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DEVELOPMENT OF CALORIMETER FOR SPACECRAFT BATTERIES

Design Study Phase

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16. Abstract This report describes the design of a calorimeter capable of measuring the thermal output of 20 ampere-hour and 100 ampere-hour sealed nickel-cadmium cells. The calorimeter as designed comprises three main units, an upper portion which contains the calorimetric unit surrounded by an adiabatic shield within a vacuum chamber, 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.			
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PREFACE

The objective of this program is 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 spacecraft load cycling. This report describes the design phase of the program and includes the electronic as well as mechanical aspects of the design. The design proposed appears to meet the stated objectives and requirements of the program.

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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 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. Therefore, conventional calorimetric techniques cannot be applied, and apparatus unique to the needs of the satellite program must be designed and constructed. This program is concerned with the design, construction, and delivery of the appropriate calorimetric apparatus.

The requirements of the program include (1) design and construction of a calorimeter capable of measuring the charge-discharge thermal output of nickel-cadmium cells, one of 20 amp-hour capacity and one of 100 amp-hour capacity; (2) testing and calibration of the instrument by cycling both cells for a specified number of cycles under simulated conditions of charge-discharge; and (3) delivery and installation of the instrument, and its calibration for both cells at -10° , 0° , 10° , 25° , and 40° C.

The needs of the program require that the sensitivity of the calorimeter be 0.05 watts (1% of 5 watts) when used with 20 AH cells and 0.25 watts (1% of 25 watts) when used with 100 AH cells. The accuracy must be 3% and the calorimeter must be stable to 1% during operation over a 24 hour period. The time lag between a signal and an output response by the calorimeter must not exceed five minutes. This report describes the design of a calorimeter which is expected to meet these requirements.

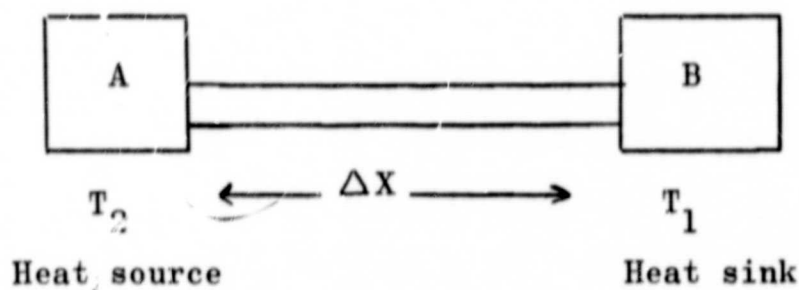
Theory

After consideration of a number of types of calorimeters, the design which appears to be most suitable, based on the criteria of sensitivity, versatility, ease and rapidity of construction, and cost is 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. 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.

The heat flow calorimeter we envision 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 for steady state heat flow (W_T)⁽¹⁾ 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

$$W_T = k A \frac{T_2 - T_1}{\Delta X} \quad (1)$$

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.

$$\text{At steady state } W_A = W_T \quad (2)$$

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 = heat added electrically to maintain T_2 constant
 W_B = heat evolved (or absorbed) by the battery
 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 as designed comprises three main units, an upper portion which contains the calorimetric unit surrounded by an adiabatic shield within a vacuum chamber, 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 (Figure 1.a, 1.b, 3)

Physical Description

The outer shell of the calorimetric vessel is in the form of an oblate spheroid formed from 2 to 1 ellipsoids joined at the equator by an "O" ring seal. The diameter is thirteen inches and the maximum height is six inches. The shell is made of 0.050 in. 6061-T6 Aluminum Alloy and is designed to operate under a five atmospheres pressure differential. Pressurization of the shell eliminates the need for clamping the cell to offset internal pressure. Sterling silver can also be used if the thermal conductivity of alloyed aluminum unduly increases equilibrium time. The calculations made to determine the wall thickness required were based on a 20,000 psi yield. They are shown in detail in Appendix A. The "O" ring flanges are also made of heat treatable aluminum alloy as is the inner "O" ring compression ring. The compression ring also serves to support the two piece cell support platform at four points.* The cell platform is made in two halves;

* The cell support platform shown in Fig. 1 is that for a 100 AH cell. The support platform and heatflow rod are removable as a unit and may be replaced with a smaller unit when a 20 AH or smaller cell is used.

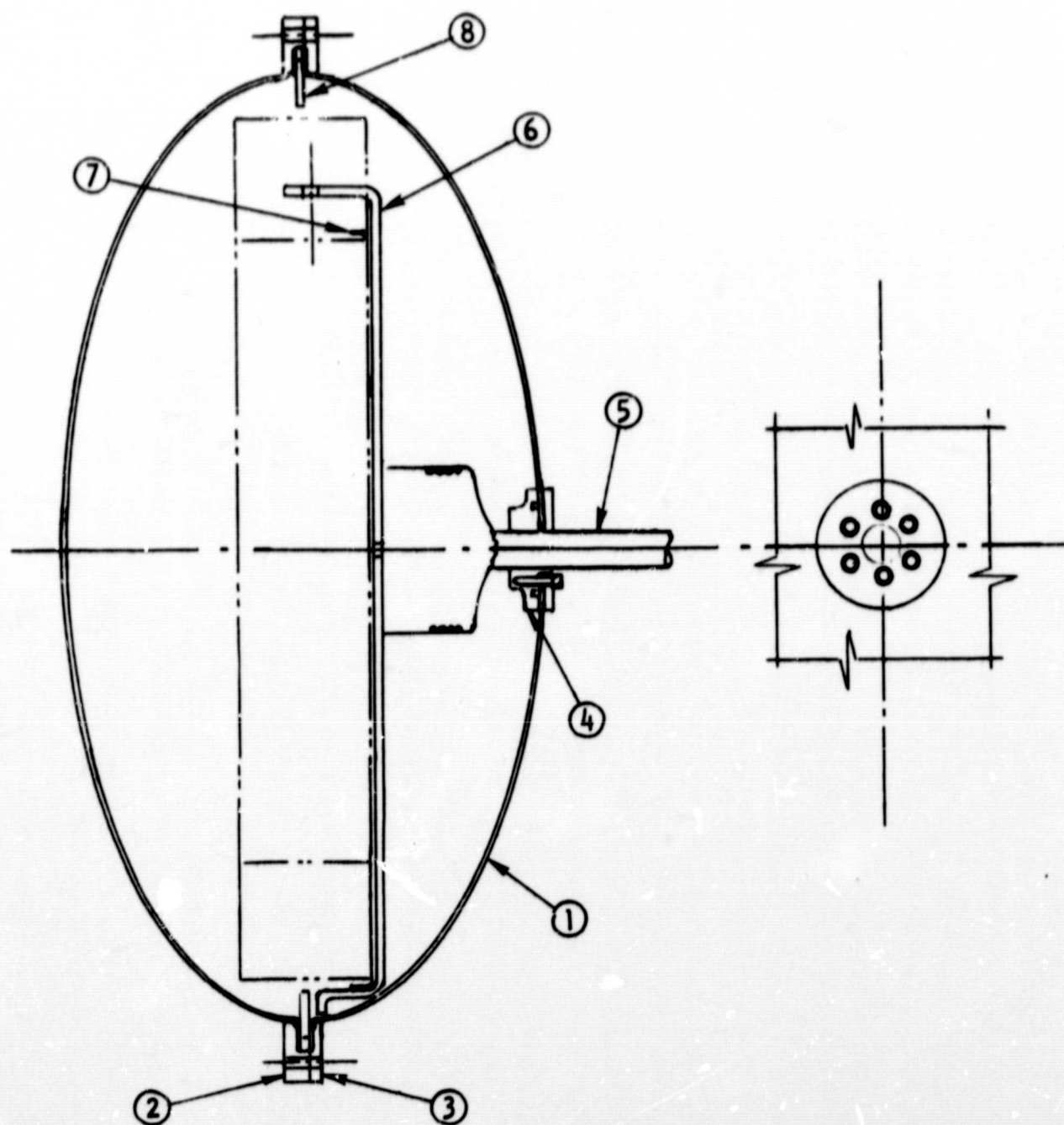


Figure 1.a. Cross Section of Calorimeter Vessel

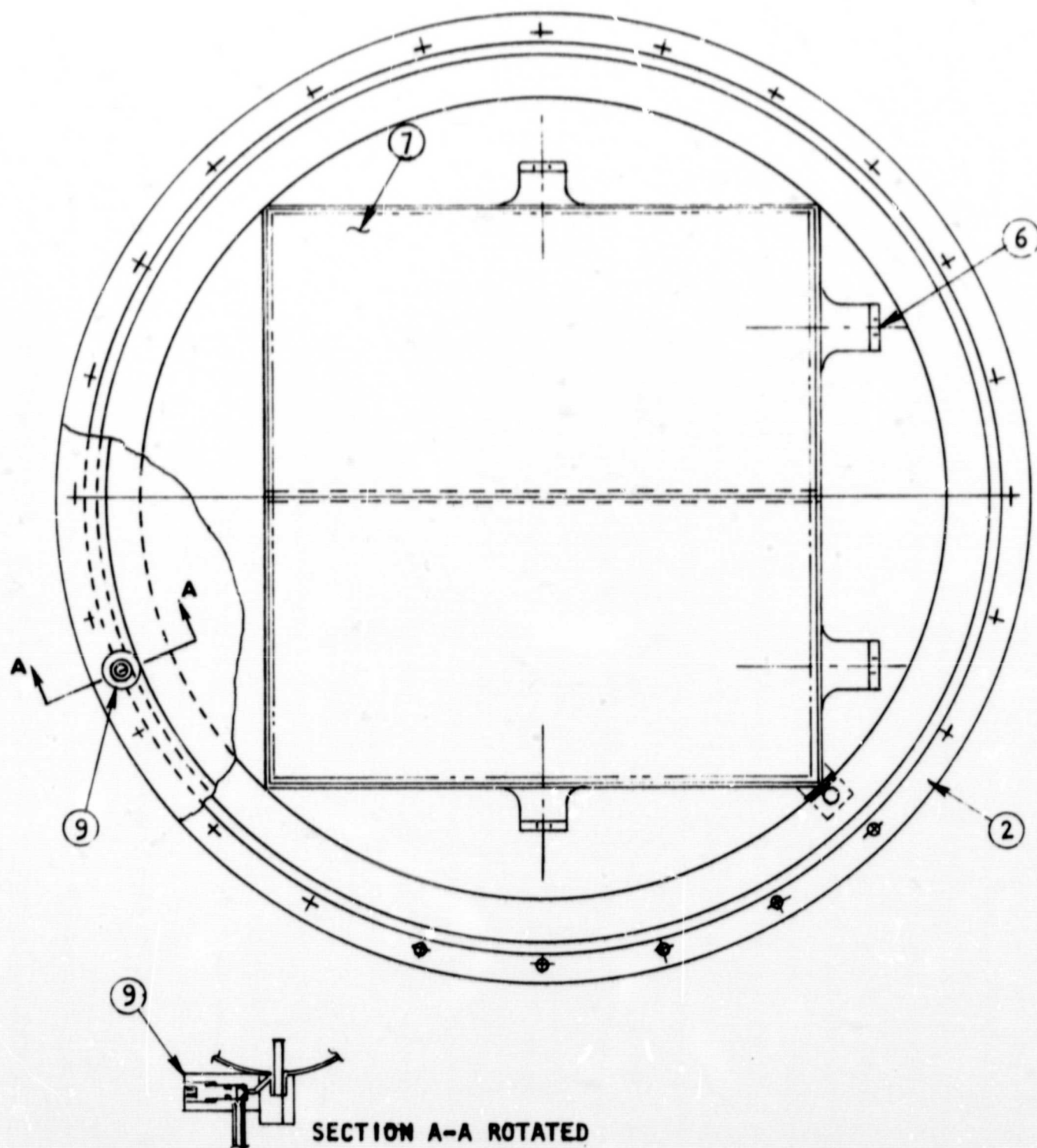


Figure 1.b. Top View of Calorimeter Vessel

each half is electrically insulated from the compression ring and from each other. The cell support platform halves serve as electrical conductors and have tabs to bring the battery charging current to the cell electrodes. Tabs are provided along the side as well as at one end of the plate to handle cells with opposing electrodes. The cell support platform is made of 0.125" thick fine silver. Sitting on the cell support platform and separated from it by a 0.00025 inch Mylar polyester sheet is a shallow silver tray of 0.030 inch thickness. The cell being tested lies on its side on the tray. A small amount of liquid on the tray enhances thermal contact between the cell and the tray.

Half cylinders of silver of 1 inch radius and 1 1/2 inches long are silver soldered to the cell support platforms and cemented together with 1/4 mil. Mylar insulation between them. In this way a two inch diameter cylinder is formed which connects the heat source with the similarly split and joined copper rod (0.448 in. diameter) which carries the heat and battery charging current to the heat sink which is immersed in liquid nitrogen. Helium at four atmospheres pressure serves as an exchange gas and also provides an external hydrostatic pressure to counter any gas pressure built up in the cell. A small valve located on the bolt circle is used for filling the vessel.

A temperature sensing thermister is located in a well in the silver cylinder and a one hundred ohm main control heater is wrapped non-inductively around the silver cylinder. A one hundred ohm calibration heater is fastened to the underside of the cell support plate. Electrical leads for use with pressure transducers and a third electrode are also located within the calorimeter vessel. The electrical leads pass out of the calorimeter through the same epoxy-lucite seal used by the copper conduction rod.

Thermal Design

The sensitivity and response time of the calorimeter will depend on the thermal mass of the calorimeter and the thermal diffusivity of the materials of construction.* 6061-T6 Aluminum Alloy, silver, and sterling silver (12% copper) 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 volume of metal in each portion of the calorimeter has been computed as shown in Appendix B. The outer shell of the calorimeter vessel has a metal volume of 329 cubic centimeters and a weight of 888 grams. This weight times the specific heat ($0.217 \text{ cal deg}^{-1} \text{ g}^{-1}$) gives a thermal mass of 192.5 calories per degree. The support structures inside the calorimeter for a 100 AH cell have a volume, weight and thermal mass of 238 cc, 2646 grams and 138 cal/deg, respectively. The total thermal mass for the empty calorimeter is the sum of the two portions or 329 cal/deg.

A smaller, lighter support platform is designed for use with a 20 AH cell. Its volume, weight and thermal mass are 54 cc, 567 grams and 31 cal/deg, respectively. This gives a total thermal mass of 209 cal/deg for a 20 AH cell configuration.

If the thermal mass of a 20 AH cell is $180 \text{ cal/deg}^{(2)}$, the thermal mass of a 100 AH cell is estimated to be 800 cal/deg. The minimum time for an output sensor with a resolution of $.01^\circ\text{K}$ to sense a 0.05 watt or 0.25 watt change in input power is shown in Table 1 for the various combinations of calorimeter and cells. The response time for the calorimeter and the 100AH cell meets the design basis of 300 seconds or less but the calorimeter containing the 20AH cell requires a slight excess of time. Minor design modifications during construction should save some weight and thereby reduce the time.

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

TABLE 1

	Thermal Mass cal/deg	Heat for .01°K Rise, cal.	Heat Input Rate, watts	Time sec
Calorimeter	324	3.24	0.05	259
Calorimeter	324	3.24	0.25	54
Cal. + 100 AH Cell	1124	11.2	0.25	186
Cal. + 20 AH Cell	389	3.89	0.05	311

Transient Effects

The temperature distribution throughout the cell support structure and the region at the top of the heat conducting rod was determined on a computer as an aid in determining the thickness of the cell support structure and the location of the main control heater and temperature sensor. The HEAT program is a generalized heat transfer program capable of solving transient and/or steady state problems in one, two or three dimensional Cartesian or cylindrical systems. The program is an up-dated version for the IBM 360 of a program originally written for nuclear reactor heat transfer problems, and appeared originally as ORNL-2734 and ASTRA 417.50.

The temperature distribution in the support structures for the case of 25 watts heat generation distributed uniformly over the interface between the cell and the silver tray and flowing down the silver cylinder and copper conductor to the heat sink (Fig. 2.b), shows a maximum ΔT of 1.7 degrees K within the support plate. An additional 0.2° of a degree temperature drop occurs across the MYLAR insulation. Thus the calculated cell surface temperature at 25 watts heat flow is about 2 degrees higher than that at quiescent state. There is also a 2 degree temperature drop in the silver cylinder between the support plate and copper heat flow rod which is within the calorimeter vessel. This temperature gradient should remain constant during operation if the control heater is located within the top half inch of the silver cylinder because the heat flow

remains constant for any combination of control heater power and cell heat generation that totals 25 watts. A portion of the temperature grid is shown in Figure 2.a. Operation at 40°C with the design heat flow of 33.5 watts will increase this internal gradient to about 2.5 degrees but will not affect the temperature in the vicinity of the cell.

The length of time it will take to sense a step change in temperature has been calculated for the case of a slab one surface of which is suddenly increased in temperature. (3)

$$T_c = T_s \left[1 - S(z) \right] \quad (3)$$

where T_c and T_s are the temperature of the two surfaces, z is $\frac{\alpha t}{l^2}$,

$$S(z) = \frac{4}{\pi} \left(e^{-\pi^2 z} - \frac{1}{3} e^{-9\pi^2 z} + \frac{1}{5} e^{-25\pi^2 z} - \dots \right) \quad (4)$$

α is the thermal diffusivity, t is the time required, and l is twice the wall thickness. Substituting into the equation the appropriate value of α and setting l equal to 10 cm gives the result that in 25 seconds the sensor will show 92% of the temperature rise introduced 5 centimeters away at the cell surface. If 25 seconds is added to the time calculated in Table 1 to generate a .01° temperature rise at a 0.25 watt heating rate, the response time becomes 208 seconds.

HEAT CONDUCTION ROD

Physical Description

The heat conduction rod (Figure 3) is silver soldered to the bottom of the silver cylinder in the calorimeter, it passes out of the calorimeter, proceeds through holes in the adiabatic shield, and after passing through a low temperature electrical insulating seal enters a liquid nitrogen bath where it dissipates its heat through fins. The rod is made of two copper half cylinders cemented together with a sheet of 0.00025 inch Mylar polyester film between them. The diameter of the rod is 0.448 inches and the length is fourteen inches. Two half



cylinders of one and a half inch diameter copper, two inches long, shaped to receive the heat conduction rod, containing nine-5/8 inch long fins are joined to the lower two inches of the copper rod with tin-indium solder. The electrical connection for the battery charging circuit are made at 1'-32 taped holes in the bottom of the half cylinders.

Thermal Design

The heat carrying capacity of the rod was computed by means of the equation for unidirectional heat flow along an insulated rod:⁽¹⁾

$$P = KA (T_2 - T_1) / \Delta X \quad (5)$$

where K = mean thermal conductivity of copper
 A = cross sectional area of the rod
 $T_2 - T_1$ = temperature gradient over the length ΔX

If $K = 4.2 \text{ watts cm}^{-1} \text{ } ^\circ\text{K}^{-1}$, $A = 1.04 \text{ cm}^2$ and $\Delta X = 30.5 \text{ cm}$, the calculated heat flow for upper temperatures of -10°C , 0°C , 25°C and 40°C is 26.4 watts, 27.8 watts, 31.3 and 33.5 watts, respectively.

The heat flow may be varied by changing the temperature of the heat sink. For example, if the heat sink is immersed in a dry ice-acetone bath (-77°C) the heat flow at 25°C is reduced to 14.5 watts.

Barometric Pressure Changes

Because barometric pressure changes will affect the boiling point of a liquid, the effect of such changes on the heat sink temperature were considered. If we assume that it is unlikely that the barometric pressure will change by more than $\pm 35 \text{ mm}$ ($\pm 1.5 \text{ inches}$) in a twenty four hour period, the boiling point of liquid nitrogen will not change more than $\pm 0.35^\circ\text{C}$. A change of this magnitude in the heat sink temperature when substituted into the heat flow equation will change the heat flow by only $\pm 0.05 \text{ watts}$. This variation is just equal to the maximum sensitivity required of the calorimeter. In the unlikely possibility that barometric pressure should vary more than this, the open dewar

could be replaced with a closed one and a simple pressure regulator used to main constancy. The temperature of the calorimeter vessel will be held constant to ± 0.01 deg and should cause negligible changes in heat flow due to temperature variations.

ADIABATIC SHIELD

Physical Description

The calorimeter is surrounded by an adiabatic shield of copper. The shield consists of a 14 inch cylinder of 0.065 wall thickness and top and bottom plates of 0.125 in thickness. A thin wash of gold will be electroplated to the inner surfaces to provide a reproducible and tarnish resistant surface of low emmissivity. The calorimeter will be supported by heavy nylon cord from a ring located near the top of the cylindrical shield. The outer surfaces of the adiabatic shield will be covered uniformly with noninductively wound heater wire to provide three separate 100 watt heaters.* 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 will be supported above the base plate by a ring of Micarta resin impregnated fabric.

* All the electrical leads from the calorimeter vessel will be wound under the shield heater windings to provide the thermal tempering needed to reduce net conductive heat transfer between the calorimeter and external surroundings.

VACUUM CHAMBER AND OUTER JACKET

The calorimeter vessel and adiabatic shield will be surrounded by a metal cylinder 16 inches in diameter which serves as a vacuum jacket. The vacuum seal at the top and bottom will be made at flanges fitted with flat rubber compression gaskets. Cooling coils will be soldered on top, side and baseplate to provide a means of cooling the chamber. Two inches of styrofoam insulation will completely surround the vacuum jacket.

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. The lower end forms a detachable skirt which is immersed in liquid nitrogen and retains the gas produced by the vaporization of the liquid nitrogen in the heat sink. This gas is conducted to the outside through a vent tube attached near the top of the inner chamber. The gas flow rate can be used to measure the amount of heat flow down the conductor since the heat of vaporization of nitrogen is known. The unit is double 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 are included in a later section. The vacuum pump out port is provided with a 1/2 inch Veeco type vacuum coupling for connecting to a mechanical vacuum pump.

HEAT EXCHANGE

The design principle of the calorimeter assumes that heat exchange occurs from the calorimeter vessel to the heat sink along the solid conduction rod and that all other means of heat exchange are both constant and negligible compared to that along the rod. To insure this condition, it is necessary to know and/or control the three means of heat exchange: radiation, conduction and convection. Convective heat exchange has been eliminated by placing the calorimeter in a vacuum of 0.1 mm or better. The following paragraphs cover the calculated radiative and conductive heat exchange as well as heating due to electron flow in the heater leads.

Radiative Heat Exchange

The calorimeter will be surrounded on all sides except around the copper heat leak by a heat shield which will be held automatically at a temperature no more than $\pm 0.01^\circ$ different from the surface of the calorimeter vessel. An approximate calculation of the radiative heat transfer between these surfaces can be made by the Stefan-Boltzman equation⁽¹⁾

$$P_1 = \sigma A_2 F_{12} (T_1^4 - T_2^4) \quad (6)$$

or if T_1 and T_2 are close together, by the derivative form

$$\frac{dP}{dT} = 4 \sigma A_2 F_{12} T^3 \quad (7)$$

where P_1 is the rate of heat exchange from the shield to the calorimeter

σ is the Stefan-Boltzman constant, 5.6×10^{-12} watts $\text{cm}^{-2} \text{K}^{-4}$

A_2 is the area of the calorimeter

F_{12} is a dimensionless factor determined by geometry and emittances.

The area of an oblate spheroid⁽³⁾ is $2\pi a^2 + \frac{b^2}{\epsilon} \log \frac{1+\epsilon}{1-\epsilon}$

where $\epsilon^2 = 1 - \frac{b^2}{a^2}$ and a and b (major and minor axis) are 6 inches and 3 inches respectively. The area of the calorimeter is 1604 cm². F_{12} for the geometry in this calorimeter can be approximated for the case of parallel plates⁽¹⁾ where

$$F_{12} = \frac{e_1 e_2}{e_2 + e_1 (1 - e_2)} \quad (8)$$

where e_1 and e_2 are the emissivities of the calorimeter and shield and are each equal to 0.03⁽⁴⁾ since the surfaces are gold plated. F_{12} is equal to 1.2×10^{-2} . Substitution into the differential form of the equation at a temperature of 300K gives a calculated heat exchange of 1.46×10^{-2} watts per degree temperature difference or 1.46×10^{-4} watts for control to 0.01 degree. It is evident that radiation heat exchange should not be an important factor even for much poorer shield control.

Radiative heat exchange will also occur between the heat conducting rod and the walls surrounding it. Equation (6) must be used for calculation rather than the differential form of the radiation equation because there are places where there is an appreciable temperature difference between the rod and the walls. For this case $A_2 = 3.58 \text{ cm}^2$ and $F_{12} = 1.6 \times 10^{-2}$ since e_1 for copper is .02, and e_2 for stainless steel is .08. The result is $P = 3.2 \times 10^{-13} (T_2^4 - T_1^4)$. A graphical estimate of the temperature profile of the rod and walls between the calorimeter vessel and the liquid nitrogen temperature reservoir is shown in Figure 4. The average heat exchange for each inch along the conduction rod was calculated and is shown in Table 2. The heat exchange was again calculated for portions of the rod which might be affected by changes in wall temperature of ten degrees. The results are shown in the third column. It is evident that changes in ambient temperature will have little effect on the heat flowing down the rod and that the absolute heat exchange is less than .01% of the total heat flow.

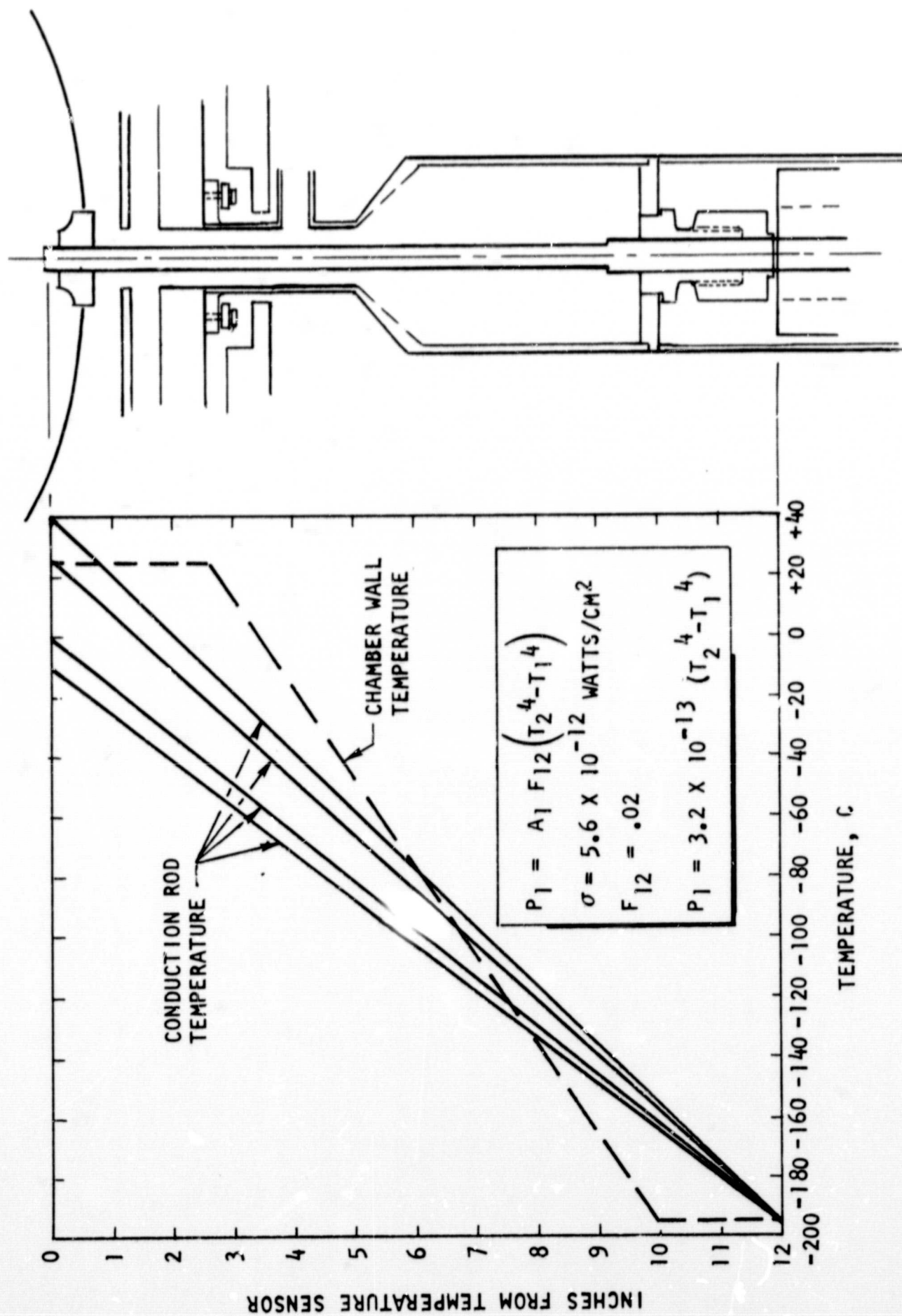


Figure 4. Temperature Differences Along Conduction Rod

TABLE 2

HEAT EXCHANGE TO ROD FROM VACUUM JACKET

Distance From Top of Rod (inches)	Heat Exchanged watts x 10^{-4}	Heat Exchanged With 10° Increase In Ambient Temp. watts x 10^{-4}
0-1	2.9	2.9
1-2	8.0	8.0
2-3	10.7	10.7
3-4	7.9	11.9
4-5	3.9	5.7
5-6	1.8	3.2
6-7	0.3	0.3
7-8	-0.4	-0.4
8-9	-0.5	-0.5
9-10	-0.7	-0.7
Total Heat Exchange	3.37×10^{-3} watts	4.1×10^{-3} watts

Resistive Heating in Electrical Leads

The charge-discharge cycling of the cells will require currents as high as 50 amperes during discharge of 100 AH cells. This high current will pass through the copper heat conducting rod from the terminals in liquid nitrogen to the silver cylinder in the calorimeter vessel and then along the silver cell support plate to the tabs where contact is made with the terminals of the cell. The area for conduction in the calorimeter vessel is made quite large for heat transfer reasons and little I^2R heat generation is expected except possibly as a result of contact resistance at the cell terminals. The area for conduction along the copper heat flow rod is limited by thermal considerations. Accordingly, estimates of the resistive heating along this rod were made. The area of each half of the heat conducting rod is 0.52 cm^2 . A copper conductor of B&S gage "0" has a cross section of 0.53 cm^2 and an electrical resistance of 8.2×10^{-6} ohms per inch at 20°C ⁽³⁾. The heat generated per inch by a pair of such wires carrying a current of 50 amperes may be computed from Ohms law.

$$\begin{aligned} W &= I^2 R \\ &= 2.5 \times 10^3 \times 8.2 \times 10^{-6} \times 2 \\ &= 4.1 \times 10^{-2} \text{ watts per inch at } 20^\circ\text{C} \\ &\text{and } 3.7 \times 10^{-2} \text{ watts per inch at } 0^\circ\text{C} \end{aligned}$$

This heat generation is the largest extraneous source of heat input to the calorimeter. Fortunately, it is a constant since the charging and discharging cycles are done under constant current conditions and can be measured during calibration of the calorimeter. Because the rod drops in temperature about 25 degrees per inch and the conductivity of copper increases rapidly with decreasing temperature, only a few inches of rod are subject to this heat generation. The total heat generation is estimated to remain less than 2.5×10^{-1} watts which is less than 1% of the design heat flow down the rod and probably will not be detected.

The main control heater is designed to generate thirty five watts and has a resistance of 100 ohms. This means that the B&S#20 current leads will carry up to 0.600 amperes of current. Since the resistance of B&S#20 copper wire is 9×10^{-3} ohms/ft at 20°C , approximately 6.4×10^{-3} watts of heat per foot will be generated in the leads. Because the lead length within the calorimeter is not more than a few inches, this heat generation is unimportant.

The calibration heater is also of 100 ohms resistance and will generate up to 25 watts. The lead wire is about four inches of B&S#20 copper wire. The heat generation of 5×10^{-3} watts per foot is also unimportant.

The current carried by the lead wires for pressure transducers or other items which might be installed inside the calorimeter is not expected to be more than a few milliamps and thus would not contribute any noticeable extraneous heating.

ELECTRICAL MEASUREMENT AND CONTROL

POWER MEASURING SYSTEM

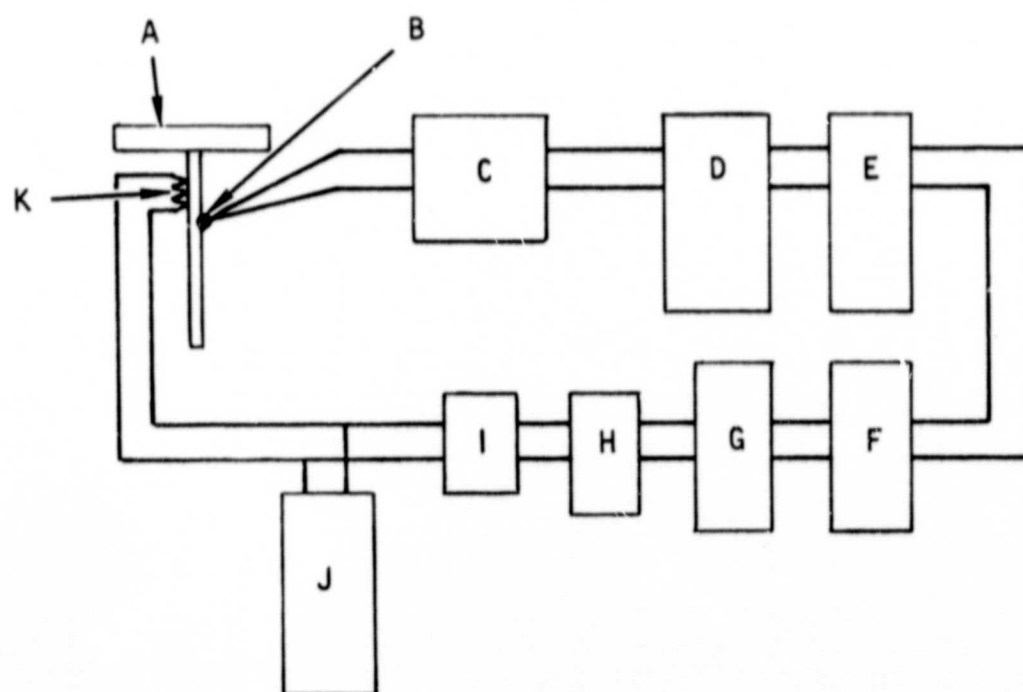
The power measuring system maintains the thermal head by sensing the temperature of the silver cylinder located in the calorimeter vessel and automatically adding or removing power from the control heater which is wound noninductively around the silver cylinder. Thermal effects originating in the nickel-cadmium cell or in the calibration heater will cause a change in the power required to maintain constant temperature. Such changes will be measured with a wattmeter and recorded. The system consists of the following items and is shown in Fig. 5.

Sensors

A bridge using either thermistors (4000 ohm) or platinum resistance thermometers will be used. Either approach will provide the 0.01°K temperature resolution and 0.25°K absolute temperature indication desired. The thermistors are smaller in size than the PRT. The type of sensor will be determined after additional tests are made. We have decided to eliminate thermocouples because of the difficulty of maintaining a reference temperature constant to 0.01°K over a long period of time.

Detection

The bridge output will be led to an L&N 9835-B dc amplifier serving as null detector.



- A CALORIMETER
- B TEMPERATURE SENSOR
- C WHEATSTONE BRIDGE CIRCUIT
- D D.C. AMPLIFIER
- E STRIPCHART RECORDER
- F 3 ACTION CONTROL UNIT
- G SOLID STATE A.C. POWER AMPLIFIER
- H VARIABLE VOLTAGE TRANSFORMER
- I RECTIFIER AND A.C. FILTER
- J WATTMETER
- K MAIN CONTROL HEATER

Figure 5. Block Diagram of Power Measurement System

Recorder, 3 Mode Controller

The 0 ± 5 MV output of the null detector will go to a recorder with a 0 ± 5 MV range. The recorder will be equipped with a control slidewire to work with an L&N Series 80 Electric Control (Model 10677 C.A.T. Electric Central module).

Power Supply

The output from the Electric Control unit is 0-5 ma into a 3,000-ohm load. It will control an L&N Model 11906-223 or equivalent solid state power package.

Rectification & Power Adjustment

The 0-110 VAC output of the power supply will be fed to a variable transformer and rectified to DC by a full wave solid state rectifier. This unit matches the power available from the SCR unit (2 KW) to the needs of the calorimeter heater (50 watts max.), thus providing finer control.

Wattmeter

The control heater will be 100 ohms of B&S#30 Evenohm wire, the electrical resistance of which is constant within 0.1% over the -10 C to +40 C operating range of the calorimeter. A wattmeter based upon the relationship $W = E^2/R$, obtained by squaring the voltage drop (E) across the 100-ohm load with an Analog Devices Model 424K multiplier has been designed. The unit is accurate to 0.1%. Outputs of 0-10 volts will be obtained for inputs of 0-5 W, 0-25 W and 0-50 W. The input impedance is 100 K for all ranges. The output baseline can be adjusted to provide 0 ± 2.5 , ± 12.5 and ± 25 watts.

ADIABATIC SHIELD CONTROL

The adiabatic shield control (Fig.6) is a single channel unit which senses the temperature difference between the calorimeter vessel, and the adiabatic shield surrounding it and automatically controls power input to the shield to minimize the difference. The shield control will maintain the difference to $\pm 0.1^{\circ}\text{C}$ or less. The system consists of the following items:

Electrical Calibration Unit

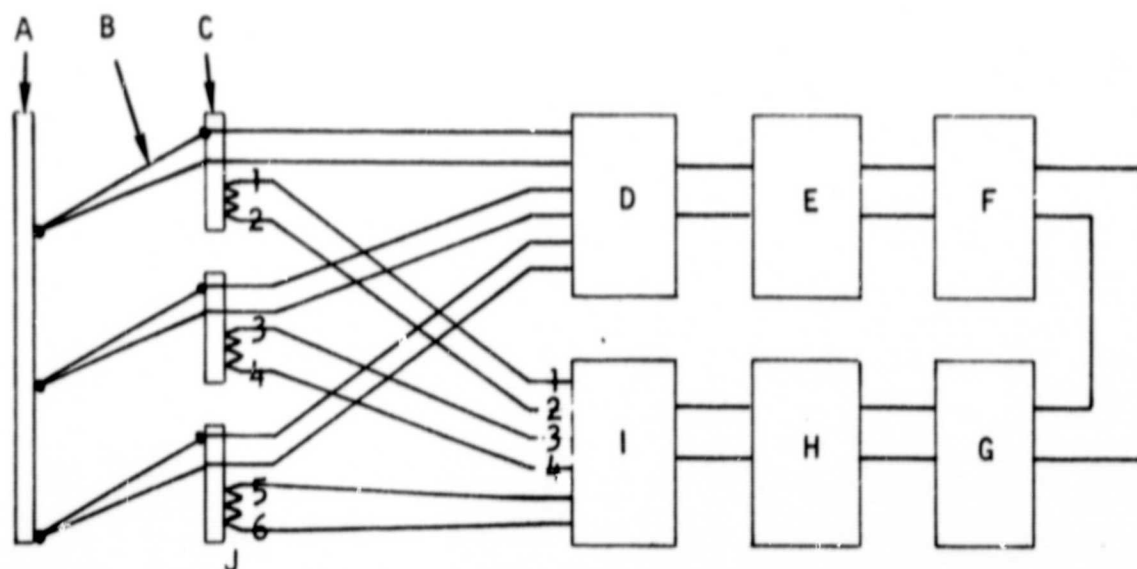
Three sets of copper-constantan thermocouples connected differentially between the calorimeter and the top, side and bottom of the adiabatic shield will be brought out of the calorimeter assembly. A selector switch (2 pole, 3 throw) selects any one of the three different thermocouples and connects it to the input of the L&N 9835-B null detector. The 0 to ± 0.5 volt output of the L&N 9835-B will be connected to a unit which will adjust the voltage output to ± 50 MV and provide a 50 MV bias voltage for connecting to a 3 mode control unit. A ΔT of 0.01°K (0.4 uv) will result in a 1 MV change in the signal to the three mode controller.

Control Unit

The three mode control unit (L&N Electromax 6261-3220-1-0 or equivalent) has a 0-100 MV input, proportional band, reset, and rate (or approach) controls, and an output of 0-5 Ma into a 2500 ohm load. A 1 MV change in input will easily be handled by these units since they are sensitive to microvolt changes.

Power Supply

The 0-5 ma output current from the control unit is fed to a solid state power supply (L&N 11906-223 or equivalent).



- 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 ISOLATION AND VARIABLE STEPDOWN TRANSFORMER
- J SHIELD HEATER

Figure 6. Block Diagram of Adiabatic Shield Extension

Power Adjustment Unit

The output of the power supply will be 0-120 VAC. This voltage will be proportioned to separate heaters located on the top, sides, and bottom of the adiabatic shield, by a panel unit containing three variable transformers and three taped output isolation transformers. Although we do not plan to rectify these supplies to DC, we will do so if AC is seen to interfere with the control functions. The electrical schematic is shown in Fig. 6.

ELECTRICAL CALIBRATION

A 100 ohm calibration resistor will be placed inside the calorimeter on the cell support mount which may be used to electrically calibrate the calorimeter system. Provisions for measuring current and potential from a power supply capable of providing up to 30 watts (.5 A, 60 V) such as the Kepco CK60-.5 M are included.

PRESSURE MEASUREMENTS

Four electrical leads terminating within the calorimeter vessel for use with bridge type pressure transducers will be provided. An additional lead for use with adhydrode terminals will also be provided. Additional leads for a strain gage will be added. The leads will be of B&S 30 gage copper.

COOLING SYSTEM

For operation below room temperature, a cooling system for the adiabatic shield will be required. A small refrigerated bath will be used to circulate ethylene glycol through the coils under the insulation surrounding the vacuum jacket.

SCHEDULE FOR REMAINING ACTIVITIES

During September the fabrication of the parts for the calorimeter mounting table, vacuum chamber and adiabatic shield should be completed and the units assembled and vacuum checked. Completion of the electrical heaters for the adiabatic shield will probably not be completed until October. The fabrication of the calorimeter vessel and its inner components is being done at an instrument shop and should be completed by the middle of October. The design of the wattmeter is complete. The electrical and electronic assembly should be complete in September and will be used to make checks on components as they are assembled. There is time in early November to permit some rework and design changes as may become necessary. Assembly and testing should be completed in November.

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3. Heat Conduction, Ingersoll, Zobel, Ingersoll, University of Wisconsin Press, Madison, 1954, p. 127.
4. Handbook of Chemistry and Physics, 45th Ed., Chemical Rubber Co., Cleveland, Ohio, 1964.

APPENDIX A

CALCULATION OF WALL THICKNESS OF OUTER SHELL

The wall thickness of a cylindrical shell due to internal pressure, is given by the relationship

$$t = \frac{PR}{S}$$

where

P is the internal pressure

R is the radius

t is the wall thickness

S is the yield strength

If P is 75 psi, R is 5.8 inches and S is 20,000 psi a wall thickness $t = \frac{75 \times 5.8}{20,000} = 0.0218$ inches is obtained.

For a 1.5 to 1 safety minimum, the wall thickness should be 0.033 inches.

APPENDIX B CALCULATION OF THERMAL MASS

A. Mass of Outer Shell

1. Volume of metal in outer shell

The volume of an ellipsoid is $V = 4.1888 abc$ where a, b, c are the radii of the major and minor axes for a 2:1 ellipsoid

$$b = c = 2a$$

$$\text{and } V = 2.0944b^3$$

$$V_{\text{metal}} = V_{\text{external}} - V_{\text{void}}$$

$$V_{\text{void}} = 2.0944b^3 \text{ when } b = 5.800 \text{ inches}$$

$$V_{\text{void}} = 408.643 \text{ cu in}$$

$$V_{\text{exterior}} = 2.0944b^3 \text{ when } b = 5.8333$$

$$V_{\text{ex}} = 415.657$$

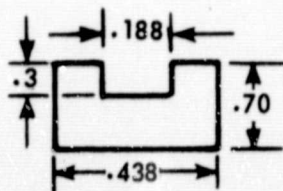
$$V_{\text{metal}} = 415.657 - 408.643 = 7.014 \text{ cu in}$$

additional metal in flange area

$$\begin{aligned} V \text{ of a flange} &= \pi(R^2 - r^2)h = \pi(R_1 + R_2)(r_1 - r_2)h \\ &= \pi(12) (.5) (.033) \\ &= .622 \text{ cu in} \end{aligned}$$

$$\text{Total volume of metal in shell} = 7.014 + .622 = 7.636$$

2. Volume of metal in the flanges



$$\text{Dia} = 12.4 \quad \text{Volume} = \pi D^1bh \text{ where}$$

D^1 = mean radius and bh = cross sectional area

$$\text{Area of section} = (.438 \times .7) - (.3 \times .188) = .2502$$

$$\text{Volume} = .2502 \times 12.4 \times \pi = 9.746 \text{ cu in}$$

3. Volume of backup ring and support tabs, 0.125 in thick, 0.55 wide

$$V = 11.4 \times \pi \times 0.125 \times .55 = 2.462$$

$$1 \times .5 \times 4 \times 0.125 \quad \frac{0.250}{2.712 \text{ cu in}}$$

Total volume of metal in outer shell = $7.636 + 9.746 + 2.712 = 20.094$ cu. in.

$$= 20.094 \times 16.39 = 329 \text{ cc,}$$

$$\text{Thermal mass} = 329 \text{ cc} \times 2.70 \frac{\text{g}}{\text{cc}} \times 0.217 \frac{\text{cal}}{\text{deg.g.}} = 191 \text{ cal/deg.}$$

B. Volume of inner cell support units for 100 AH cell.

1. Volume of small pan = $7.5 \times 7.625 \times .030 = 1.71$ cu in

2. Volume of cell support plate

$$\text{Area} = 7.5 \times 7.625 = 57.19 \text{ sq in.}$$

$$\text{Area of tabs} \quad 7.4 \times 6.25 = \frac{4.63}{\text{ " "}}$$

$$\text{Total area} \quad 61.82 \text{ sq in.}$$

$$\text{Volume} = 61.82 \times .125 = 7.728 \text{ cu in.}$$

3. Volume of cylinder on bottom of cell support plate, diameter = 2 inches, length = $1 \frac{5}{8}$ in.

$$V = \pi \times 1 \times 1.625 = 5.1 \text{ cu in}$$

$$\begin{aligned} \text{Total volume of inner parts} &= 1.71 + 7.728 + 5.1 = 14.54 \text{ cu in} \\ &= 14.54 \times 16.39 = 238 \text{ cc} \end{aligned}$$

$$\text{Thermal mass of inner parts} = 238 \text{ cc} \times \frac{.58 \text{ cal}}{\text{cc deg}} = 138.2 \text{ cal/deg}$$

$$\text{Total thermal mass} = 191 + 138 = 329 \text{ cal/deg}$$

C. Thermal mass of inner supports for 20AH cell

1. Cell support plate

$$V = 3 \times 6.5 \times 0.100 = 1.95 \text{ in.}^3 \times 16.39 = 31.9 \text{ cm}^3$$

2. Cylinder on bottom of plate = 1" dia.

$$V = \frac{\pi D^2}{4} \times 1.75 = 1.36 \text{ in.}^3 \times 16.39 = \frac{22.0 \text{ cm}^3}{\text{Total} = 53.9 \text{ cm}^3}$$

$$\text{Total} = 53.9 \text{ cm}^3$$