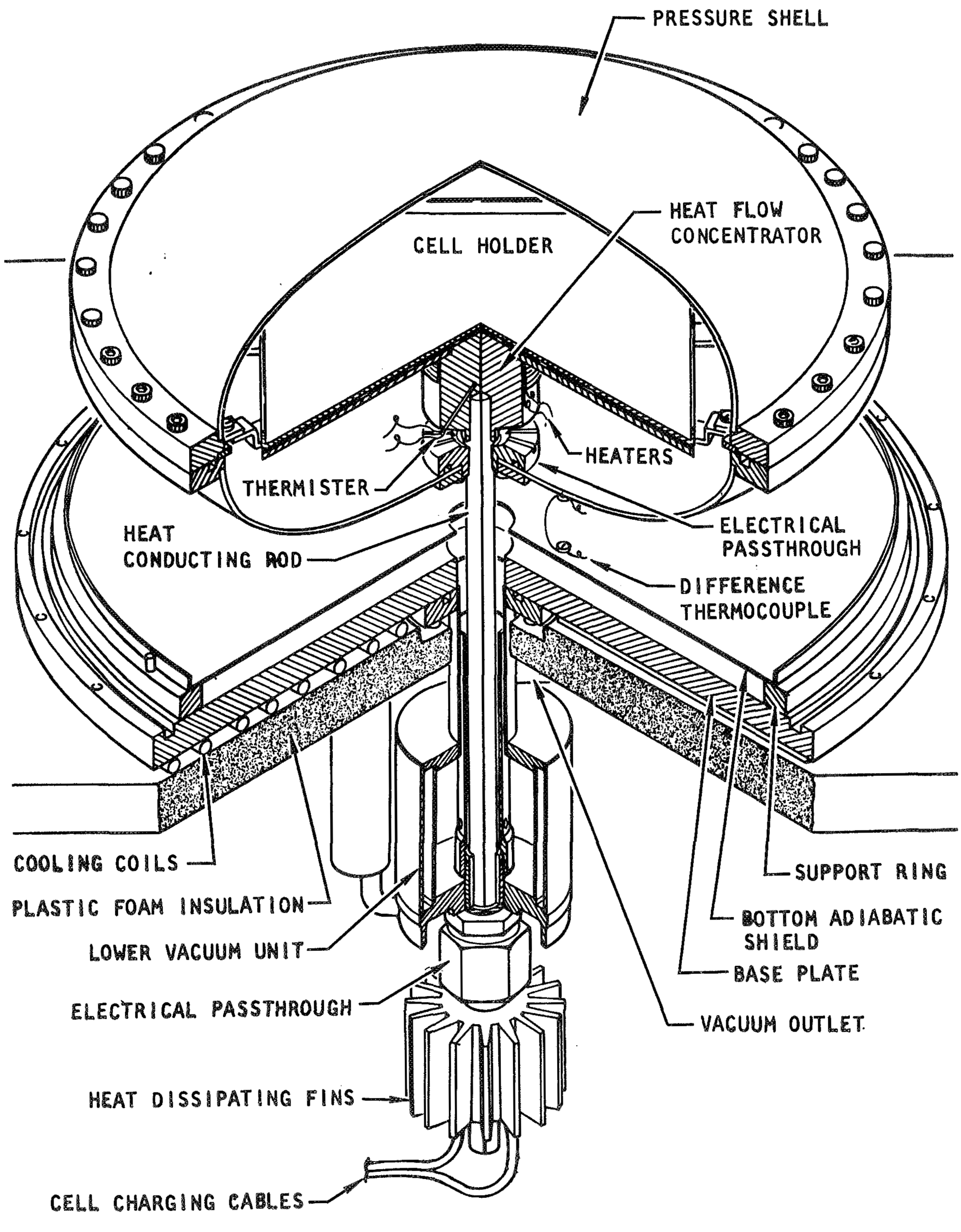


Figure 4. Quarter Section Drawing of Calorimeter

Located directly below the support platform, and extending up through a 1.50 inch hole in it, is a split silver cylinder 1.929 inches in diameter and two inches long which tapers to 0.625 inches diameter at the bottom. This cylinder serves as a funnel for the heat flow from the support platform to the copper heat conduction rod. The main control heater and the calibration heater are located in the top quarter of an inch and the thermister is located in a well near the bottom (see Fig. 4). The cylinder was made by casting an oversize cylinder, cutting it in half, and soft soldering the two halves together. The joined halves were machined to final size and separated by melting the solder. Each half cylinder was silver soldered to one of the halves of the cell support plate. The copper heat conduction rod was formed by soldering the two half sections, machining to final dimensions, and separating the finished halves by melting the soft solder. The copper half cylinders were then joined to the silver half cylinders with silver solder. The flat sides of the half cylinders were cleaned of all burrs and lapped until smooth. The metal surfaces were then given a thin coat of DC 991 Silicone Varnish, coated with an epoxy made of a 50-50 weight percent mixture of Shell Epon 828 and Versamid 125, and joined together after a sheet of 0.00025 inch thick MYLAR was inserted between them. The pieces were clamped together and cured for three days. The insulation resistance between the joined pieces was greater than 20 megohms.

The diameter and length of the heat conduction rod were designed to provide a heat flow of about 31 watts. The heat conduction rod, after leaving the calorimeter vessel, passes through an opening in the adiabatic shield, through a Conax Model EGT-500 low temperature electrical insulating seal at the bottom of the lower unit, and enters a liquid nitrogen bath where it dissipates its heat through fins. Two half cylinders of one and a half inch diameter copper, two inches long, containing nine 5/8-inch long fins are clamped to the lower two inches of the copper rod with 8-32 machine screws insulated from the opposing cylinder with nylon sleeves. The electrical connection for the battery charging circuit are made at 8-32 tapped holes in the bottom of the half cylinders. The Conax seal is of Teflon and, because Teflon has a low temperature transition which causes a contraction, it is necessary to remove the liquid nitrogen bath and retighten the seal after each cooldown from room temperature.

Sitting on the cell support platform, and separated from it by an epoxy and MYLAR joint made in the same manner as described previously, is a silver tray 7.6 inches on a side and made of 0.020 inch sheet. The cell being tested lies flat on the tray. A small amount of silicone oil on the tray is used to enhance thermal contact between the cell and the tray. The thin layer of MYLAR and epoxy effectively insulates the tray electrically from the voltage on the cell support structure but hinders heat flow only slightly because of the large contact area. The photograph of Fig. 5 shows this tray and the interior of the calorimeter.

The calorimetric unit is supported in the calorimeter by four brackets of 0.125 inch silver which are soldered to the cell support structure near the corners. The brackets are fastened with nylon bolts to tabs on an aluminum ring which rests in a recess machined from the inner edge of the upper and lower flanges. Teflon tape with an adhesive backing is used to provide electrical insulation between the tabs and the brackets.

A nylon electrical passthrough is located at the bottom of the lower half of the pressure vessel. The passthrough is attached permanently to the copper conduction rod with epoxy and may be considered a part of the calorimetric unit. Sixteen electrical leads are brought out of the calorimeter through this passthrough. The leads are located in a 0.625 inch diameter circle closely surrounding the copper rod. The leads for the heaters are B&S #20 copper conductor to reduce self heating and the remainder are Amphenol No. 220-S01 female Micro-Miniature Poke-Home Contacts. Identical contacts are provided in the inside of the passthrough so that removal or change of wiring is facilitated. The contacts are imbedded in epoxy. Gas leakage is prevented by an "O" ring seal between the passthrough and the

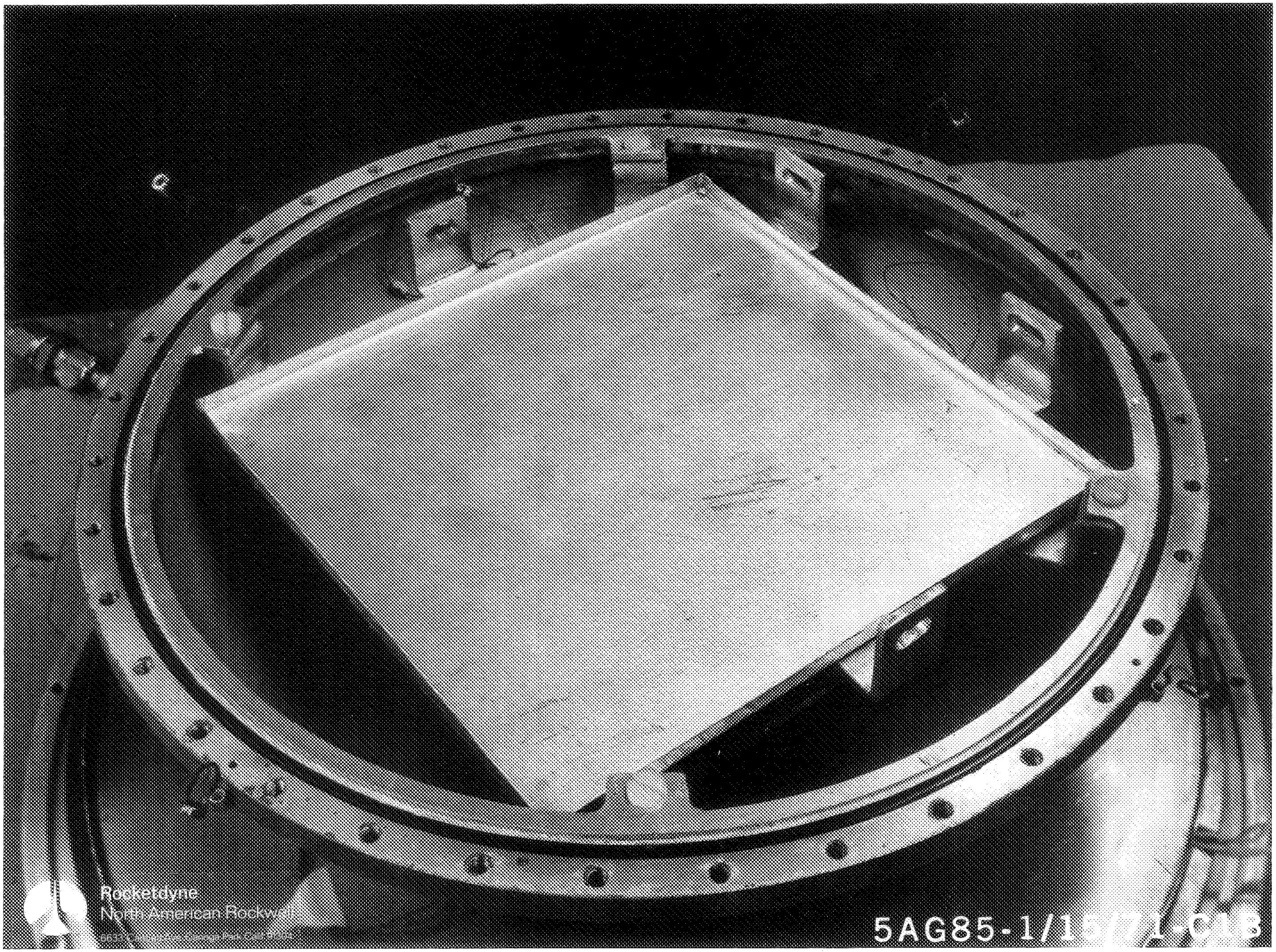


Figure 5. View of Open Calorimeter

pressure vessel. A groove for the AN 6227-25 "0" ring is machined in the nylon part. An aluminum backing ring is used on the outside of the pressure vessel so that tightening six 8-32 machine screws provides a uniform clamping pressure between the pressure vessel and the "0" ring. All components of the pressure vessel were checked for leaks with a helium mass spectrometer type leak detector.

Thermal Design

The sensitivity and response time of the calorimeter depend on the thermal mass of the calorimeter and the thermal diffusivity of the materials of construction*. 6061-T6 aluminum alloy and fine silver are used throughout the calorimeter to reduce thermal gradients and to reduce the time constant. Aluminum has about the same thermal mass/cc of metal as silver, but its thermal conductivity is half that of silver. The thermal mass for the empty calorimeter is calculated to be approximately 350 cal/deg. The details of the calculation may be found in the report of the design study phase of this program (Ref. 2).

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* The sensitivity of the calorimeter is equal to the minimum amount of heat that can be added to the calorimeter before the resulting rise in temperature can be detected.

ADIABATIC SHIELD

The calorimeter is surrounded by an adiabatic shield of copper. The shield consists of a 14-inch cylinder of 0.065 inch wall thickness and top and bottom plates of 0.125 inch thickness. A thin wash of gold is electroplated to the inner surfaces to provide a reproducible and tarnish resistant surface of low emmisivity. The calorimeter is supported in four places by 20 pound test nylon fish line with an adjustable swivel connected to a ring located near the top of the cylindrical shield. Separate heating elements of 100 watts rating each were cemented to the top, side and bottom surfaces of the adiabatic shield. The heating elements are made of resistance wire wound non-conductively and surrounded by a thin sheet of silicon rubber. The heaters were custom made by Electrofilm, Inc.** The top and bottom are their part No. 112057-B. The side heater is part No. 112241. The mass to be controlled is matched to the heater windings so that equal power input will result in nearly constant surface temperatures. Copper-constantan difference thermocouples are connected between the calorimeter and the top, side, and bottom of the adiabatic shield to sense temperature differences which will be corrected by the shield heaters*. The adiabatic shield is supported above the base plate

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* The thermocouples are electrically insulated from the contact surfaces.
** Electrofilm, Inc., 7116 Laurel Canyon, North Hollywood, Calif. 91605

by a ring of Micarta resin impregnated fabric. A photograph of the calorimeter surrounded by a portion of the adiabatic shield is shown in Fig. 6.

VACUUM CHAMBER AND OUTER JACKET

The calorimeter vessel and adiabatic shield are surrounded by a 0.125 inch thick aluninum cylinder 16 inches in diameter which serves as a vacuum jacket. The top and bottom plates of 6061 aluminum alloy are 0.50 inch thick. The top and bottom plates are fastened to the cylinder by six 8-32 machine screws. Grooves in the top and bottom plates contain the 2-278 size "0" rings used to affect the vacuum seal. Aluminum cooling coils are soldered on the top, side, and baseplate to provide a means of cooling the chamber. The outside of the vacuum jacket is insulated with a 2-1/2 inch thick layer of low density polurethane foam obtained by stacking 24 inch rectangles of the foam with a sixteen inch center hole.

The lower vacuum unit is a double walled cylinder of 0.015-0.020 inch thick stainless steel which provides a vacuum around the heat conducting rod. Additional protection from changes in radiative heat exchange are provided by a 6-inch long brass cylinder which is threaded into the bottom of the lower unit and extends upward to the vicinity of the base plate.

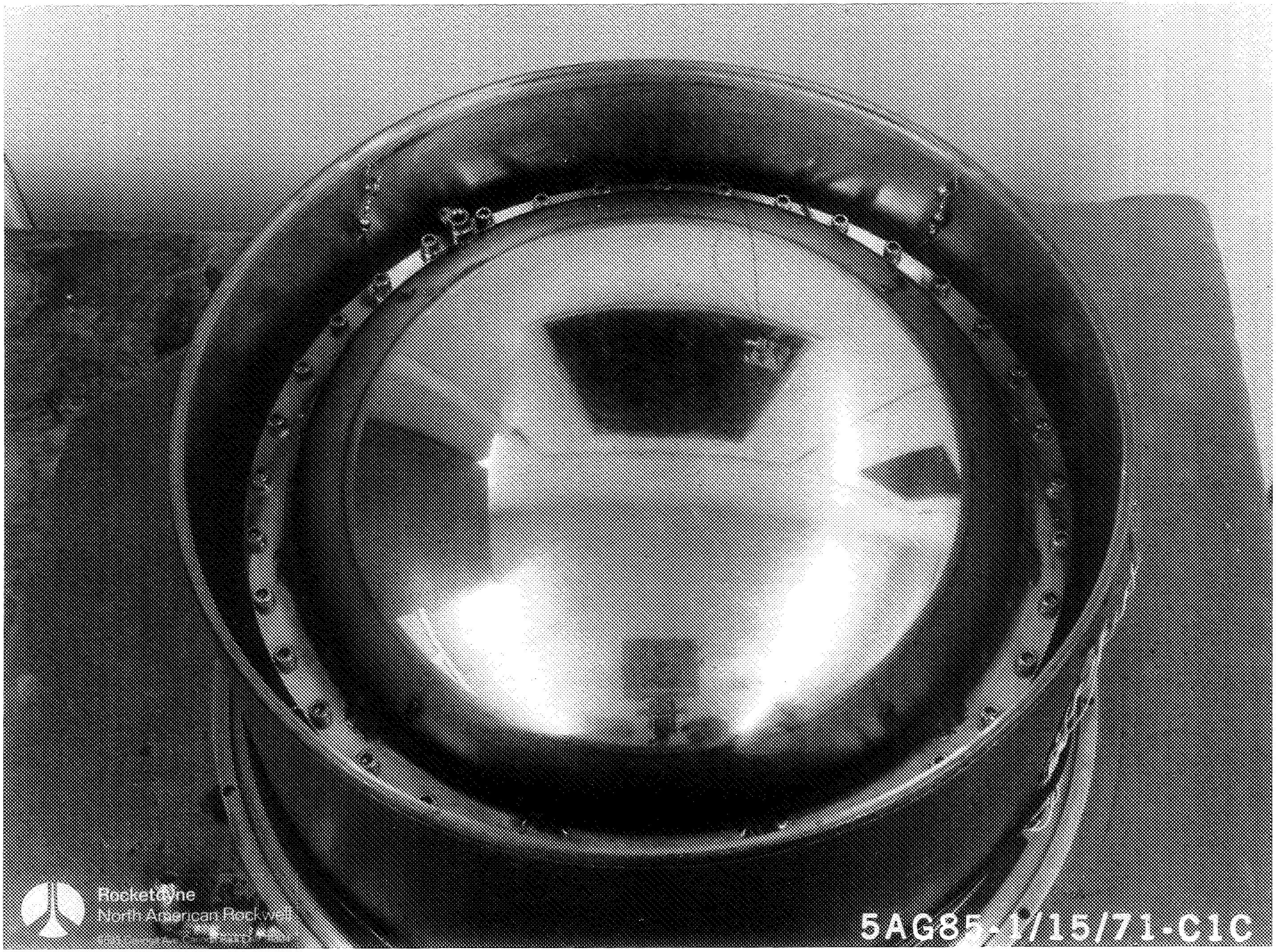


Figure 6. Closed Calorimeter and Radiation Shield

The unit is triple walled with vacuum space between so that changes in liquid nitrogen level will have a minimal effect on the temperature of the inner wall. This is done to improve the constancy of heat transfer between the heat conducting rod and the walls surrounding it. Calculation of the radiation heat transfer and the effect of ambient temperature changes were included in an earlier report (Ref. 2). A vacuum pump out port is located in the lower unit. Figure 7 is a photograph of the lower unit showing also the heat exchange fins attached to the heat conduction rod. Figure 8 is a cross section of the lower unit.

The calorimeter is mounted on a sturdy Unistrut table measuring 36 x 24 x 30 inches high with an aluminum top. A hinged platform to support a 5 liter dewar, containing the liquid nitrogen needed to maintain the heat sink, is located beneath the table. The electrical wiring is brought to the outside of the calorimeter through an opening in the base plate and terminates at a Bendix RD414-1009-0063 multi pin hermetic seal located at the rear of the calorimeter.

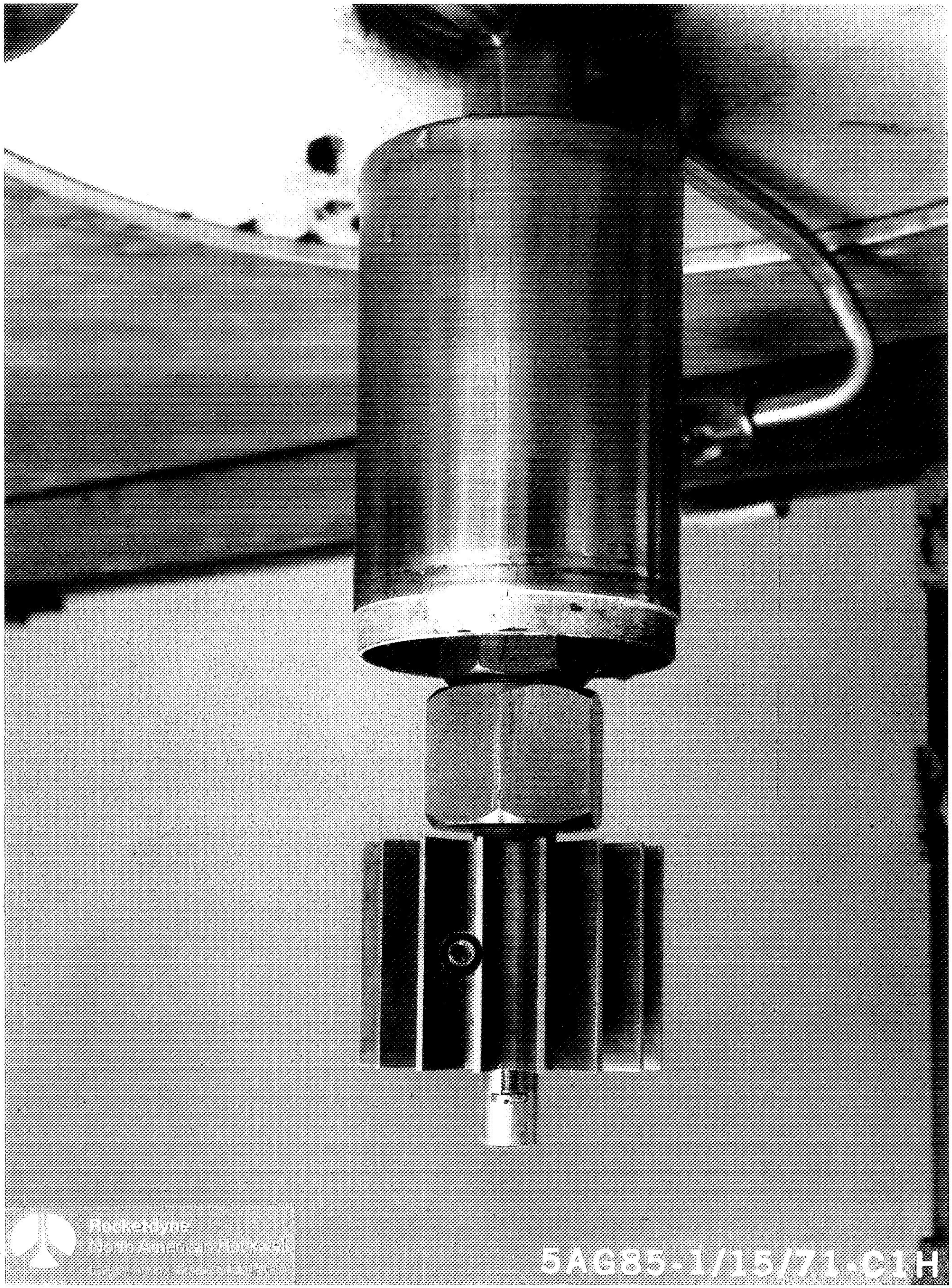
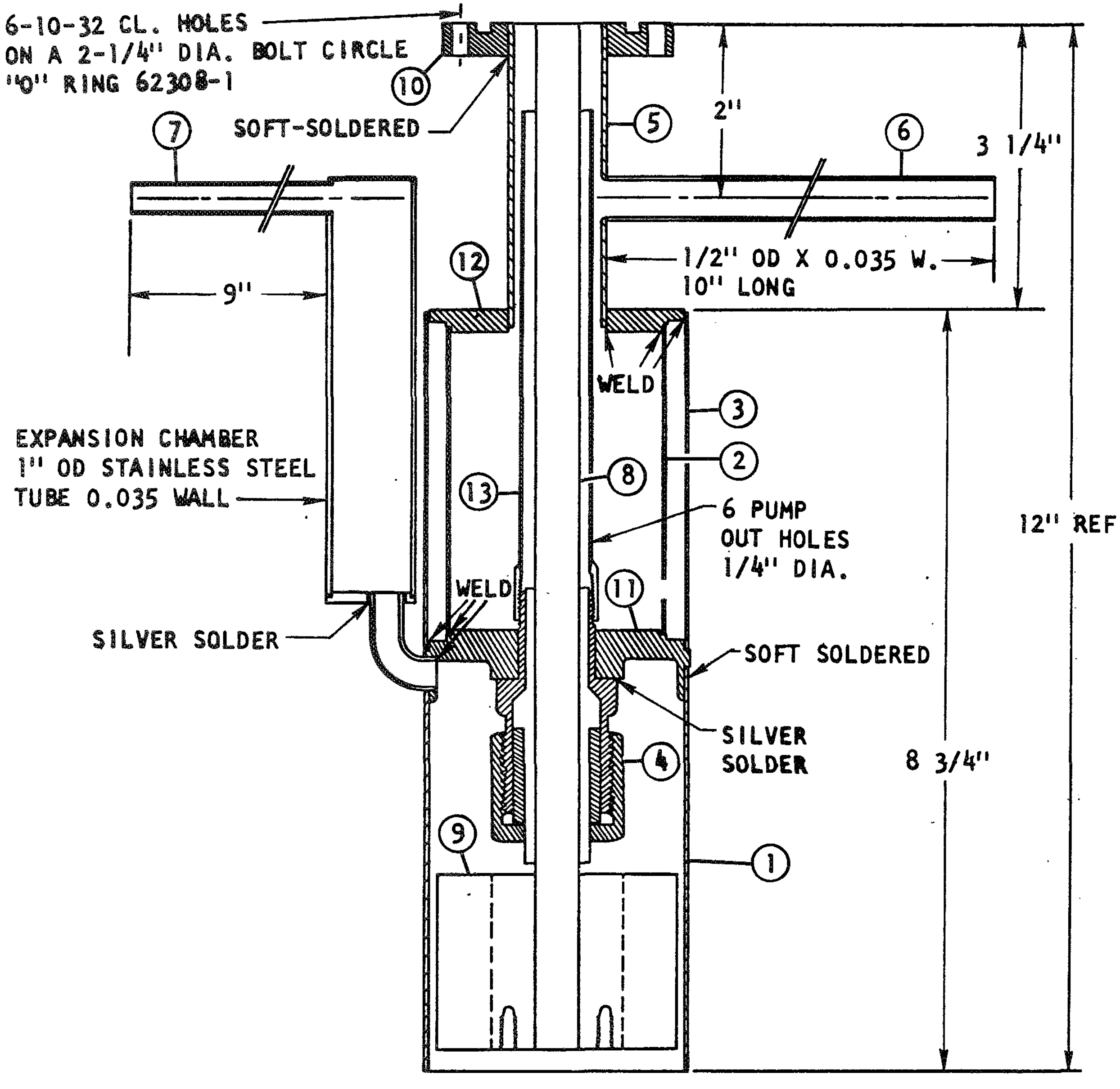


Figure 7. External View of Lower Vacuum Unit



1. 3" OD COPPER TUBE 4 5/8" LONG SOFT SOLDERED TO -11 BULKHEAD
2. 2-1/2" OD STAINLESS STEEL HEAT SHIELD WITH 4 1/4" PUMP OUT HOLES. WELDED TO -11 AND -12 BULKHEADS
3. 3" OD STAINLESS STEEL TUBE VAC. LEAK TIGHT WELDED TO -11 AND -12 BULKHEADS
4. CONAX GLAND (PURCHASED ITEM) MODIFIED
5. 1-1/8" OD STAINLESS STEEL TUBE
6. 1/2" STAINLESS STEEL TUBE
7. 3/8" OD STAINLESS TUBE
8. SPLIT COPPER CONDUCTOR SHAFT
9. SPLIT COPPER FINNED CONDUCTOR
10. STAINLESS STEEL TOP FLANGE
11. STAINLESS STEEL LOWER VACUUM FLANGE
12. STAINLESS STEEL UPPER VACUUM FLANGE
13. DEFLECTION SHIELD FOR -8 CONDUCTOR

Figure 8. Drawing of Lower Vacuum Unit

ELECTRICAL MEASUREMENT AND CONTROL

TEMPERATURE MEASUREMENT

The temperature of the calorimeter vessel is measured by means of a thermister inserted in a 0.062 inch diameter re-entrant well, 1-inch deep in the split silver cylinder that serves as a base for the cell platform (see Fig. 3). The thermister head was located one inch below the cell platform and 1/8 inch from the center of the silver cylinder. A temperature gradient, between the thermister head and the cell support platform, will exist depending upon the total heat flow from the calorimeter vessel. This temperature difference was calculated by means of a computerized heat transfer program (Ref. 2) and determined to be 2 degrees at 25 watts heat flow and 2.5 degrees at 33.5 watts. These heat flows are the extreme values for the operating temperature range of the calorimeter.

The thermister serves as one arm of a 2,000 ohm wheatstone bridge (Fig. 9). The two fixed arms are a matched pair (matched to 0.1 ohm) of 2,000 ohm wire wound precision resistors. The bridge is balanced by means of a 6 decade resistance box (Electro Scientific Industries Model DS625A) with a resolution of 0.1 ohm and an accuracy of 0.01 percent. The bridge is powered by a mercury cell.

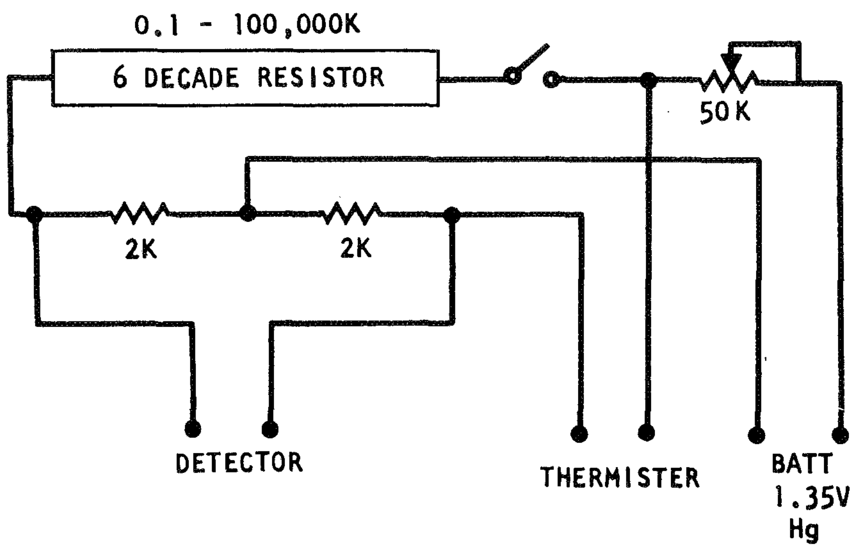


Figure 9. Wheatstone Bridge Circuit

The thermister (Fenwall Model GB32M62) is a nominal 2,000 ohms ± 0.2% at 25 C. Its resistance was measured at the triple point of water and at -10 C, 0 C, 25 C, and 40 C and compared with the resistance of a L&N Model 8163 platinum resistance thermometer which was calibrated by the National Bureau of Standards. The resistance was measured by the current and potential method. Thermometric potential measurements are made with a Guildline 9180-B potentiometer together with a Guildline 9790 d-c microvolt amplifier and a strip-chart recorder. The smallest chart division was made equal to 0.05 μv. The thermometer current is supplied by a North Hills CS-11 constant current source. All potential and resistance measurements are referred to standards or devices calibrated by the National Bureau of Standards. The thermister was attached to the platinum resistance thermometer and both were immersed directly into the appropriate temperature baths. A semi-logarithmic plot of the resistance vs temperature is contained in Fig. 10. The resistance of the thermister is 9261.4, 5776, 3710, 2004.2, & 1129.2 ohms at -10, 0, 10, 25, and 40 C, respectively. Resistance at other temperatures may be calculated from the manufacturers standard R/R_o curves.

POWER CONTROL AND MEASUREMENT

The power measuring system maintains the thermal head by sensing the temperature of the silver cylinder located in the calorimeter vessel and automatically adding or removing power from the 100.9 ohm control heater which is wound noninductively around the silver cylinder. Thermal effects origi-

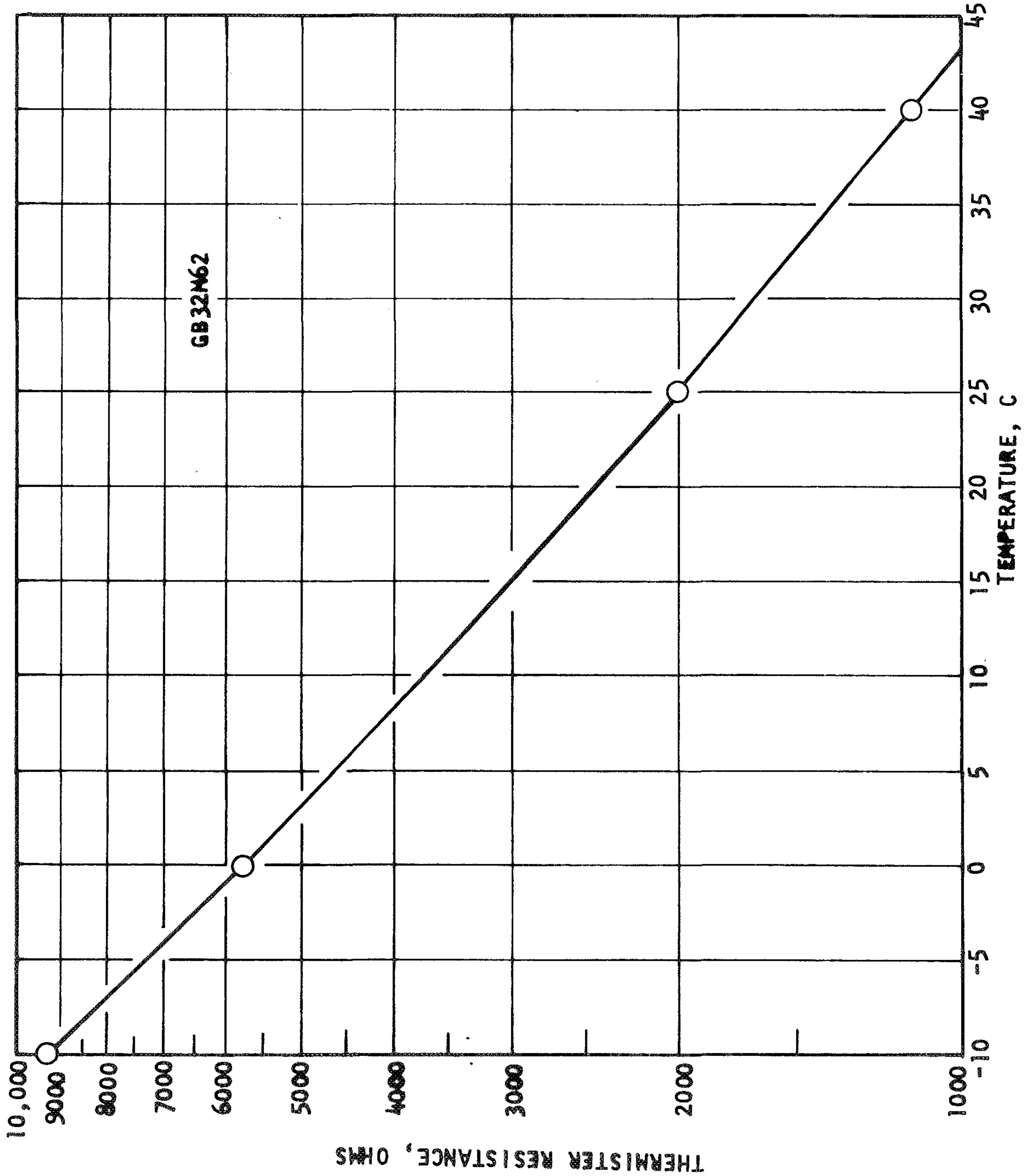
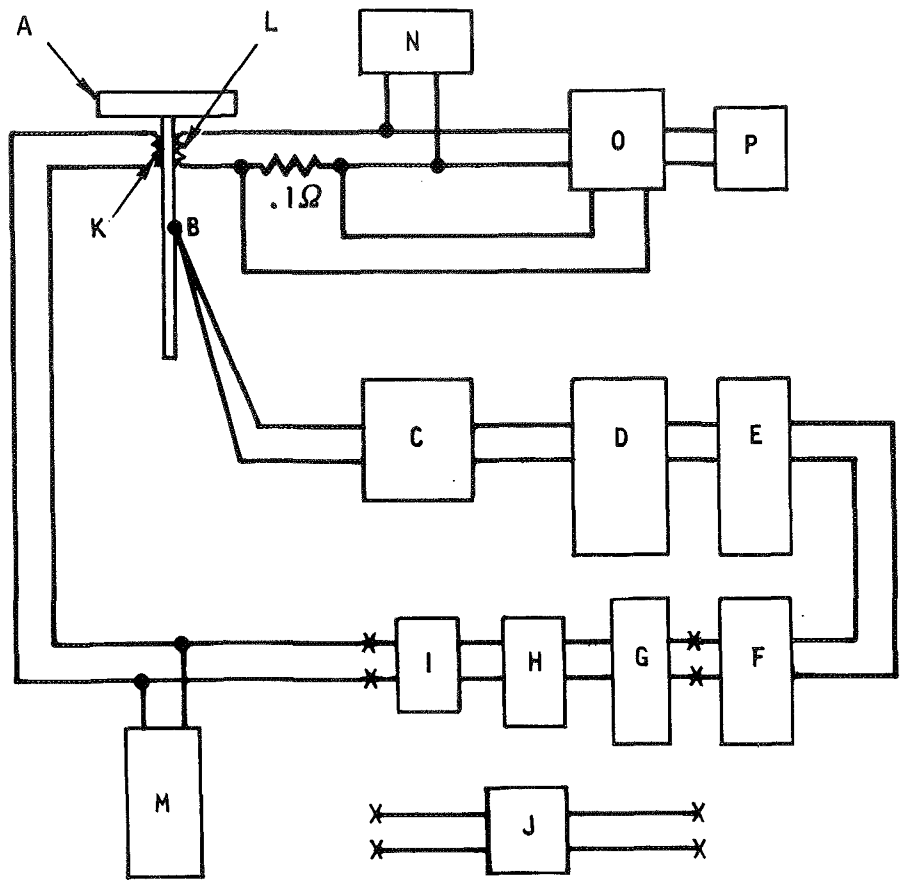


Figure 10. Thermister Calibration

nating in the nickel-cadmium cell or in the calibration heater will cause a change in the power required to maintain constant temperature. Such changes are measured with a wattmeter and recorded. The system is shown schematically in Fig. 11.

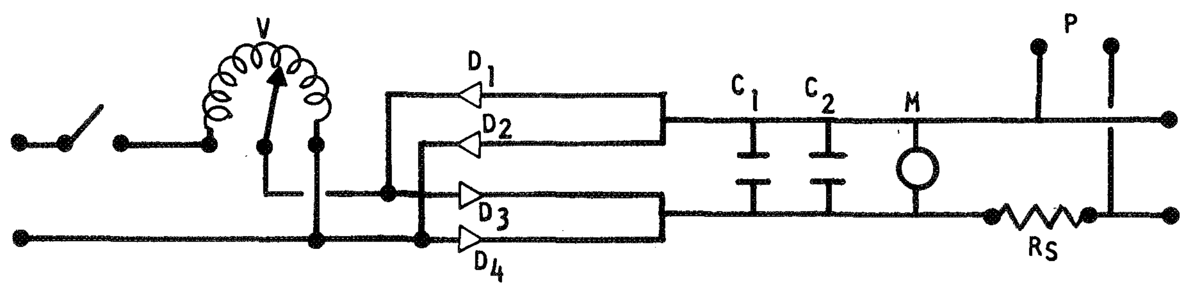
The output of the wheatstone bridge containing the thermister is amplified by a Leeds and Northrup Model 9835-B microvolt amplifier and recorded on a zero center $\pm$ 5 μv recorder equipped with a L&N Series 80 3-mode current adjusting type control unit. This control unit provides an output which is used to control the d-c power supplied to the control heater in the calorimeter vessel. This power supply may be either a d-c power supply with remote voltage control or a (lower cost) phase shift type silicon control rectifier (Loyola Industries Model L2-120-4) with a well-filtered d-c rectifier added (diagram in Fig. 12). Both types of power supply have been used. The power supply must be capable of 0.7 amps at 70 volts.

The system, as described, has a sensitivity at 25 C of 0.001 degrees per chart division and controls temperature under steady state and charge cycling conditions to $\pm$ 0.0005 degrees. Additional discussion of the performance of the system may be found beginning on page 44.



A CALORIMETRIC UNIT
B THERMISTER
C WHEATSTONE BRIDGE
D MICROVOLT AMPLIFIER
E STRIPCHART RECORDER
F 3 ACTION CONTROL UNIT
G SOLID STATE AC POWER AMP
H VARIABLE VOLTAGE TRANSFORMER
I RECTIFIER AND AC FILTER
J PROGRAMABLE DC
POWER SUPPLY
K MAIN CONTROL HEATER
L CALIBRATION HEATER
M WATTMETER
N CALIBRATION POWER SUPPLY
O SWITCH
P POTENTIOMETER OR DVM

Figure 11. Block Diagram of Power Measurement System



V	VARIABLE AUTO TRANSFORMER
D_1, D_2, D_3, D_4	MOTOROLA 1602 DIODE
C_1, C_2	150 μf, 150V CAPACITOR
M_1	100V DC METER
P	VOLTAGE MEASURING TERMINAL
R_S	CURRENT MEASURING SHUNT

Figure 12. AC Rectifier (Used with SCR Power Supply)

Wattmeter

A high accuracy, precision wattmeter to measure the electrical power supplied to the calorimeter heater was designed and built by the Instrumentation Laboratory at Rocketdyne. A photograph of the wattmeter is provided as Fig. 13. The wheatstone bridge takes up the left half of the panel. The design of the wattmeter is based upon the ohms law relationship which states that

$$\text{Watts} = \frac{E^2}{R}$$

where E is the voltage drop across the heater of resistance R. This design has the advantage that only voltage need be measured if the heater resistance remains constant. Evanohm*, a special alloy developed for high precision resistors, has a temperature coefficient of less than 10 ppm over the temperature range of -65 to +150 C. The control heater is wound noninductively with 100.9 ohms of B&S No. 30 gauge wire with Formvar insulation.

The wattmeter consists of a ranging section which conditions the input voltage to 0-10 volts, an electronic multiplier which squares the voltage,

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* Wilbur B. Driver Co., Newark, New Jersey

Figure 13. Precision DC Wattmeter

and a signal conditioning section which adjusts the output to a recorder and a digital voltmeter. The multiplier is Analog Devices Model 424K and has a specification of 0.1% on precision and accuracy. This provides an ultimate precision of 0.03 watts in a total of 30 watts. The wattmeter is linear to 25% overrange.

The wattmeter has three ranges, 5, 25, and 50 watts, corresponding to inputs of 22.36, 50.0, and 70.7 volts, respectively. A schematic of the wattmeter is shown in Fig. 14. The ranging section, through the use of negative feedback around the operational amplifier A_1 and the resistances R_2 through R_8 and R_{30} reduces these voltages to 10 volts. This may be measured at test point $\boxed{3}$. This voltage is applied to both the X and Y inputs of the high accuracy multiplier to accomplish the squaring. The multiplier performs the function

$$\frac{XY}{10} = Z$$

so that 10 volts output is obtained for 10 volts input to both X and Y. This voltage is measured at $\boxed{6}$.

The output section contains the operational amplifier A_2 which operates at unity gain using negative feedback for stability and switches and re-

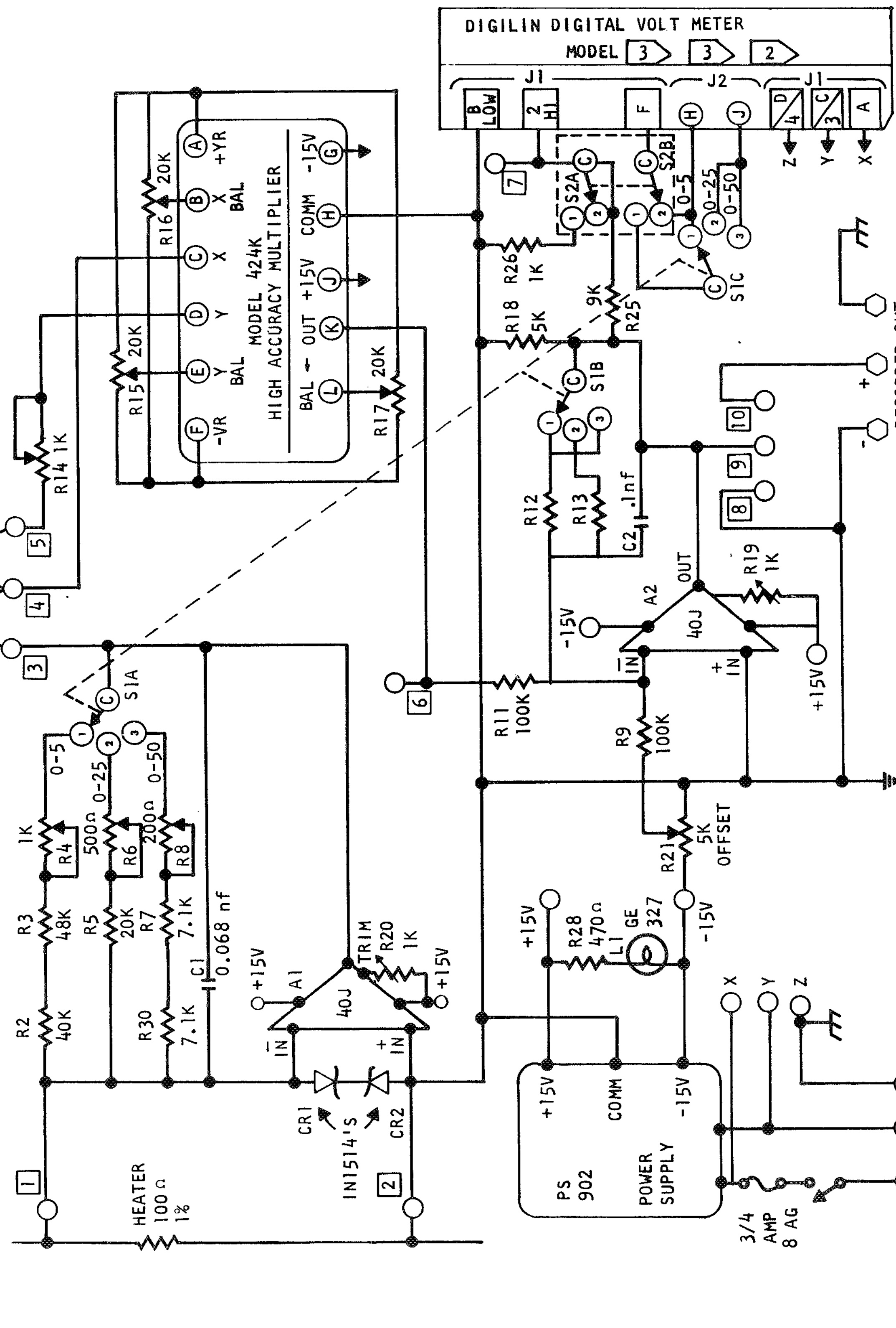


Figure 14. Electrical Circuit for Precision Wattmeter

sistors which provide decimal switching and a 0-1 volt signal for the digital voltmeter. A ten position 1, 2, 4, 8 attenuator is connected to $\boxed{8}$, $\boxed{9}$, $\boxed{10}$ to provide full range outputs between 9.76 millivolts and 10 volts and, when used with the offset voltage potentiometer (R21), serves to expand a smaller portion of the range for increased resolution when used with a recorder. A description of such a use is contained in the following example. When operating in the 50 watt range with 50 watts equal to full scale on the recorder, the resolution per division is 0.5 watt. If it is desired to increase resolution to say 0.0625 watts per division, the gain can be increased by a factor of 4 by moving the attenuator to three positions less attenuation and using the offset potentiometer to keep the signal on scale. Full span of the recorder is now approximately 1/4 of 50 or 12.5 watts. This is accomplished without any change to the inputs to the multiplier. The output signal from the wattmeter always contains a resolution of at least 0.05 watts and can be read to this resolution by a four digit voltmeter without altering the attenuator. This is possible because of the stability and linearity of the multiplier unit.

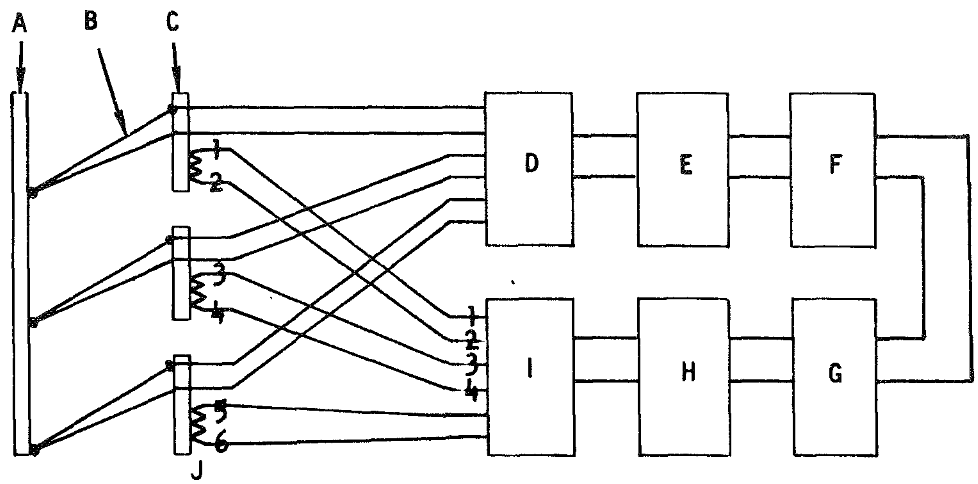
A three-digit bipolar DVM (Digilin Inc. Model 332) is incorporated into the wattmeter to provide a visual indication of the wattmeter output. The DVM reads directly in watts with a resolution of 0.01 watt when the wattmeter is operating in the 5 watt range and a resolution of 0.1 watt when the wattmeter is operating in the 25 and 50 watt range. A 10X output multiplier range is incorporated which increases the resolution to 0.01 watt on the 25 and 50 watt if the offset potentiometer is adjusted to buck out all but 5 watts equivalent output voltage. This expansion is independent of the attenuator setting but affects the position of the pen on an analog recorder. Instructions for the calibration and adjustment of the wattmeter are contained in Appendix A.

Calibration Heater

A calibration heater is wound on the silver cylinder directly below the cell support platform. The heater is made of Formvar insulated B&S #34 Evanohm resistance wire wound noninductively. A layer of 0.00025 inch MYLAR film insulates the wire from the silver cylinder. The wire is cemented in place with General Electric 7031 Electrical Insulating varnish. Lead wires of Teflon-insulated B&S #30 copper connect the heater to the passthrough terminals. Leads used to measure the potential drop across the heater during calibration are located at the external terminal connection and are arranged to include current lead resistance. In this manner, all heat generated within the calorimeter thermal boundary is measured. The resistance of the calibration circuit in the calorimeter is 100.12 ± 0.03 ohms at 25 C. The calibration was made by the current and potential method using a North Hills Model CS-12 precision current source, a 0.1 Ω standard resistor to measure current, and a Vidar Model 510 DVM and an ESI Model 330 Portametric voltmeter to measure potential. A schematic of the instrumentation is included in Fig. 11.

Adiabatic Shield

A single channel servo system controls the adiabatic shield which insures a uniform thermal environment around the calorimeter vessel. Figure 15 is a block diagram of the adiabatic shield control. The signal from either of the three copper-constantan difference thermocouples located between the top, side, and bottom of the adiabatic shield and the calorimeter vessel is selected by a rotary switch and fed to a L&N 9835-B microvolt amplifier. The zero center ± 0.5 volt output from the amplifier is reduced to a maximum of ± 50 mv by a voltage divider serving as a sensitivity control and biased upward by 50 mv (Fig. 16a), thus providing a 0-100 mv input (with zero equal to 50 mv) to a L&N Model 6261-3220-1-0 Electromax signalling controller with proportional band, reset, and approach control forms. The control point may be located at any portion of the meter scale but is normally operated at 50 mv. The output of the signalling controller drives a L&N 11906-233 pulsating type solid state



A CALORIMETER VESSEL SURFACE

B THERMOCOUPLE

C ADIABATIC SHIELD

D THERMOCOUPLE SELECTOR SWITCH

E D.C. PREAMPLIFIER

F VOLTAGE DIVIDER AND VOLTAGE BIAS

G INTERMEDIATE AMPLIFIER AND 3 ACTION CONTROL

H SOLID STATE AC POWER AMPLIFIER

I POWER DISTRIBUTION CONTROL

J SHIELD HEATER

Figure 15. Block Diagram of Adiabatic Shield Control

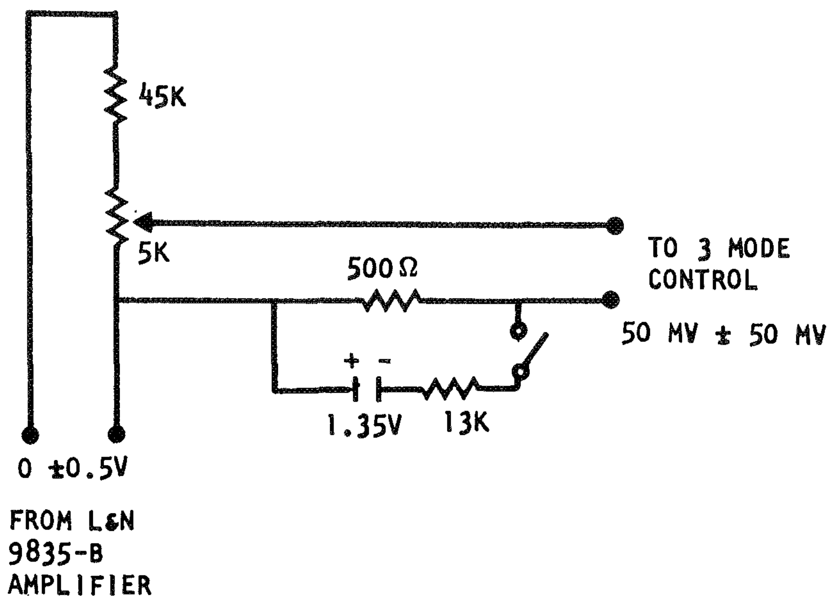


Figure 16a. Voltage Divider and Bias Unit

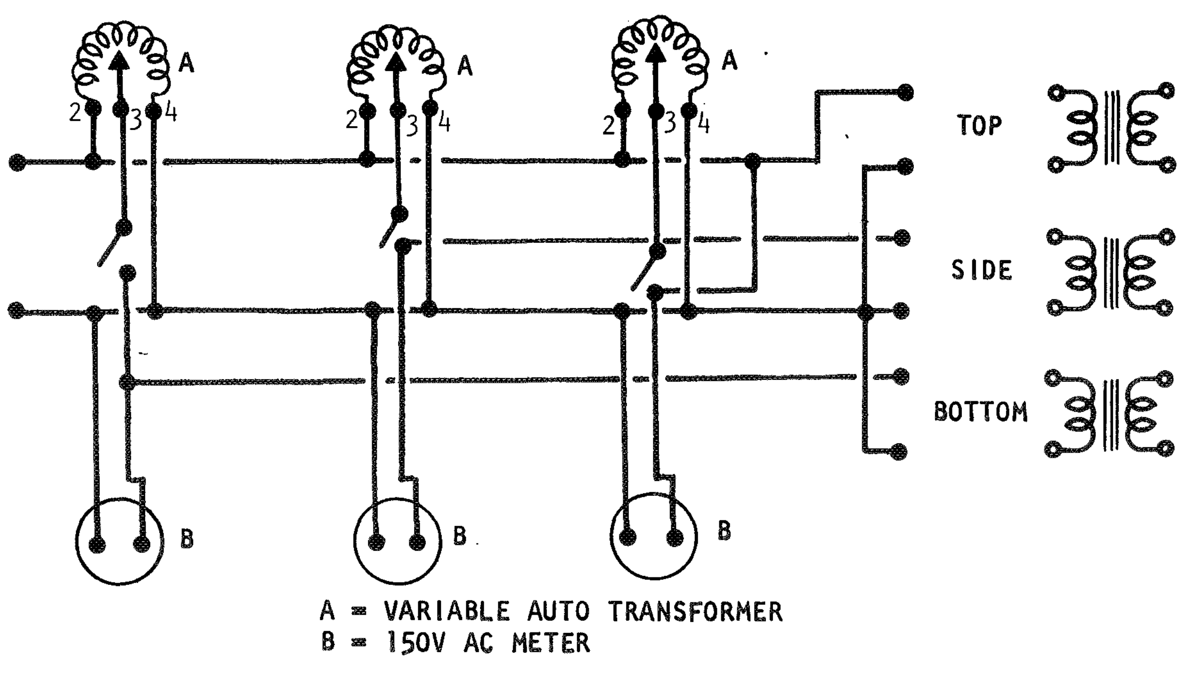


Figure 16b. Adiabatic Shield Power Distribution Control

power supply. The 0-110 vac signal output is fed to three variable autotransformers connected in parallel (Fig. 16b). These autotransformers allow individual adjustment of the power to the heaters located on the outside surfaces of the adiabatic shield sections. One hundred watt isolation transformers are located between the autotransformers and the heaters. The servo loop automatically maintains one surface at zero differential and the autotransformers controlling the other two surfaces are used to trim them to a zero differential.

The basic sensitivity of the system is such that a half microvolt input (0.0125 degrees) signal will cause a full scale indication on the set point deviation meter. The control circuitry will operate to maintain the setpoint to within 5% of this full scale value. The sensitivity may be reduced either by reducing the gain of the pre-amplifier or by adjusting the ten turn potentiometer which serves as part of the voltage divider on the output of the pre-amplifier. The deviation from the set point can be readily maintained to less than 0.002 degrees during operation at a fixed temperature.

ELECTRICAL CONNECTIONS

The pin identification for the passthroughs at the bottom of the calorimeter vessel and for the multipin hermetic seal at the base of the vacuum jacket is contained in Appendix B. Appendix C contains the wiring code and wire color identification for the interconnecting cables between the calorimeter and the instrumentation relay racks. Appendix D contains the wire identification for internal wiring of the instrumentation relay rack at the NASA-Goddard installation.

PERFORMANCE

CHARACTERISTICS OF THE CALORIMETER

Heat Flow

The electrical power required to maintain steady state heat flow in the calorimeter is 33.0, 30.3, 27.5, 26.3, 25.1 watts at 40, 25, 10, 0 and -10 C, respectively. These values correspond to the maximum exothermic reaction which can be measured at that temperature. Endothermic reactions to 50 watts can be measured at any temperature.

Baseline Stability

The baseline stability of the calorimeter including the wattmeter was determined by measurement of the constancy of the electrical power needed to hold the temperature of the calorimeter vessel at 25 C with the cold end of the heat flow rod held in boiling liquid nitrogen. The baseline power level was found to remain constant over a forty hour period to within 0.03 watts with 30.3 watts of total heat flow. An even more stringent stability test is the reproducibility of the baseline after 70 hours of electrical cycling the 20 AH and 100 AH cells. In each case, the baseline was found to be identical with the strip-chart recording at the beginning of the cycling test (sensitivity 1 div = 0.06 watts). The design requirement was a stability of ± 0.05 watts for the 20 AH cell and ± 0.25 watts for the 100 AH cell over a 24 hour period.

Sensitivity

The sensitivity of the calorimeter to a thermal effect is determined by the attenuator and the range setting on the wattmeter and ultimately by the sensitivity of the thermister bridge to a change of temperature in the calorimeter. At 25 C, the thermister has a sensitivity of 80 ohms per degree of temperature change. This translates to a 0.001 C per division of the recorder controller with the d-c amplifier at highest gain The recorder controller rarely deviates more than half of a division. The sensitivity per division on the recorder at 40 C, 25 C, 0 C and -10 C versus amplifier gain are contained in Table 1.

TABLE 1

Temperature Resolution of Thermister Thermometer*

Temperature	Thermister Sensitivity	Amplifier Range 50 μv	100 μv	200 μv	500 μv	1000 μv	2000 μv
40 C	27 Ω/deg	0.0022	0.0044	0.0088	0.022	0.044	0.088
25 C	80 Ω/deg	0.001	0.002	0.004	0.010	0.020	0.040
0 C	250 Ω/deg	0.00067	0.0013	0.0026	0.065	0.013	0.026
-10 C	500 Ω/deg	0.0004	0.0008	0.0016	0.004	0.008	0.016

* per division on recorder-controller

The power resolution is at least 0.1 watts when operating with a full scale of 25 watts and is at least 0.03 watts when operating at 5 watts full scale on a recorder. These values, 0.4% and 0.6% of the 25 watt and 5 watt ranges, respectively, exceed the design requirement of 1% resolution. If a digital voltmeter is used to read the wattmeter output, a resolution of at least 0.03 watts can be obtained on any scale.

Response Time

The response to a one-watt input to the calibration heater occurs within two seconds. The time required for the servo loop to adjust to the new power requirement depends upon the settings on the control unit loop. For a one watt change, the average time to the new power requirement is less than 15 seconds. For a 25 watt input, the servo loop requires about two minutes to stabilize. The response time with a cell installed remains approximately the same as for the empty calorimeter. The limiting parameter in each case (proportional band, rate, and reset) is the response of the servo loop to the change of demand.

Calibration

The calorimeter may be calibrated at the start of each experiment by noting the deflection of the recorder pen from the base line for known power inputs into the calibration heater. The output is linear to the readibility of the strip chart and the linearity of the recorder circuitry. The wattmeter reading is based on a heater resistance of 100.0 ohms whereas the heater has a resistance of 100.9 ohms. The wattmeter reading should be multiplied by a correction factor of 0.9911 to correct for this difference. The linearity of the wattmeter circuitry is measured to be within 0.2% $\pm$ 1 digit over its range. These results greatly exceed the design requirements of 3%.

CHARGE CYCLING OF SEALED NICKEL-CADMIUM SPACE CELLS

The operation of the calorimeter was checked out by charge cycling both a 100 AH cell and a 20 AH cell at 25 C for a minimum of 40 cycles.

100 Ampere Hour Cell

The 100 ampere hour cell was manufactured by General Electric and measured 7.14 by 7.34 by 1.6 inches thick and weighed about 9 lbs. It was equipped with a third electrode called the adhydrode. The potential across a 300 ohm resistor connector between the adhydrode and the negative terminal of the cell is related roughly to the oxygen pressure within the cell.

Preparation for Cycling. The 100 ampere hour cell is stored uncharged and must be conditioned before use. The cell is clamped between 0.375 inch thick aluminum plates and charged for 16 hours at 10 amperes followed by a discharge to 0.97 volts at 50 amperes. The discharge takes about 3 hours. The cell is removed from the plates and prepared for the calorimeter by wrapping 5-half inch wide strips of copper foil backed with a conducting adhesive (Scotch Electrical Tape No. X-1181, 3MCo) around the cell. The purpose of the foil is to enhance the flow of heat generated at the upper surface to the heat conducting tray thereby reducing upper surface temperature and increasing thermal response. Thirty-six ml of DC704 silicone oil were added to the tray to enhance thermal contact between the cell and the tray. The terminals on the cell were connected directly to the silver tabs which serve as electrodes with 10-32 machine screws. Figure 17 is a photograph of the cell as placed in the calorimeter.

After the lid to the calorimeter was bolted on, the interior of the calorimeter was pressurized to 52 psi. The pressure serves to counter balance the internal pressure, which is generated within the cell during charging, and to maintain the internal geometry of the cell. The cell was equilibrated at 25 C for several hours before initiating the cycling test. The baseline heat flow was 30.2 watts.

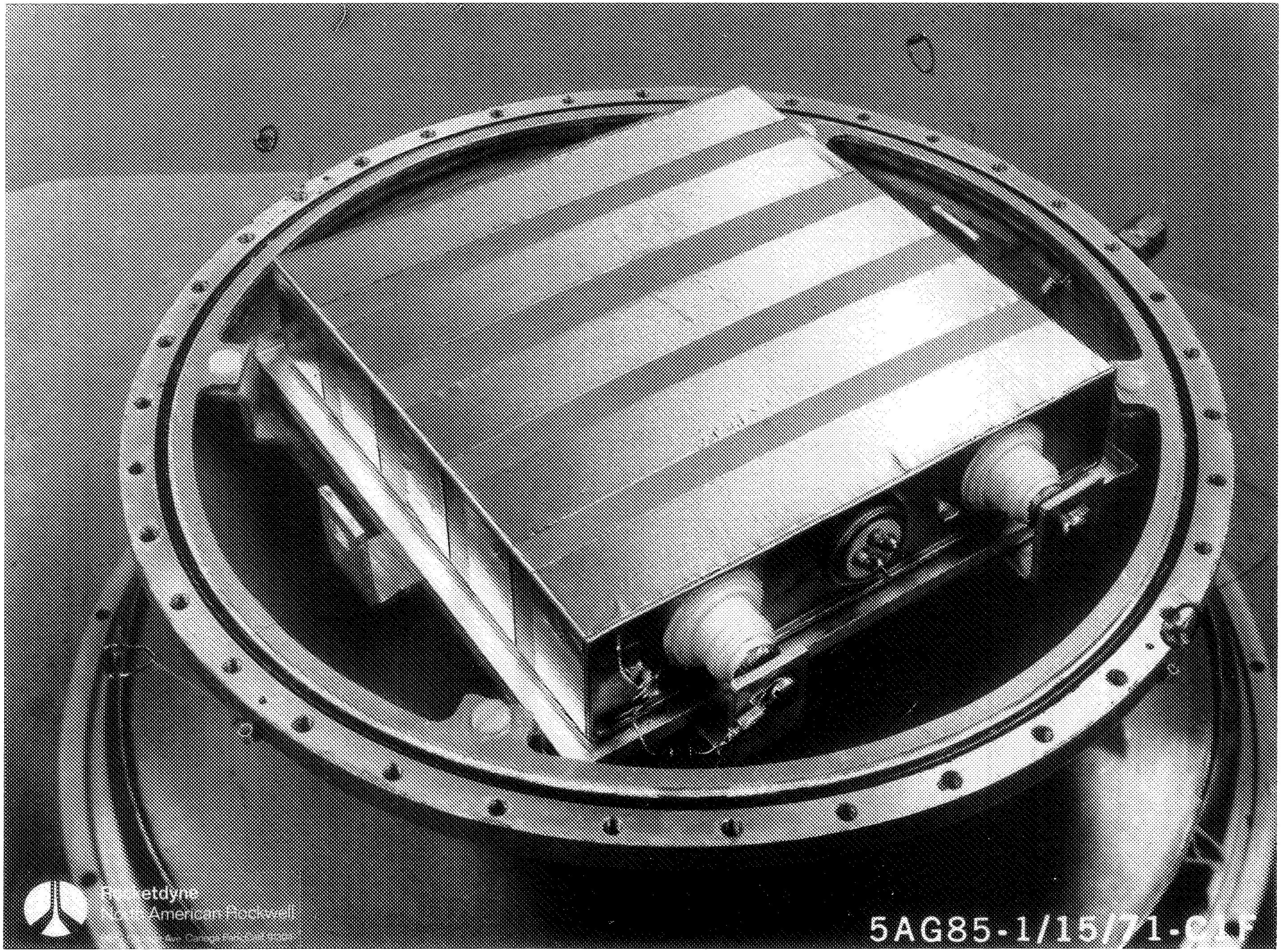


Figure 17. 100 Ampere-Hour Cell Installed in Calorameter

Thermal Effects. The cell was charged at 10 amperes (C/10) for sixteen hours followed by discharge for 30 minutes at 50 amperes (C/2). The cell absorbed heat (endothermic) to a maximum of 0.5 watt during the first seven hours of the charging cycle, reversed itself and became increasingly exothermic as the charging proceeded. After 15 hours of charging, the cell was releasing heat at a rate of 13.5 watts. During the final hour, the heat release reduced to 11.5 watts. An additional 2.5 watts of heat was released during the initial discharge cycle.

An automatic cycling unit provided by NASA-Goddard was used to charge the cell at 28.75 ± 0.02 amperes for 60 minutes followed by discharge at 50 amperes for 30 minutes. The charge-discharge sequence was continued for 50 cycles. The cell voltage, current, signal electrode voltage and thermal effects were recorded continuously during this time. The data taken are recorded in Table 2. A portion of the strip chart showing one cycle of the thermal effects is shown in Fig. 18. About three cycles were required for the cell to settle into a pattern which remained essentially constant for the remainder of the test. The heat generated within the cell is only slowly released and the cell remained exothermic during all portions of the cycling. The peak heat release during discharge averaged 8.47 ± 0.07 watts. During charging, the cell becomes less exothermic for

TABLE 2

CYCLING OF 100 AH CELL

Cycling Condition: Discharge 30 min at 50 amps to 25% depth; recharge 60 min. at 28.75 amps to 115% charge; recharge voltage upper limit of 1.48 volts.

Cycle	Heat Flow Start Watts	End Watts	Difference Watts	Peak Watts at - % of Charge	Minimum Cell Voltage	Voltage Limit at % Charge
1D	-11.5	-14.25	2.50		1.21	
2C	-14.25	- 6.00	-8.25	-4.75 at 73%		76
2D	- 6.00	-11.00	+5.00		1.20	
3C	-11.00	- 5.00	-6.00	-3.75 at 73%		80
3D	- 5.00	- 9.75	+4.75		1.20	
4C	- 9.75	- 4.00	-5.75	-3.75 at 80%		83
4D	- 4.00	- 8.75	+4.75		1.20	
5C	- 8.75	- 3.75	-5.00	-3.25 at 85%		83
5D	- 3.75	- 8.50	+4.75		1.20	
6C	- 8.50	- 3.50	-5.00	-3.25 at 85%		83
6D	- 3.50	- 8.50	+5.00		1.20	
7C	- 8.50	- 3.50	-5.00	-3.25 at 85%		86
7D	- 3.50	- 8.50	+5.00		1.20	
8C	- 8.50	- 3.50	-5.00	-3.25 at 85%		86
8D	- 3.50	- 8.25	+4.75		1.19	
9C	- 8.25	- 3.50	-4.75	-3.50 at 85%		86
9D	- 3.50	- 8.25	+4.75		1.175	
10C	- 8.25	- 3.50	-4.75	-3.50 at 85%		86
10D	- 3.50	- 8.25	+4.75		1.175	
11C	- 8.25	- 3.50	-4.75	-3.50 at 85%		86
11D	- 3.50	- 8.25	+4.75		1.175	
12C	- 8.25	- 3.75	-4.75	-3.75 at 85%		86
12D	- 3.75	- 8.50	+4.75		1.175	
13C	- 8.50	- 3.75	-4.75	-3.75 at 85%		86
13D	- 3.75	- 8.50	+4.75		1.175	
14C	- 8.50	- 3.75	-4.75	-3.75 at 85%		86
14D	- 3.75	- 8.50	+4.75		1.175	
15C	- 8.50	- 3.90	-4.40	-3.90 at 85%		86
15D	- 3.90	- 8.50	+4.60		1.175	
16C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
16D	- 4.00	- 8.50	+4.50		1.175	
17C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
17D	- 4.00	- 8.50	+4.50		1.175	
18C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
18D	- 4.00	- 8.50	+4.50		1.175	
19C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
19D	- 4.00	- 8.50	+4.50		1.175	

TABLE 2. (Continued)

	Heat Flow					
Cycle	Start Watts	End Watts	Difference Watts	Peak Watts at - % of Charge	Minimum Cell Voltage	Voltage Limit at % Charge
20C	- 8.50	- 3.75	-4.75	-4.00 at 85%		86
20D	- 3.75	- 8.25	+4.75		1.175	
21C	- 8.25	- 3.75	-4.50	-4.00 at 85%		86
21D	- 3.75	- 8.25	+4.50		1.175	
22C	- 8.25	- 4.00	-4.25	-4.00 at 85%		86
22D	- 4.00	- 8.75	+4.75		1.175	
23C	- 8.75	-*	-	-4.00 at 85%		86
23D	(-)*	- 8.50	-		1.175	
24C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
24D	- 4.00	- 8.50	+4.50		1.17	
25C	- 8.50	-*	-	-4.00 at 85%		86
25D	-*	-	-		1.17	
26C	-	- 4.00	-	-4.00 at 85%		86
26D	- 4.00	- 8.50	+4.50		1.17	
27C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
27D	- 4.00	- 8.50	+4.50		1.17	
28C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
28D	- 4.00	- 8.50	+4.50		1.17	
29C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
29D	- 4.00	- 8.50	+4.50		1.17	
30C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
30D	- 4.00	- 8.50	+4.50		1.17	
31C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
31D	- 4.00	- 8.50	+4.50		1.17	
32C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
32D	- 4.00	- 8.50	+4.50		1.17	
33C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
33D	- 4.00	- 8.50	+4.50		1.17	
34C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
34D	- 4.00	- 8.50	+4.50		1.17	
35C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
35D	- 4.00	- 8.50	+4.50		1.17	
36C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
36D	- 4.00	- 8.50	+4.50		1.17	
37C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
37D	- 4.00	- 8.50	+4.50		1.17	
38C	- 8.50	- 4.00	-4.50	-4.00 at 85%		86
38D	- 4.00	- 8.50	+4.50		1.17	

TABLE 2. (Concluded)

	Heat Flow					
Cycle	Start Watts	End Watts	Difference Watts	Peak Watts at - % of Charge	Minimum Cell Voltage	Voltage Limit at % Charge
39C	- 4.25	- 8.50	-4.25	-4.00 at 85%		86
39D	- 8.50	- 4.25	+4.25		1.17	
40C	- 4.25	- 8.50	-4.25	-4.00 at 85%		86
40D	- 8.50	- 4.25	+4.25		1.17	
41C	- 4.25	- 8.50	-4.25	-4.00 at 85%		86
41D	- 8.50	- 4.25	+4.25		1.17	
42C	- 4.25	- 8.50	-4.25	-4.00 at 85%		86
42D	- 8.50	- 4.25	+4.25		1.17	
43C	- 4.25	- 8.50	-4.25	-4.00 at 85%		89
43D	- 8.50	- 4.25	+4.25		1.17	
44C	- 4.25	- 8.50	-4.25	-4.00 at 85%		89
44D	- 8.50	- 4.25	+4.25		1.17	
45C	- 4.25	- 8.50	-4.25	-4.00 at 85%		89
45D	- 8.50	- 4.25	+4.25		1.17	
46C	- 4.25	- 8.50	-4.25	-4.00 at 85%		89
46D	- 8.50	- 4.25	+4.25		1.17	
47C	- 4.25	- 8.50	-4.25	-4.00 at 85%		89
47D	- 8.50	- 4.25	+4.25		1.17	
48C	- 4.25	- 8.50	-4.25	-4.00 at 85%		89
48D	- 8.50	- 4.25	+4.25		1.17	
49C	- 4.25	- 8.50	-4.25	-4.00 at 85%		89
49D	- 8.50	- 4.00	+4.50		1.17	
50C	- 4.00	- 8.25	-4.25	-4.00 at 85%		89
50D	- 8.25	- 4.00	+4.25		1.17	

*( ) - indicates anomalous data point.

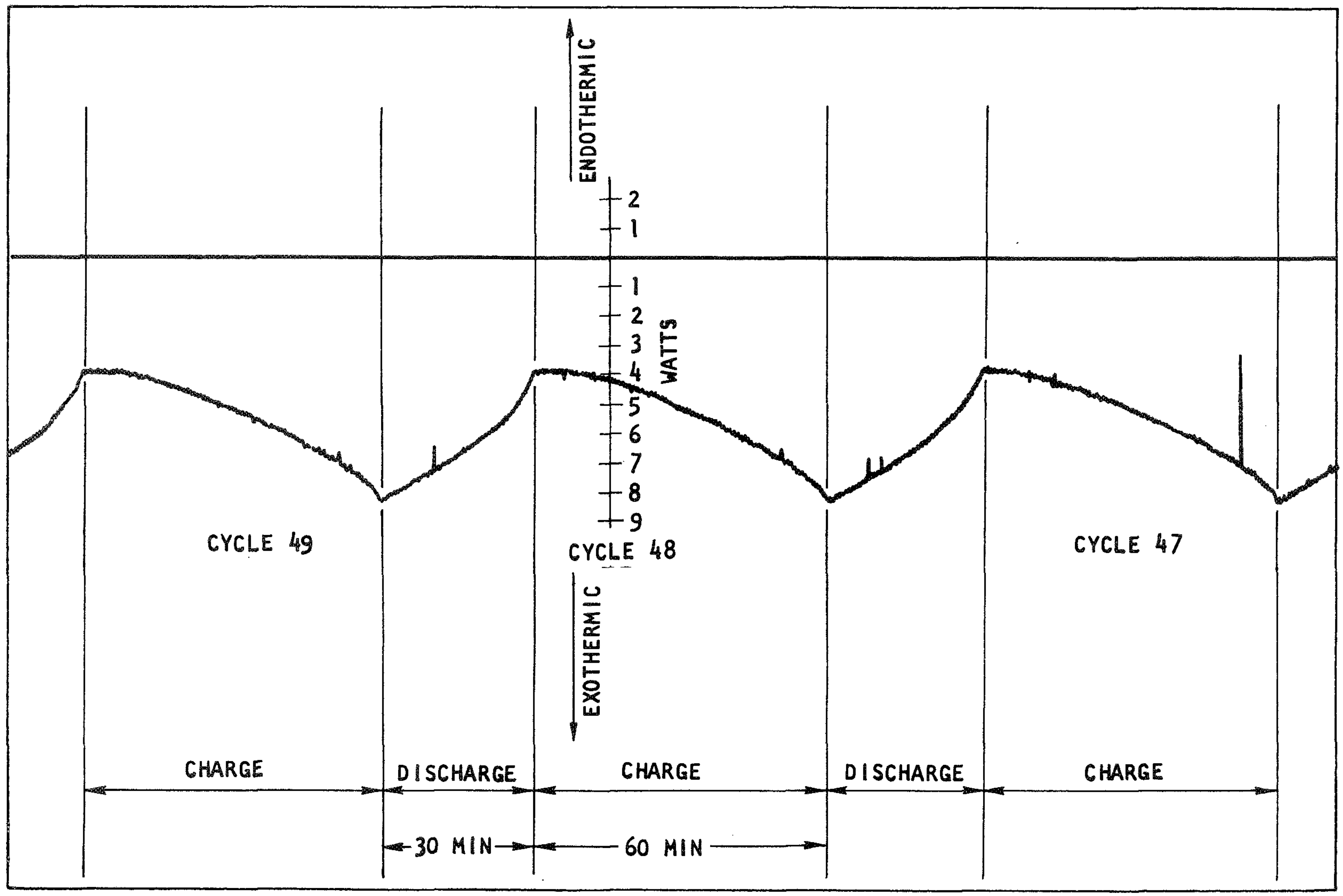


Figure 18. Chart Record During Cycling 100 A-H Cell

about 80% of the charge cycle for the first four cycles increasing to 90-95% of the charge cycle after 10 cycles. For the remainder of the cycle, the cell heat exchange either remains constant or becomes no more than 0.25 watts more exothermic. The total thermal fluctuation for one complete cycle changed during the progression of cycles from 4.75 watts near the beginning to 4.25 watts for the final 12 cycles. After completing the cycling, the quiescent cell took 12 hours to return to the original baseline.

Voltage Effects. The cell voltage during charge was limited to 1.48 volts. The portion of the charge cycle completed before voltage cutoff increased gradually from an initial 76% to 89%. The voltage at the end of discharge fell gradually from 1.21 to 1.17 volts. No voltage abnormalities were observed. The signal electrode voltages were recorded but provided no direct correlation with pressure measurements made on smaller cells. After initial charge, the signal electrode read 630 mv. During the cycling, the signal electrode voltage remained between 625-630 mv at end of charge and slowly dropped to 550 mv at end of discharge. The signal electrode developed a 9-10 mv jump during the course of the charge which occurred progressively at 0 to 89% of charging time as the number of cycles increased. The signal electrode voltage also developed from two to four small steps during discharge. These steps, although not reproducible with each cycle, are believed due to the cell and not the instrumentation. The gradual increase of the signal electrode voltage from 530 mv to 630 mv over a seven hour period during the equilibration of the cell at the end of the test is an indication of the slowness of response of the signal electrode to processes taking place in the cell.

After completion of the test, the calorimeter was opened up and the cell was observed to puff slightly indicating an internal pressure.

Twenty Ampere Cell

The twenty ampere hour cell was manufactured by Gulton Industries and measured 6.5 by 3.0 by 1.0 inches thick. The cell was conditioned prior to being installed in the calorimeter by charging it for 16 hours at 2 amperes (C/10) followed by discharge at 10 amperes (C/2) to 0.97 volts. The cell voltage at the end of charge was 1.448 volts. The cell was clamped between steel plates during the conditioning process to prevent distortion caused by internal gas generation.

Preparation for Cycling. The cell was placed in the cell support tray and connected to the electrodes by short lengths of #12 solid copper wire which were soldered to the cell terminals and bolted to the electrodes. The connector wire size was selected so that the total heat generated in these leads during maximum current flow is less than 0.05 watts. The calorimeter was pressurized to 52 psi to compensate for any gas pressure which might be generated internally. The cell was again conditioned by a 50% overcharge of 2 amperes for 16 hours, followed by discharge for 30 minutes at 10 amperes (C/2). The cell became 0.06 watts endothermic during the first 12 hours of charging (to 12% overcharge), but began releasing heat at that time and by the end of the charging cycle was releasing heat at a 1.5 watt rate. The initial discharge current of 10 amperes resulted in an increased heat release of 0.68 watts. The cell was then cycled by charging at 5.75 amps for 60 minutes followed by discharge at 10 amperes for 30 minutes. This was repeated for 47 cycles. The thermal effects, cell voltage, and current were recorded continuously. The data obtained are tabulated in Table 3. A typical example of the thermal effects accompanying the cycling is shown in Fig. 19. During charging, the cell is endothermic for about 65-70% of the cycle and then inverts thermally and becomes rapidly more exothermic as the charging cycle continues. About two cycles are required for the cell to adjust thermally from the charging process. After this time,

TABLE 3

CYCLING OF 20 AH CELL

Cycling Conditions: Discharge 30 min at 10 amps to 25% depth; recharge 60 min at 5.75 amps to 115%; recharge voltage upper limit of 1.48 volts.

Cycle	Heat Flow Start Watts	End Watts	Difference Watts	Peak at % of Charge	Minimum Cell Voltage	Voltage Limit at % Charge
1D	- 1.375	- 2.06	+ 0.68		1.235	
2C	- 2.06	- 1.03	- 1.03	2.22 at 50		83
2D	- 1.03	- 1.906	+ 0.88		1.235	
3C	- 1.906	- 0.81	- 1.10	1.48 at 73		86
3D	- 0.81	- 1.84	+ 1.03		1.235	
4C	- 1.84	- 0.81	- 1.03	1.87 at 65		86
4D	- 0.81	- 1.81	+ 1.00		1.23	
5C	- 1.81	- 0.81	- 1.00	1.81 at 73		86
5D	- 0.81	- 1.75	+ 0.94		1.225	
6C	- 1.75	- 0.81	- 0.94	1.81 at 65		86
6D	- 0.81	- 1.81	+ 1.00		1.225	
7C	- 1.81	- 0.93	- 0.88	1.81 at 65		86
7D	- 0.93	- 1.87	+ 0.94		1.225	
8C	- 1.87	- 1.00	- 0.87	1.90 at 73		86
8D	- 1.00	- 1.75	+ 0.75		1.225	
9C	- 1.75	- 0.81	- 0.94	1.84 at 65		86
9D	- 0.81	- 1.75	+ 0.94		1.225	
10C	- 1.75	- 0.81	- 0.94	1.88 at 65		86
10D	- 0.81	- 1.68	+ 0.87		1.225	
11C	- 1.68	- 0.81	- 0.87	1.77 at 70		86
11D	- 0.81	- 1.66	+ 0.85		1.22	
12C	- 1.66	- 0.81	- 0.85	1.63 at 70		86
12D	- 0.81	- 1.84	+ 1.00		1.22	
13C	- 1.81	- 1.00	- 0.81	1.89 at 65		86
13D	- 1.00	- 1.68	+ 0.68		1.22	
14C	- 1.68	- 0.94	- 0.74	1.77 at 70		86
14D	- 0.94	- 1.75	+ 0.81		1.22	
15C	- 1.75	- 1.00	- 0.75	1.84 at 73		86
15D	- 1.00	- 1.65	+ 0.65		1.22	
16C	- 1.65	- 1.12	- 0.53	1.62 at 68		86
16D	- 1.12	- 1.75	+ 0.63		1.22	
17C	- 1.75	- 1.12	- 0.63	1.69 at 60-70		90
17D	- 1.12	(- 2.03)*			1.22	

* (   ) indicated anomalous data point.

TABLE 3 (Continued)

Cycle	Heat Flow Start Watts	End Watts	Difference Watts	Peak at % of Charge	Minimum Cell Voltage	Voltage Limit at % Charge
18C	LN_2 Supply Failed			1.69 at 60-70		86
18D	LN_2 Supply Failed				1.22	
19C	LN_2 Supply Failed			1.69 at 60-70		86
19D	LN_2 Supply Failed				1.22	
20C	LN_2 Supply Failed			1.69 at 60-70		90
20D	- 0.72	- 1.53	+ 0.81		1.22	
21C	- 1.53	- 0.75	- 0.78	1.74 at 60-70		90
21D	- 0.75	- 1.59	+ 0.84		1.22	
22C	- 1.59	- 0.75	- 0.84	1.71 at 70		90
22D	- 0.75	- 1.75	+ 1.00		1.22	
23C	- 1.75	- 1.00	- 0.75	1.66 at 65-70		90
23D	LN_2 Supply Failed				1.22	
24C	LN_2 Supply Failed			1.66 at 65-70		90
24D	LN_2 Supply Failed				1.22	
25C	LN_2 Supply Failed			1.66 at 65-70		90
25D	LN_2 Supply Failed				1.22	
26C	LN_2 Supply Failed			1.66 at 65-70		90
26D	LN_2 Supply Failed				1.22	
27C	LN_2 Supply Failed			1.66 at 65-70		90
27D	LN_2 Supply Failed				1.22	
28C	LN_2 Supply Failed			1.66 at 65-70		90
28D	LN_2 Supply Failed				1.22	
29C	LN_2 Supply Failed			1.66 at 65-70		90
29D	LN_2 Supply Failed				1.22	
30C	LN_2 Supply Failed			1.66 at 65-70		90
30D	LN_2 Supply Failed				1.22	
31C	- 1.62	- 0.88	- 0.74	1.66 at 65-70		90
31D	- 0.88	- 1.78	+ 0.90		1.22	
32C	- 1.78	- 0.94	- 0.84	1.72 at 60-70		90
32D	- 0.94	- 1.78	+ 0.84		1.22	
33C	- 1.78	- 0.81	- 0.87	1.81 at 60-70		90
33D	- 0.81	- 1.68	+ 0.87		1.22	
34C	- 1.68	- 0.75	+ 0.93	1.70 at 60-70		90
34D	- 0.75	- 1.68	- 0.93		1.22	
35C	- 1.68	- 0.63	+ 1.05	1.72 at 60-70		90
35D	- 0.63	- 1.69	- 1.05		1.22	
36C	- 1.69	- 0.94	+ 0.75	1.69 at 60-70		90
36D	- 0.94	- 1.78	- 0.84		1.22	
37C	- 1.78	- 0.88	+ 0.90	1.84 at 60-70		93
37D	- 0.88	- 1.75	- 0.87		1.22	

TABLE 3. (Concluded)

Cycle	Heat Flow Start Watts	Heat Flow End Watts	Difference Watts	Peak at % of Charge	Minimum Cell Voltage	Voltage Limit at % Charge
38C	- 1.75	- 0.81	+ 0.94	1.78 at 60-70		93
38D	- 0.81	- 1.75	- 0.94		1.22	
39C	- 1.75	- 0.81	+ 0.94	1.78 at 60-70		93
39D	- 0.81	- 1.72	- 0.91		1.22	
40C	- 1.72	- 0.94	+ 0.78	1.81 at 60-70		93
40D	- 0.94	- 1.69	- 0.75		1.22	
41C	- 1.69	+ 0.75	+ 0.94	1.80 at 60-70		93
41D	- 0.75	- 1.63	- 0.88		1.22	
42C	- 1.63	- 0.81	+ 0.82	1.72 at 60-70		93
42D	- 0.81	- 1.69	- 0.88		1.22	
43C	- 1.69	- 0.69	+ 1.00	1.72 at 60-70		93
43D	- 0.69	- 1.69	- 1.00		1.22	
44C	- 1.69	- 0.81	+ 0.88	1.81 at 60-70		93
44D	- 0.81	- 1.69	- 0.88		1.22	
45C	- 1.69	- 0.69	+ 1.00	1.74 at 60-70		93
45D	- 0.69	- 1.75	- 1.06		1.22	
46C	- 1.75	- 0.94	+ 0.81	1.84 at 60-70		93
46D	- 0.94	- 1.63	- 0.69		1.22	
47C	- 1.63	- 0.75	+ 0.88	1.74 at 60-70		93

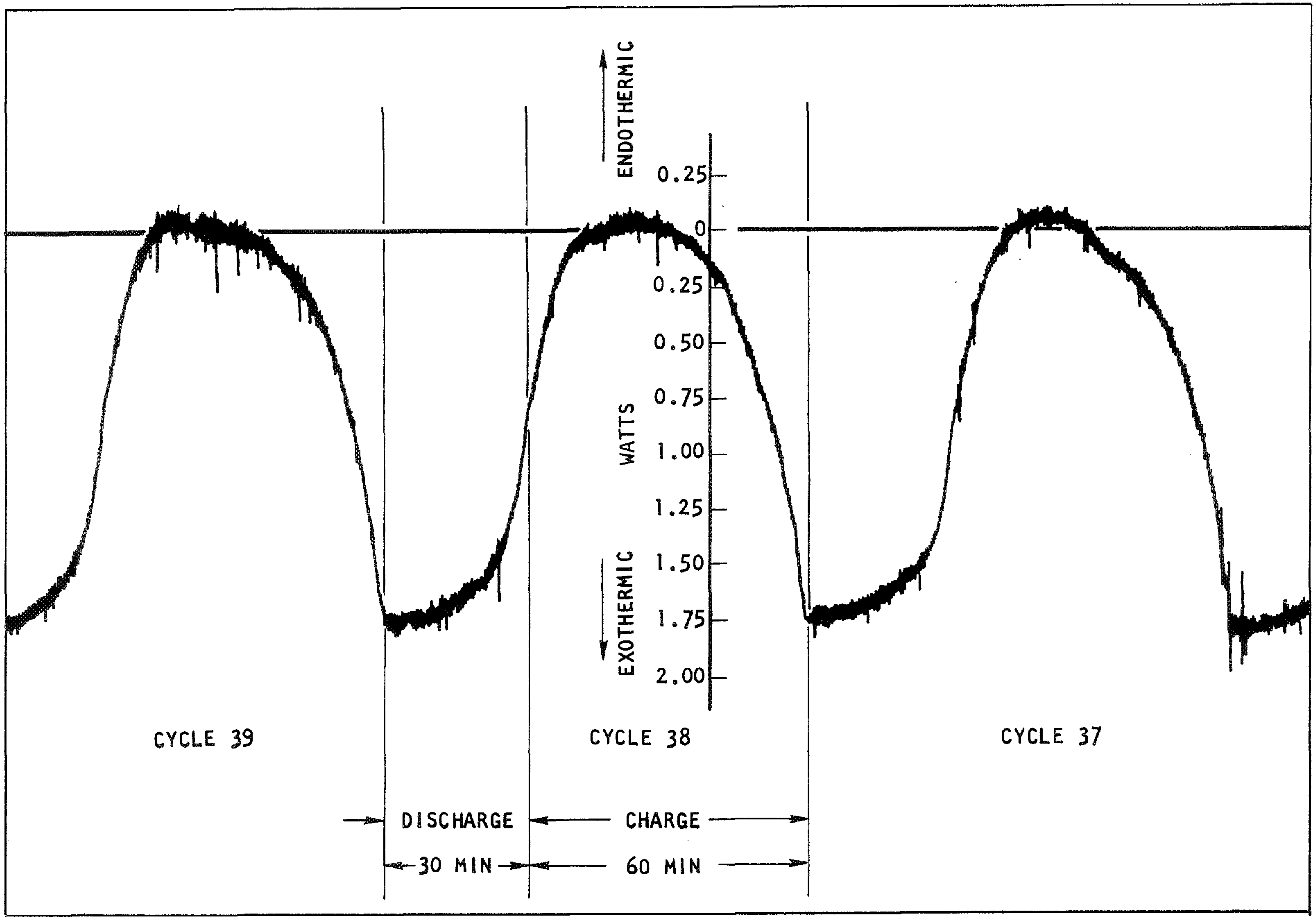


Figure 19. Chart Record During Cycling of 20 A-H Cell

the peak heat release during discharge averaged 1.72 $\pm$ 0.05 watts. The peak heat absorption averaged 0.05 watts. The sum of these values, averaged for each cycle, indicates a thermal fluctuation of about 1.77 $\pm$ 0.06 watts during a typical cycle.

Voltage Effects. The cell voltage during charge was limited to 1.48 volts. The charging current was automatically cut back to maintain this voltage. Voltage saturation was reached during each charge cycle. The percentage of the charge cycle required before saturation increased monatomically from 83% to 93% from the second through the forty-seventh cycle. The minimum voltage during discharge dropped gradually from 1.235 to 1.21 volts during the cycling.

REFERENCES

1. Mechanical Engineers Handbook, Lionel S. Marks Fifth Edition, McGraw-Hill, New York, New York (1951).

2. Johnston, W. V., "Development of a Calorimeter for Spacecraft Batteries," Report No. R-8295, Design Study Phase, September 1970.

APPENDIX A

ALIGNMENT PROCEDURE FOR WATTMETER
(See Figure 14)

Preparation

Disconnect the jumper between terminals 3, 4, and 5 on the strip at the rear of the chassis. Obtain an oscillator capable of supplying 10 volts-peak (20 volts peak-to-peak) at 10 Hz, a d-c voltmeter with resolution to 5 digits, a meter capable of reading 10 cps a-c in millivolt levels (absolute accuracy is not important), and a stable (0.05%) voltage (d-c) supply (0-75 vdc).

Procedure

1. Connect terminals 4 and 5 to 2 or 8 (common). Connect d-c meter (+) to terminal 6, (-) to terminal 8. Adjust R17 for zero output at terminal 6. Disconnect terminals 4 and 5 from common.

2. Connect oscillator to terminal 4 and connect terminal 5 to common (terminal 2 or 8). Set oscillator to 20 V.P-P. at 10 Hz. Connect a-c meter to terminal 6. Adjust R15 for minimum reading. Disconnect terminal 5 from common.

3. Connect oscillator to terminal 5 and terminal 4 to common. Adjust R16 for minimum output at terminal 6. Disconnect terminal 4 from common.

4. Restore jumper between terminals 4 and 5. Connect 10 volts to terminals 4 and 5 (as read on the d-c voltmeter). Connect d-c meter (+) to terminal 6, (-) to terminal 8. Adjust R14 for reading of 10 volts on terminal 6.

5. Connect d-c meter (+) to terminal 9, (-) lead to terminal 8. Connect terminals 4 and 5 to terminal 8. Adjust R19 to obtain zero at terminal 9. (Be sure offset control is at zero setting for this step.)

6. Connect terminal 1 to terminal 2. Restore the jumper between terminals 3 and 4. Connect the d-c voltmeter (+) to terminal 3 and (-) to terminal 2. Adjust R20 for zero reading at terminal 3. Check readout meter (Digilin) for zero reading. Range switch is on 5 watt scale for this step.

7. Set range switch to 50 watts. Remove connection between terminal 1 and terminal 2. Connect the voltage source to terminals 1 and 2; (+) to 1 and (-) to 2. Set voltage level to 70.711. Adjust R8 for a reading of 10 volts at terminal 3. Check Digilin meter for 50.0

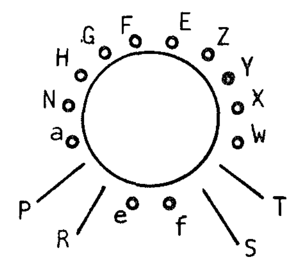
reading; if this is different by more than 2 digits check voltage at terminal 6 for 10 volts and terminal 9 for 5 volts. If these are correct, adjust the Digilin meter for 50.0 (the adjustment is a small screw in lower left corner of the bezel on the meter face in the slot which runs across the bottom of the bezel.)

8. Adjust the voltage source to 50.0 volts (25 watts). Change range switch to 25 watt range. Adjust R6 to 10 volts at terminal 3. Check reading of 25.0 on the Digilin meter.

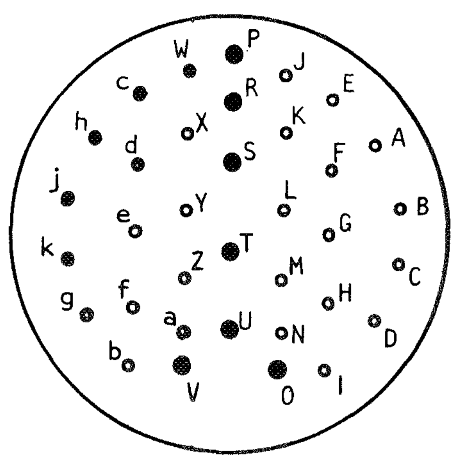
9. Change range switch to the 5 watt range. Adjust the voltage source to 22.361 volts. Adjust R4 for reading of 10 volts on terminal 3.

APPENDIX B

PASSTHROUGH TERMINAL WIRING IDENTIFICATION



HERMETIC SEAL



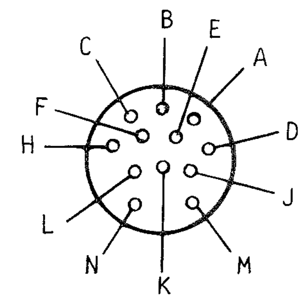
BENDIX RD 414-1009-0063

APPENDIX C

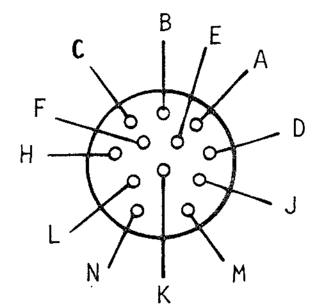
INTERCONNECTING CABLE WIRING CODE

(Bendix RD 414-1009-0063)

Pin No.	Component	Output Cable	Color Code		Panel Connector Pin
A	Top Heater	6 Cond. Shielded	Red	Twist lock	
B	Top Heater	6 Cond. Shielded	Blue		
C	Side Heater	6 Cond. Shielded	Green	Twist lock	
D	Side Heater	6 Cond. Shielded	Black		
I	Bottom Heater	6 Cond. Shielded	Brown	Twist lock	
O	Bottom Heater	6 Cond. Shielded	White		
P	Main Heater Current	12 Cond. Intercom	Black	(green)	a
R	Main Heater Current	12 Cond. Intercom	White		b
S	Calibration Heater Current	12 Cond. Intercom	Red	(red)	c
T	Calibration Heater Current	12 Cond. Intercom	Black		d
J	Main Heater Potential	12 Cond. Intercom	Green	(blue)	e
K	Main Heater Potential	12 Cond. Intercom	Black		f
L	Calibration Heater Potential	12 Cond. Intercom	Blue	(blue)	h
M	Calibration Heater Potential	12 Cond. Intercom	Black		j
U	Spare #30 Pair	12 Cond. Intercom	Black	(blue)	k
V	Spare #30 Pair	12 Cond. Intercom	Yellow		l
h	Thermocouple Top	12 Cond. Intercom	Green	(blue)	a
j	Thermocouple Top	12 Cond. Intercom	Black		b
k	Thermocouple Side	12 Cond. Intercom	Blue	(blue)	c
g	Thermocouple Side	12 Cond. Intercom	Black		d
c	Thermocouple Bottom	12 Cond. Intercom	Yellow	(blue)	e
d	Thermocouple Bottom	12 Cond. Intercom	Black		f
e	Thermister	12 Cond. Intercom	Brown	(blue)	j
f	Thermister	12 Cond. Intercom	Black		h
w	Pressure Transducer	12 Cond. Intercom	Black	(red)	k
x	Pressure Transducer	12 Cond. Intercom	Red		l
y	Pressure Transducer	12 Cond. Intercom	White		m
z	Pressure Transducer	12 Cond. Intercom	Black		n
E	Strain Gage Leads	6 Cond. Shielded	Red		A
F	Strain Gage Leads	6 Cond. Shielded	Black		B
G	Strain Gage Leads	6 Cond. Shielded	Blue		C
H	Strain Gage Leads	6 Cond. Shielded	Green		D
N	Adhydrode	6 Cond. Shielded	White		E
a	Adhydrode	6 Cond. Shielded	Brown		F



Amphenol 67-02E14-12-S



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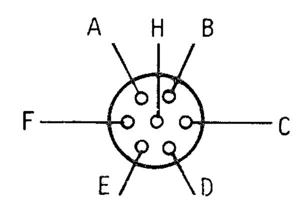
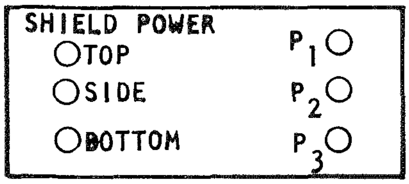


Amphenol 126-192

APPENDIX D

RELAY RACK INPUT PANEL WIRING CODE AT NASA-GODDARD



P_1 Amphenol 67-02E14-12-S

Connector Pin	Color Code		Connected To
A	Brown	Twisted pairs	Heater current supply +
B	Black		Heater current supply -
C	Red	Twisted pairs	Calibration current supply +
D	Black		Calibration current supply -
E	Orange	Twisted pairs	Wattmeter input +
F	Black		Wattmeter input -
H	Yellow	Twisted pairs	Calib. heater potential +
J	Black		Calib. heater potential -
K	Green	Twisted pairs	Not used
L	Black		Not used

P_2 - Amphenol 67-02E14-12-S

Connector Pin	Color Code	Connected To
A	Brown	Thermocouple switch + position 1
B	Black	Thermocouple switch - position 1
C	Red	Thermocouple switch + position 2
D	Black	Thermocouple switch - position 2
E	Orange	Thermocouple switch position + 3
F	Black	Thermocouple switch position - 3
H	Red	Wheatstone bridge
J	Green	Wheatstone bridge
K	Green	Pressure transducer control unit
L	Black	Pressure transducer control unit
M	Blue	Pressure transducer control unit
N	Black	Pressure transducer control unit

P_3 - Amphenol 126-192 panel mount

Connector Pin	Color Code	Connected To
A	Brown	Strain gage
B	Black	Strain gage
C	Red	Strain gage
D	Black	Strain gage
E	Orange	Adhydrode +
F	Black	Adhydrode -