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DETECTION OF EXTRATERRESTRIAL MICROORGANISMS BY MICROCALORIMETRY

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Prepared for:

National Aeronautics and Space Administration
Ames Research Center
Moffett Field, California 94035

Ames Technical Monitor—Glenn Pollock

Ames Contract Administration—Robert D. Dolan

Beckman® INSTRUMENTS, INC.
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FORWARD

This Final Report is the result of a program to study the feasibility of fabricating a microcalorimeter of minimum size, weight, and power consumption for extraterrestrial life detection. This program was conducted for NASA Ames, as part of the NASA program to study methods of extraterrestrial life detection on Mars.

The microcalorimeter program was conducted by the Advanced Technology Operation of Beckman Instruments, Inc., of Fullerton, California, under the direction of the following staff: Walt Donner, Manager; Mal Greene, Chief Project Engineer; Gary Thomas, Project Engineer; William Pearson, Fred Perez, Everett Peterson, and George Reeves, engineering and technical associates.

ABSTRACT

An engineering feasibility and preliminary design study to delineate and specify the design parameters of a microcalorimetric system for the detection of Martian microorganisms has been performed by the Advanced Technology Operations of Beckman Instruments, Inc. The parameters considered were:

1. Size
2. Weight
3. Power Requirements
4. Thermal Characteristics
5. Ambient Temperature and Pressure Requirements
6. Interfacing with proposed surface sampling systems
7. Sample and Nutrient Requirements
8. Sample and Nutrients Manipulations
9. Programming
10. Interface Capabilities and Limitations
11. Data output

For completness a theoretical discussion of the key portions of a microcalorimeter is included. An optimum system is then proposed.

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1.0 INTRODUCTION

1.1 Background

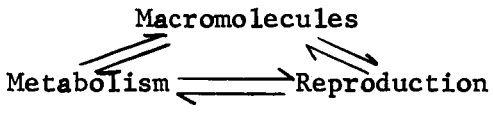
1.1.1 Why Extraterrestrial Life Detection

The Bioscience Advisory Committee for the National Aeronautics and Space Administration advised that the basic study of extraterrestrial environments should be a major goal of the post Apollo period of space exploration. The reason for this interest stems primarily from man's interest in his own origin. The detection of life on another planet would: (1) be a monumental technological achievement, (2) substantiate the theory that life originated at some other point in the universe, and (3) provide another clue as to the nature of the universe.

Probably the most important of the above mentioned reasons for extraterrestrial life detection is (2). If life is detected on Mars and contamination can be ruled out, the chemical structure is of key importance. If the chemical structure is different than that of life on the earth it would give sufficient proof for the separate origin of extraterrestrial life. If the chemical structure is the same, it means one of two things: (1) Contamination, (2) life (maybe in a different state of evolution) probably comes from a common origin.

1.1.2 What Is Life?

Probably the greatest controversy has raged over the philosophical question, "What is life?" Rather than add to the existing controversy by adding yet an another definition, only the minimum requirements or attributes of life will be presented. A circular equation can best be used to describe the three basic attributes of life: Macromolecules, Metabolism, and Reproduction. This equation takes the form:



A fourth attribute of life that is discussed at some length in Appendix A is adaptation. It is considered outside the scope of this report to philosophically defend the use of these three fundamentals of life. Rather one of the three will be used as it has direct application in the use of microcalorimetry.

1.1.3 Chemical Structure of Extraterrestrial Life

Life as it is known on earth is based upon carbon. A small yet real possibility exists that extraterrestrial life might be based upon some other element or solvent system. Although extraterrestrial life might be based upon some chemical system other than carbon, there is a reasonable probability that the three basic fundamentals of life will still hold. This leads to the conclusion that a life detection system based upon one of the three fundamentals might possibly detect life that would be undetectable to a straight chemical system. This simply says that there is an increased

probability of life detection when a system is capable of looking at a pure fundamental.

1.1.4 Environmental Considerations

Another requirement for extraterrestrial life detection is that the life detection system must be capable of operation in an exotic environment. If a terrestrial environment were carried along with the system, equipment reliability would be higher. However, this would be much the same as examining the viability of aerobic bacteria in an anaerobic environment. The life that is being sought, however, is in an exotic environment. The ideal system in this environment will perform measurements and disrupt the habitat of native organisms as little as possible.

1.1.5 Instrumentation

The first problem of a life detection system is sample collection and manipulation. Assuming that through proper engineering the problems of sample collection and manipulation are solved so that a soil sample is presented in the proper configuration to the life detection system, obviously, the next problem is sample analysis.

Of all the life detection systems that are operable, only the Wolf Trap looks at a fundamental attribute of life without utilization of chemical analysis. Its operation is also independent of the element upon which the life might be based. The one possible negative factor to the Wolf Trap is the fact that the soil sample is placed in a liquid medium which might very well be a hostile environment to any organisms contained in it.

1.2 The Microcalorimeter

1.2.1 The Basic Concept

Microcalorimetry is as the name implies, the measurement of very small amounts of heat. There are many types of calorimeters, but the basic concept holds for all types. The object of interest is monitored by a heat sensor that observes the heat taken on or given off in some reaction. This observation is then presented as some form of read out. The sensor can be an infra-red sensor, a thermometer, a heat resistance bridge, a thermocouple, etc.

1.2.2 The Microcalorimeter as a Life Detection Instrument

The microcalorimeter, like the Wolf Trap, looks at a fundamental of life; in this case metabolism. Also like the Wolf Trap, its operation is independent of chemical analysis and the sample's elemental base. Unlike the Wolf Trap, the sample need not be placed in a foreign medium. Temperatures and environmental atmosphere need not be changed from the sample's native habitat. The experiment is non-destruct and monitored in real time. The detection of life by microcalorimetry is in reality an *in situ* experiment. Theoretically, using differential techniques, an experiment could be run even in the harsh Martian enviornment where the temperature of the microcalorimeter would follow the diurnal temperature variations.

The only factor that keeps the experiment from being a perfect *in situ* experiment is that the sample will not be subjected to light or any other radiations except those inherent in the soil. If some form of extraterrestrial

life depends on light or some other form of radiation for energy it probably would not remain viable in the microcalorimeter.

The microcalorimeter does not have the sensitivity of some of the other life detection instruments; but because of the basic premise from which it operates, the possibility exists that it can detect life where other more sensitive instruments fail.

In the case where the microbial life is metabolizing at a rate below the threshold of the most sensitive microcalorimeters, provision must be made for the injection of nutrient to increase metabolic rate and promote reproduction, thus increasing heat output.

Although it is out of the scope of this report, it should be noted that the choice of nutrient is very important and a great problem. Nutrient to terrestrial life might be poison to extraterrestrial life.

2.0 ASSUMPTIONS

Since this report is concerned with the preliminary design of a microcalorimeter for detection of Martian life, a number of basic assumptions must be made. These assumptions are based on the best data available concerning the Martian environment. In each instance a worst case was used so that the feasibility study would hold under the worst possible conditions. The microcalorimeter is expected to interface directly with its environment.

2.1 Environmental Considerations

2.1.1 Temperatures

2.1.1.1 Inflight

It will be assumed that inflight temperatures will stay within -70°C and +125°C. Since the microcalorimeter will not be in operation at this time, no further treatment of these extremes will be made.

2.1.1.2 Martian

-80°C to +30°C.

2.1.2 Atmosphere

2.1.2.1 Pressure

5 millibars at the surface.

2.1.2.2 Contents

CO_2 and water vapor.

2.1.3 Radiation

Since the Martian atmosphere is so thin and the magnetic field is negligible, it can be assumed that the radiation levels will be similar to those encountered on the moon or free space surrounding Mars. These levels will not be considered hazardous for missions shorter than three months duration.

2.1.4 Shock and Vibration at Impact

Only the worst case will be noted; the assumption being that all the other situations can be easily accepted. A figure for g-loading at impact was obtained verbally from the Jet Propulsion Laboratory; this figure is 2,000 g.

2.2 Sterilization

2.2.1 Temperature

125°C.

2.2.2 Duration

(2) 53-hour cycles.

2.2.3 Gas

450-650 mg Ethylene oxide per liter of gaseous atmosphere.

2.2.4 Duration

6 cycles. 30 Hours.

3.0 THEORETICAL ANALYSIS

3.1 Design of Thermal Isolation Enclosure

3.1.1 General

The best estimates of ambient conditions on Mars indicate a diurnal temperature variation of -80 to +30°C. The average temperature, To, is therefore about -30°C. It is desired that microbiological experiments be performed at 5 to 30°C, with control at 5°C increments available. Since the controlled temperature is greater than the average Martian temperature in all cases, it is possible to design the control for heating only. The necessary condition for such a control to operate properly is that the surroundings be at a temperature below 5°C (the lowest required control point) at all times.

The approach under consideration may be described in relation to the design shown in Figure 3-1. In this apparatus the microcalorimeter cells are housed within an enclosure which is to be temperature controlled at the desired temperature, Tc, of 5, 10, 15, 20, 25 or 30°C. The microcalorimeter cells will operate at the same temperature, but must be sufficiently insulated thermally to respond very slowly to variations in Tc for minimizing transient signals due to minor variations of Tc. For example, it is desirable that variations of ± 0.1°C at the controlled wall produce no more than ± 0.0001°C difference between microcalorimeter sample and reference cell temperatures.

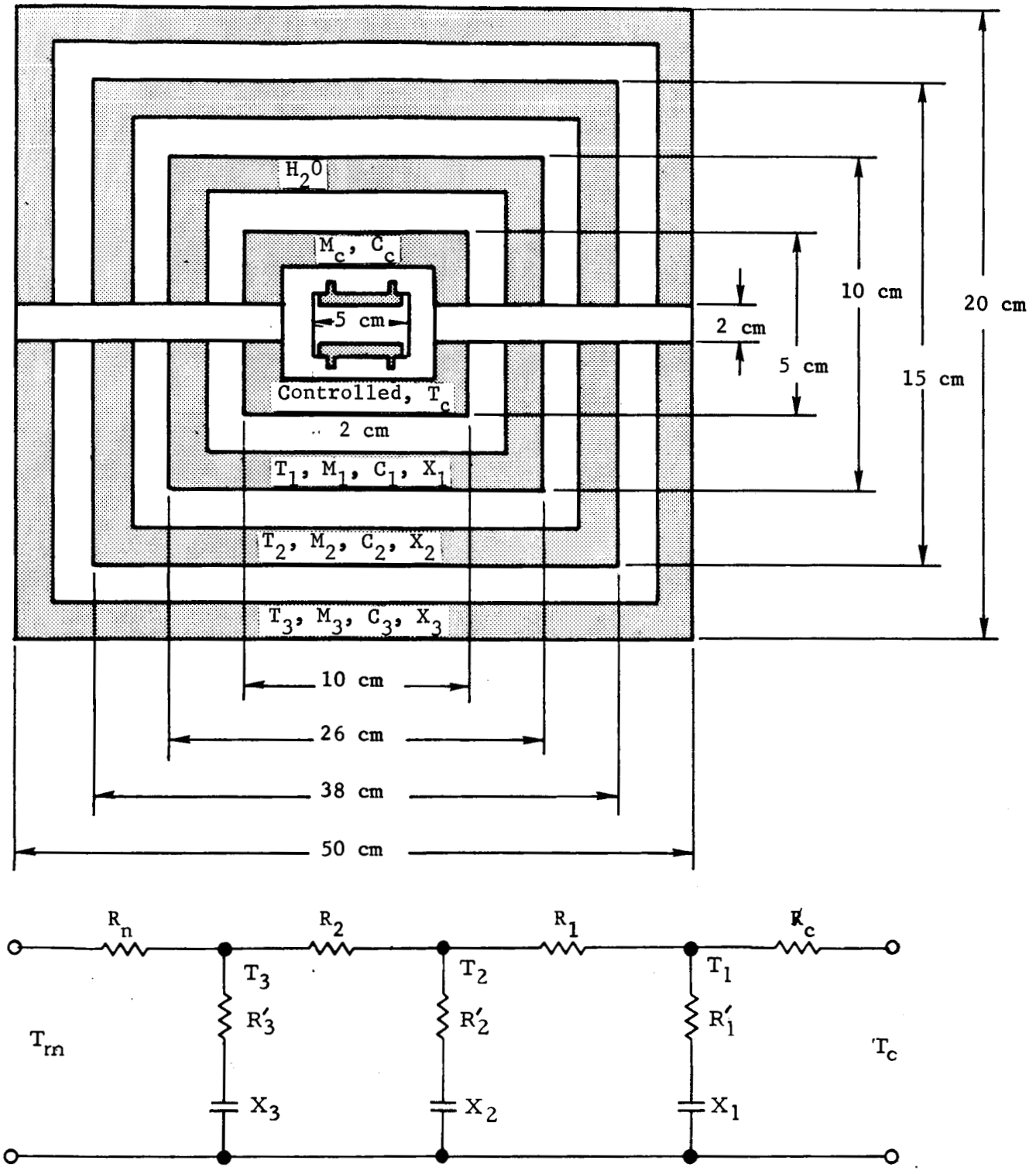


Figure 3-1. Temperature Controlled Enclosure for Microcalorimeter Cells (1 of 2)

Corresponding Quantities

Electrical	Thermal
Potential, V	Temperature, T
Charge, q	Thermal energy, Q
Current, $dq/dt = I$	Heat transfer, $\frac{dQ}{dt}$
Resistance, $R = \frac{V}{I} = \frac{\rho L}{A}$ (for wires)	Thermal resistance, $R = \frac{1}{KA}$
Capacitance, $C = q/V$	Thermal capacity, $C_H M = Q/T$
Ohm's Law, $V = IZ$	Heat Conduction Law, $T = \frac{dQ}{dt} Z$
Capacitive impedance, $X_c = \frac{1}{\omega C}$	Thermal capacitive impedance, $X = \frac{1}{\omega C_H M}$
Electrical impedance, $Z = R + jX$	Thermal impedance, $Z = R + jX$
Electrical conductance $= \frac{1}{Z}$	Thermal conductance $= \frac{1}{Z}$
ρ = Resistivity, ohm · cm	K = thermal conductivity, cal/cm. sec. ^{o}C
A = Area, cm^2	A = Area, cm^2
L = Length, cm	L = Length, cm
ω = Frequency, radians/sec.	M = Mass of material, gm
$j = \sqrt{-1}$	ω = Frequency, radians/sec.
	C_H = Specific heat, cal/gm ^{o}C.

Figure 3-1. Temperature Controlled Enclosure for Microcalorimeter Cells (2 of 2)

Furthermore, to achieve a controlled temperature stability of $\pm 0.1^{\circ}C$ with simple electronics, it is desirable that the variations in temperature of the enclosure surrounding the controlled wall be less than about $\pm 10^{\circ}C$, although a variation of $\pm 30^{\circ}C$ about the Martian mean of $-30^{\circ}C$ would be theoretically permissible (for control at $5^{\circ}C$ and higher).

In the following paragraphs the feasibility of designing an enclosure which would accomplish the desired thermal stability at the microcalorimeter cells is demonstrated. Further, it is shown to be feasible to provide this thermal stability with an average power of several watts.

The Martian ambient temperature (Tm) may be expressed as:

$$Tm = To + Tp\ f_1(t) \tag{1}$$

where: To is the mean diurnal temperature

Tp is the peak excursion referenced to To

$f_1(t)$ is a harmonic function of time

It is required that variations in Tm have an acceptable effect upon T_1, the temperature of the enclosure to which the controlled wall looses heat. If a structure such as that shown in Figure 3-1 is employed, then the microcalorimeter cells are housed within a first enclosure controlled at temperature Tc, surrounded by a second enclosure at temperature T_1, of mass M_1 and specific heat per unit mass of C_1. This enclosure is surrounded by another at temperature T_2, having Mass M_2 and specific heat C_2, and an outer housing of mass M_3 and specific heat C_3 is exposed directly to the

Martian ambient conditions. The following equations expressing T_1 in terms of Tm, To, and Tc may be written. The heat flows $\frac{dQ_1}{dt}$, $\frac{dQ_2}{dt}$, etc. are those entering enclosures 1, 2, etc. $\frac{dQc}{dt}$ is the control power.

$$\frac{dT_1}{dt} = \left(\frac{dQ_1}{dt} + \frac{dQc}{dt}\right) \frac{1}{C_1M_1} \tag{2}$$

$$\frac{dT_2}{dt} = \left(\frac{dQ_2}{dt} - \frac{dQ_1}{dt}\right) \frac{1}{C_2M_2}, \text{ or } \frac{dQ_1}{dt} = -C_2M_2 \frac{dT_2}{dt} + \frac{dQ_2}{dt} \tag{3}$$

$$\frac{dT_3}{dt} = \left(\frac{dQ_3}{dt} - \frac{dQ_2}{dt}\right) \frac{1}{C_3M_3}, \text{ or } \frac{dQ_2}{dt} = \frac{dQ_3}{dt} - C_3M_3 \frac{dT_3}{dt} \tag{4}$$

$$\frac{dQ_3}{dt} = f_2 \ (Tm, T_3), \text{ where } f_2 \text{ and all } \frac{dQ}{dt} \text{ terms involve conductivity, radiation and convection mechanisms.} \tag{5}$$

Combining equations 2 through 5

$$\frac{dT_1}{dt} = \frac{1}{C_1M_1} \left(\frac{dQc}{dt} + f_2 \ (Tm, T_3) - C_2M_2 \frac{dT_2}{dt} - C_3M_3 \frac{dT_3}{dt}\right) \tag{6}$$

The above equations are completely general, the values for $\frac{dQ}{dt}$ including all heat transfer mechanisms. For purposes of sample calculations, however, simplifying assumptions are made in Paragraph 3.1.2.

3.1.2 Electrical Analogy

Utilizing the electrical analogy of the thermal system, expressions may be obtained which relate the temperature of enclosure one to the Martial temperature, the control power, and the heat transfer mechanisms between enclosures.

The analogous electrical and thermal systems are shown in Figure 3-1. It should be noted that the equations are analogous only for the thermal conductivity mode of heat transfer, and do not include convective and radiation mechanisms except as such may be expressed in terms of equivalent transfer by conduction. For the contemplated system, however, this is not a severe limitation, because conductive heat transfer will dominate. In the following derivations, the thermal resistances of the enclosures are neglected, it being assumed that the walls are formed of a good conductor, thick enough to minimize thermal gradients at all times. These thermal resistances are represented by R_1', R_2', and R_3' in the analog circuits.

$$T_1 = (Tc - To)\frac{R_1+R_2+Rm}{\Sigma R} + jT_2X_1 \frac{Rc}{R_1(Rc+jX_1)+jRcX_1} \tag{7}$$

$$T_2 = (Tc - To)\frac{R_2+Rm}{\Sigma R} + jT_3X_2 \frac{Z'}{R_2(Z'+jX_2)+jX_2Z'} \tag{8}$$

$$T_3 = (Tc - To)\frac{Rm}{\Sigma R} + jTmX_3 \frac{Z}{Rm\ (Z+jX_3)+jX_3Z} \tag{9}$$

$$Z' = \frac{R_1(Rc+jX_1) + jX_1Rc}{Rc + jX_1} \tag{10}$$

$$Z = \frac{R_2(Z'+ jX_2) + jX_2Z'}{Z'+jX_2} \tag{11}$$

$$\Sigma R = R_1+R_2+Rm+Rc \tag{12}$$

Combining equations 7 through 9 and 12:

$$T_1 = (Tc - To)\frac{R_1+R_2+Rm}{\Sigma R} + X_1'\left\{(Tc-To)\frac{R_2+Rm}{\Sigma R} + X_2'\left[(Tc-To)\frac{Rm}{\Sigma R} + TmX_3'\right]\right\}, \text{wherein}$$

$$1)\quad X_1' = \frac{jX_1Rc}{R_1(Rc+jX_1)+jX_1Rc}$$

$$2)\quad X_2' = \frac{jX_2Z'}{R_2(Z'+jX_2)+jX_2Z'} \qquad (13)$$

$$3)\quad X_3' = \frac{jX_3Z}{Rm(Z+jX_3)+jX_3Z}$$

Rearranging equation 13:

$$T_1 = \frac{Tc - To}{\Sigma R}\left[R_1+R_2(1+X_1') + Rm(1+X_1'+X_1'X_2')\right] + TmX_1'X_2'X_3' \qquad (14)$$

In the above equation the first term and a part of the second establish the mean value of T_1. That is, by combining equation 13 and equation 1, T_1 is expressed by:

$$T_1 = \frac{Tc - To}{\Sigma R}\left[R_1+R_2(1+X_1')+Rm(1+X_1'+X_1'X_2')\right] + X_1'X_2'X_3'To + X_1'X_2'X_3'Tpf_1(t). \qquad (15)$$

In equation 15 only the last term is considered to be a function of time, and it may be seen immediately that the diurnal variation of the Martian temperature is attenuated at enclosure one by the factor $X_1'\ X_2'\ X_3'$. The other terms establish the mean value of T_1, about which T_1 varies as a function of time. The necessary condition for stability of control at Tc when only heating is to be employed is $T_1 \leq Tc$ at all times. In the derivation of the above equations, it was assumed that the Martian temperature varied about a

mean value, To. The equations are greatly simplified when To is arbitrarily made zero for the temperature scale. Equation 15 becomes:

$$T_1 = \frac{Tc}{\Sigma R}\left[R_1+R_2(1+X_1') + Rm(1+X_1'+X_1'X_2')\right] + X_1'X_2'X_3'Tpf_1(t). \qquad (16)$$

To a reasonably good approximation, $f_1(t)$ may be assumed to be sinusoidal, in which case:

$$T_1 = \frac{Tc}{\Sigma R}\left[R_1+R_2(1+X_1')+Rm(1+X_1'+X_1'X_2')\right] + X_1'X_2'X_3'Tp \sin\omega t. \qquad (17)$$

where ω is the angular frequency of Mars in radians/unit time.

Equation 17 may be utilized in design of an actual enclosure to provide any desired mean value of the temperature, T_1, of the enclosure surrounding the controlled enclosure. That is, the thermal resistances and capacities can be established in design to provide a given average value of T_1(first term of the equation) for any given control temperature. These parameters can also be selected to provide the required maximum variation of T_1(second term of the equation).

3.1.3 Heat Transfer Mechanisms and Relative Importance

To justify the use of the equations derived in Paragraph 3.1.2, it is necessary to establish the approximate values of heat transfer by the various mechanisms for a practical example of a microcalorimeter enclosure. As a first example, consider a cylindrical enclosure similar to that shown in Figure 3-1. The radial heat transfer for concentric cylinders is:

$$\frac{dQ}{dt} = \frac{2\pi KL}{\ln \frac{R2}{R1}} (\Delta T) \qquad (18)$$

where: K is the thermal conductivity of the material between cylindrical radii R_1 and R_2

L is the length of the cylinder

ΔT is the temperature drop between radii R_1 and R_2

Assuming that $R_2/R_1 = e^3$, $L = 50$ cm, and that felt is used as the insulation material ($K = 10^{-4}$ cal/cm ^oC sec), the radial heat loss for $\Delta T = 100^oC$ would be approximately 1 cal/sec, or 4 watts. These are all practical values, since both $R_1 = 1.25$ cm and $R_2 = 25$ cm, making $R_2/R_1 = e^3$, are reasonable values. Since this figure does not include either end losses or losses through supports, it is apparent that a higher quality of insulation is desirable. Several "Super Insulations" produced by the Linde Company provide insulation with a combined loss rate of about 1/100 that of felt. These materials must be evacuated to about 1 micron of Hg absolute pressure to provide such excellent insulation, but it appears that this approach is warranted. With such insulation, which is in powder form, the radial heat loss would be only about 0.04 watts under the assumed conditions. With multi-layer quilts of insulating and reflective materials, and at 1 micron Hg or less, the heat loss could be about 0.004 watts.

It may reasonably be assumed that for a properly designed enclosure conductive heat transfer through the supports would dominate other transfer mechanisms. The design shown in Figure 3-1 would rely upon a tube of good mechanical properties, and low thermal conductivity, to both hold the concentric cylinders in place and to complete the wall of the vacuum chambers

(for optimum insulation). Such a tubular passage would also provide access to the microcalorimeter chamber within the enclosure in a symmetrical fashion. Heat transfer along such a tube would be given by the expression:

$$\frac{dQ}{dt} = \frac{K\pi(r_2^2 - r_1^2)}{L} \Delta T \qquad (19)$$

where: r_1 and r_2 are inner and outer radii of the tube

K is the conductivity of the material

L is the length of the tube

ΔT is the temperature drop across length L of the tube

As an example, for stainless steel tubing ($K = 0.1$ cal/cm sec ^{o}C) with radii of 0.96 and 1.00 cm, a length of 20 cm and $\Delta T = 100^{o}$C, the heat transfer rate is about 0.12 cal/sec, or 0.5 watts from one end, or 1.0 watt for both ends. Since total losses through "Super Insulation" would be less than about 0.1 watts, only the heat transferred down the supporting structure need be considered for approximate calculations. While the dimensions used for these sample calculations are arbitrary, they probably come within a factor of 5 of representing a valid design. As a further example, reduction of the larger enclosure cylindrical radius to 10 cm (from 25) would increase radial losses by only 30%, to about 0.05 watts, and inclusion of end losses through the super insulation would increase this figure to approximately 0.075 watts. The use of laminar super insulation instead of powder could reduce the losses to 0.0075 watts, if required by engineering considerations, and provided that adequate mechanical support could be achieved with a tubular support of the demensions assumed.

As a practical matter the tubular passages would be closed by plugs except when samples were being inserted into the microcalorimeter. These plugs could be designed with good thermal conductors mating to the enclosure walls with insulation between. If properly insulated between enclosure "plugs", the convective and radiative modes of heat transfer could be made negligible, and their contribution to the total thermal conductivity could be included in the expressions for the other support structure terms. They should not increase heat transfer by more than about 10%, if properly designed.

In conclusion, it appears that a trade-off between the power required to maintain thermal control of the microcalorimeter and use of high quality, highly evacuated, insulation is required. If evacuated insulation is selected, then heat transfer through the support structure will predominate, and total power requirements will depend almost entirely upon the mechanical support requirements. In the following sections estimates are made of the masses of the enclosures required to sufficiently attenuate the Martian ambient temperature. From these estimates it will be possible to establish the structural support requirements, from which it will be possible to arrive at a final estimate of power requirements.

3.1.4 Mass Requirements for Thermal Attenuation

3.1.4.1 Rough Estimates of Copper Enclosures

Assuming that the minimum acceptable attenuation of the ambient temperature is 1/8 (about $\pm 7^{\circ}C$) at the enclosure adjacent to the controlled wall, then from equation 16, it is required that:

$$|X_1'|\ |X_2'|\ |X_3'| \leq 1/8 \qquad (20)$$

A simple and sufficient condition for this inequality to apply is that $|X_1'|$, $|X_2'|$, and $|X_3'| \leq 1/2$. With regard to $|X_1'|$ only, it follows from the definition of $|X_1'|$ that $|jX_1| / |R_1 + jX_1| \leq 1/2$, or $R_1 \geq |jX_1|$, is a sufficient condition. Referring to the table of Figure 3-1 and to Figure 3-1 for typical dimensions:

$$R_1 = 7.5 \times 10^2 \ \frac{\text{sec } ^\circ\text{C}}{\text{cal}} \tag{21}$$

for each end, for a stainless steel support tube 6 cm long, having a 2 cm outside diameter, and a 0.04 cm wall. Similarly,

$$X_1 = 1.8 \times 10^2 \ \frac{\text{sec } ^\circ\text{C}}{\text{cal}} \tag{22}$$

for a copper enclosure having 0.2 cm thick walls, 25 cm long, and with a diameter of 10 cm.

The above example indicates that $|X_1'| = 1/3$ for the assumed conditions. In this calculation R_1 must be reduced by a factor of 1/2 to allow for thermal transfer from both ends. A copper mass of about 800 gm (0.1 cm thick enclosure) would be required. Without entering into the tedious calculation of X_2', it is apparent that for the dimensions shown in Figure 3-1, the mass of the second enclosure would be about 50% greater, or 1200 gm, and that X_2 would be only about 2/3 of X_1. On the other hand R_2 would equal R_1, and therefore, the attenuation coefficient X_2' would be about 2/9, which is less than that required. The expression for X_3' is even more complicated, but it is sufficient for present purposes to note that usable attenuation (1/3 x 2/9 = 2/27) would be provided by the other two enclosures alone, even if T_3 = Tm. This would be the case if X_3 was large compared to Rm, and Rm was so small that the outer enclosure effectively followed the Martian ambient temperature.

It remains to be shown that the necessary mechanical strength could be achieved without badly upsetting the thermal properties of the design. It should be noted, in passing, that aluminum, or its alloys, are better than copper in terms of specific heat and thermal conductivity per unit mass. Aluminum alloys are also better structural materials than is copper.

3.1.4.2 Effectiveness of a Water Jacket for Thermal Attenuation

In the above section, it was shown that two enclosures of copper with masses of 1,200 gm and 800 gm could provide adequate attenuation of the Martian ambient temperature. The assumed supports for these masses, however, probably would not tolerate the high shock loading associated with a landing on Mars. More effective attenuation per unit mass is highly desirable.

The specific heat of water is approximately 10 times that of copper, and 5 times that of aluminum. In the above example the first enclosure could consist of, say, 80 gm of copper and 80 gm of water, and provide attenuation at temperatures above $0^{o}C$ equal to that provided by 880 gm of copper. The high latent heat of ice (80 cal/gm) would make the equivalent copper mass about 7280 gm for the transition from water to ice and vice versa. This is 9 times the capacity at 1/5 the mass. Even below the ice point, the specific heat of ice is five times as great as that of copper, providing an equivalent copper mass of 480 gm for 80 gm of copper and 80 gm of water.

Obviously, the optimum arrangement would utilize the latent heat of the ice-water system, and operate at approximately $0^{o}C$ at all times. Operation

with an average T_1 of 0^oC could be achieved by design, utilizing the design equations of Paragraph 3.1.2, but slight additional power would be required from an auxiliary control to assure that the average temperature was not less than 0^oC.

A very useful trade-off between system total mass and complexity of design is available by utilization of the large latent heat of an ice-water mass, as outlined above. This is particularly important in view of the fact that larger supports than those assumed for sample calculations may well be required to withstand the high impact of landing. Simultaneously, larger supports would require greater enclosure masses for adequate thermal attenuation, which is a self defeating proposition.

To allow for the combined specific heats of metal jackets and water (or ice), and for the latent heat of the water-ice phase change, the values of C and M in all of the above equations need only be replaced by equivalent expressions, in accordance with the following equation:

$$Ceq\ Meq = Cm\ Mm + Cw\ (kMw) + C_I\ (1-k)\ Mw + \begin{cases} H_L kMw & \text{for rising temperature, or} \\ H_L\ (1-k)\ Mw & \text{for decreasing temperature} \end{cases} \quad (23)$$

where: Cm and Mm are the specific heat and mass of metal

Cw and C_I are the specific heats of water and ice

k is the fraction of the total mass of ice and water which is water

H_L is the latent heat of the ice to water phase transition.

Note that the last term is different for increasing and decreasing temperature, since such a phase transition is equivalent to a discontinuity in the specific heat of the material at $0^{o}C$.

In the electrical analogy, an ice-water system corresponds to a battery which is fully charged when 100% ice, and fully discharged when 100%water. The battery would be discharged continuously at a constant rate for a given controlled temperature Tc, and simultaneously cyclically charged and discharged by the Martian ambient temperature. Since the Martian mean temperature is expected to be less than $0^{o}C$, additional heat might be required to prevent cummulative freezing on successive cycles (Martian days). To assure adequate temperature control, the design value of the mean Martian temperature should be higher than the best estimate, and provisions should be made to compensate for an opposite error by increased electrical heat capability. An auxiliary control would supply heat directly to the first enclosure to prevent T_1 from going significantly below $0^{o}C$.

It should also be noted that from the standpoint of thermal attenuation, the use of a water jacketed enclosure for establishing T_1 could eliminate the necessity for an intermediate enclosure (2 of Figure 3-1), even with the use of additional supports between the two enclosures.

3.2 Design of the Microcalorimeter Cell

3.2.1 Discussion of the Basic Properties of Thermocouples

When two dissimilar metals (or semiconductors) are joined together, the junction produces a potential which varies with temperature. If both ends

of the dissimilar metals are at the same temperature, no continuous current can be observed with a current detecting device joining the second pair of ends, because both ends of each conductor are at the same potential. If, however, the second pair of ends are at a temperature other than that of the junction, a continuous current may be detected. The magnitude of the voltage observed at the reference junction (the pair of ends terminating at the detector) depends upon the difference between junction temperatures, and the polarity depends upon whether the thermal junction is at a higher or a lower temperature than the reference junction.

Every connection made between all conductors in a circuit is a "thermal junction". Any number of different materials may be connected in series, but the voltage at the detector will depend only upon the temperatures and types of junctions in the circuit. If any even number of like junctions are at the same temperature there will be no net contribution. Components such as resistors and switches contain internal thermal junctions, as well as those at external terminals.

3.2.2 Design of Circuits for Measuring Small DC Signals

From the above discussion, it is apparent that random thermal junction effects can easily produce sizable signals. Most pairs of dissimilar metals can produce no more than 0.05 mv/^{o}C, this being the approximate sensitivity of standard thermocouple wires. A component such as a wire wound resistor may produce a net voltage when a thermal gradient exists across it, but choice of materials of construction can reduce the sensitivity to considerably less than 0.05 mv/^{o}C. In addition, precautions may be taken against assymmetry

of design and lay-out of circuits, since assymmetry promotes thermal gradients. Maintenance of constant temperature throughout the circuitry is beneficial. Finally, the number of junctions of dissimilar metals may be minimized, and like junctions can be made in close proximity to promote equality of temperature under all conditions. All of these factors must be considered when designing a circuit for measuring small DC signals. The requirements with regard to detecting and amplifying the output of a mircocalorimeter are considered in the following sections of this discussion.

3.2.3 Theoretical Consideration of Thermocouple Design for a Microcalorimeter

3.2.3.1 Conventional Wire Thermocouples

The heat produced within a microcalorimeter cell can be detected by measurement of the thermal gradient established by conduction of heat out of the cell to the environment. If the thermal gradient is measured by one or more thermocouples in series, then the output voltage is a function of the rate at which heat is produced. It is also a function of the amount of heat conducted through the thermocouples and through other media, with maximum signal being developed when all heat is conducted through the thermocouples. For an ideal case of perfect cell wall conductivity, and perfect thermal contact between a single thermocouple and the cell and heat sink walls, the temperature drop may be calculated as follows:

$$\Delta T = \frac{dQ/dt}{\frac{K_T\ A_T}{L_T} + \frac{Kc\ Ac}{Lc} + \frac{Ks\ Ls}{\ln R_2/R_1}} \qquad (24)$$

where: $\frac{dQ}{dt}$ is the rate at which heat is being produced in the cell

K's are thermal conductivity constants,

A's are areas of thermal conductors

L's are lengths of the thermal conductors

subscripts T, C and S are for one element of the couple, the other element of the couple, and for stray conduction paths, respectively.

It is assumed that the cell is cylindrical, with a length Ls and a radius of R_1, and that the heat is lost to a concentric cylinder of radius R_2. End losses from the cylinder are neglected for simplicity. If N thermocouples are used between the cell and heat sink the first two terms of the denominator are multiplied by N, which lowers ΔT. If the N couples are connected electrically in series (aiding), however, the output voltage will be $kN\Delta T$, where k is the thermocouple constant. The expression for the output voltage of N couples is, therefore:

$$\Delta e = \frac{kN\ (dQ/dt)}{N\left(\frac{K_T A_T}{L_T} + \frac{KcAc}{Lc}\right) + \frac{Ks\ Ls}{\ln R_2/R_1}} \tag{25}$$

The maximum output voltage will be achieved when:

$$N\left(\frac{K_T A_T}{L_T} + \frac{KcAc}{Lc}\right) \gg \frac{KsLs}{\ln R_2/R_1} \quad + \text{End losses} \tag{26}$$

If this condition is met, equation 25 reduces to:

$$\Delta e = \frac{k\ dQ/dt}{\frac{K_T A_T}{L_T} + \frac{KcAc}{Lc}} \tag{27}$$

From the above two equations, it is apparent that KA/L for both elements of the couples should be minimized, provided that a reasonable value of N will meet the inequality condition of Equation 27. Minimizing stray losses is very beneficial, since increasing the thermocouple heat conductivity instead will lower Δe.

In a practical case the situation will be complicated by the thermal barriers between the thermocouple and the walls of the cell and sink. A part of ΔT, as calculated by Equation 24,will appear across the thermocouple and the balance across the two barriers. The full value of ΔT will apply for the stray losses, however, and hence the value of Δe will be smaller than that calculated from Equation 25. The form of the equation, and the effect of using N thermocouples having equal barriers, will not be altered drastically. If $B = K_B A_B / L_B$ is the thermal conductance of both barriers, then Equation 24 becomes:

$$\Delta T = \frac{dQ/dt}{\dfrac{B\ K_T A_T}{BL_T + K_T A_T} + \dfrac{B\ KcAc}{BLc + KcAc} + \dfrac{KsLs}{\ln R_2/R_1}} \tag{28}$$

The temperature drop across the thermocouple would be given by:

$$\Delta T = \frac{\dfrac{1}{\text{Conductance of Couple}}}{\dfrac{1}{\text{cond. of couple + cond. of barriers}}} \tag{29}$$

Combining Equations 28 and 29:

$$\Delta T_{TC} = \left[\frac{dQ/dt}{\dfrac{BK_T A_T}{BL_T + K_T A_T} + \dfrac{BKcAc}{BLc + KcAc} + \dfrac{KsLs}{LnR_2/R_1}}\right] \left[\frac{\dfrac{K_T A_T}{L_T} + \dfrac{KcAc}{Lc}}{\dfrac{BK_T A_T}{BL_T + K_T A_T} + \dfrac{BKcAc}{BLc + KcAc}}\right] \tag{30}$$

The expression above provides a convenient mathematical demonstration of the intuitively apparent fact that good thermal contact between the thermocouple junctions and the cell and sink walls is required for maximum temperature drop across the thermocouples. Equation 30 reduces to Equation 24 when the following conditions are met:

$$BL_T \gg K_T A_T, \text{ and } BL_C \gg K_C A_C$$

Since $B = K_B A_B / L_B$, the inequalities of the above expression may be rewritten as:

$$\frac{K_B A_B L_T}{K_T A_T L_B} \gg 1, \text{ and } \frac{K_B A_B L_C}{K_C A_C L_B} \gg 1$$

Hence, for any given couple and geometrical arrangement the sensitivity may be made to approach the theoretical maximum value by maximizing $K_B A_B$ and minimizing L_B.

Returning to the question of the optimum number of thermocouples, a few sample calculations will be of value. For the dimensions shown in Figure 3-1 the stray loss component of heat conduction (cylindrical only) from Equation 24 would be:

$$\frac{1}{R_S} = \frac{K_S L_S}{\ln R_2/R_1} = \frac{(2\pi) \times 2.5 \times 10^{-4} \text{ cal/sec.cm}^{\circ}\text{C}}{\ln (2/0.9)} \approx 24 \times 10^{-4} \text{ cal/sec } ^{\circ}\text{C}$$

using a value of $K = 10^{-4}$ cal/sec $^{\circ}$C cm, which is approximately correct for felt, foamed plastics, etc. In the absence of appreciable end losses and neglecting thermocouple heat conductivity, this figure predicts a temperature rise of 4×10^{-4} $^{\circ}$C per microcalorie/sec generated within the cell. For

the assumed geometry and insulation this value represents the largest ΔT per unit power obtainable.

The thermal conductance of the couples may be computed for the same example, to establish relative values. For copper wire 0.005" in diameter and 1 cm long, the thermal conductance is:

$$\frac{1}{R_{cu}} = \frac{K_{cu}A_{cu}}{L_{cu}} = \frac{\frac{.9\ \text{cal}}{\text{cm sec}\ ^{o}\text{C}} \times \frac{\pi(.005 \times 2.54)^2\ \text{cm}^2}{4}}{1\ \text{cm}} = 1.1 \times 10^{-4}\text{cal/sec}\ ^{o}\text{C}. \tag{31}$$

For constantan, which has a K of only 0.05 cal/cm sec ^{o}C, we have $\frac{1}{R_{con.}}$ = 0.06×10^{-4} cal/sec ^{o}C; and for iron, $\frac{1}{R_{Fe}} = 0.2 \times 10^{-4}$ cal/sec ^{o}C.

Thus for N iron constantan couples, the thermocouple and stray conductances are equal when N = 24 /.26 = 92, under the assumed conditions. From Equation 25, for each microcalorie/sec,

$$\Delta e = \frac{5 \times 10^{-5}\ \text{volts/couple}\ ^{o}\text{C} \times 12\ \text{couples} \times 10^{-6}\ \text{cal/sec}}{48 \times 10^{-4}\ \text{cal/sec}\ ^{o}\text{C}} = 0.96\text{x}10^{-6}\text{volts} \tag{32}$$

From Equation 24, for the same conditions, $\Delta T = 2 \times 10^{-4}\ ^{o}$C, which is only one half of the maximum value for the assumed geometry and insulation. By making N much larger Δe/microcalorie/sec may be made twice as large at best, and ΔT would be reduced in proportion to N. For very large N the signal-to-noise ratio of each couple may be expected to approach unity, because ΔT approaches zero. Consequently, it is probable that N should not exceed the value which makes thermocouple conductance one to ten times that of the insulation conductance, for optimum signal-to-noise ratio. In the above

example these ratios are 92 to 120 couples of 0.005" diameter iron and constantan wires, one cm long. To minimize B, the thermal impedance between the couples and the cell and sink walls, each couple could be terminated on a small sheet of relatively large area, of a good conductor such as copper, contoured to fit the wall. The sheets could then be electrically insulated from, but bonded to, the wall with a thin layer of adhesive. In this manner $B = K_B A_B / L_B$ would be maximized, making the inequalities

$$\frac{K_B A_B L_T}{K_T A_T L_B} \gg 1 \text{ , and } \frac{K_B A_B L_C}{K_C A_C L_B} \gg 1$$

valid.

3.2.3.2 Cylinder Ends as Thermocouple Elements

As an alternative approach, the use of thermocouple material sheet ends joining the concentric cylinders should be considered. With this configuration the space could be evacuated, and insulation 10 to 100 times as effective as felt or foam could be employed. The thermal conductances of such discs would be calculated as that for the insulation.

$$\frac{1}{R_d} = \frac{2 \; K_d L_d}{\ln R_2/R_1} \approx \frac{\frac{0.05 \text{ cal}}{\text{cm sec}^{\circ}\text{C}} \times .01 \text{ cm} \times 2\pi}{.8} \approx 36 \times 10^{-4} \text{ cal/sec } ^{\circ}\text{C}, \qquad (33)$$

for 0.01 cm thick constantan and the dimensions assumed above. For two discs, 1/Rd 70 x 10^{-4} cal/sec.$^{\circ}$C.

If super insulation (evacuated) were used between the cell and sink cylinders the stray losses would be negligible(about 0.3 to 0.03 x 10^{-4}cal/sec $^{\circ}$C), and end losses would be similar to those for wire couples. Hence, the output would be about 0.008 x 10^{-6} volts per microcalorie/sec, using 0.01 cm thick constantan at both ends of the concentric cylinders.

The suggested configuration is shown in Figure 3-2, and utilizes various properties of thermal junctions discussed above. The outer heat sink wall is of copper, and the inner cell wall may also be of copper, if desired. The inner wall is separated into sample and reference compartments for purposes of thermal insulation between the two. The outer wall is a single unit of high thermal conductivity to provide a good thermal sink for both sample and reference chambers. There are two constantan/copper couples at each wall for each cell. As long as each wall is isothermal no currents will circulate in the loops formed by the constantan discs, yet the thermal potential will exist between the two cell walls, and leads connected as shown would provide an output of $\Delta e = k\Delta T$.

There are a number of structural advantages to be gained by employing an approach such as that shown in Figure 3-2, compared to the usual multielement fine wire thermopile. Simplicity and ruggedness of design are major contributors to the overall reliability of any system. In addition, the stray heat paths due to inferior insulation could readily be avoided, and loss of seal on the vacuum would lower the output by only about 50%. Thermal barriers at the junction of thermocouples and cell and sink walls would be at an absolute minimum since no electrical insulation would be required.

3.2.3.3 Evacuated Annular Space with Conventional Thermopiles

The cylinder ends could be closed by glass or ceramic hermetic seals to permit evacuation, and the thermal difference could be measured by more conventional thermocouples. A trade-off between thermal conductance and mechanical properties is required. Handbook data indicates that glass discs could be about 25 times

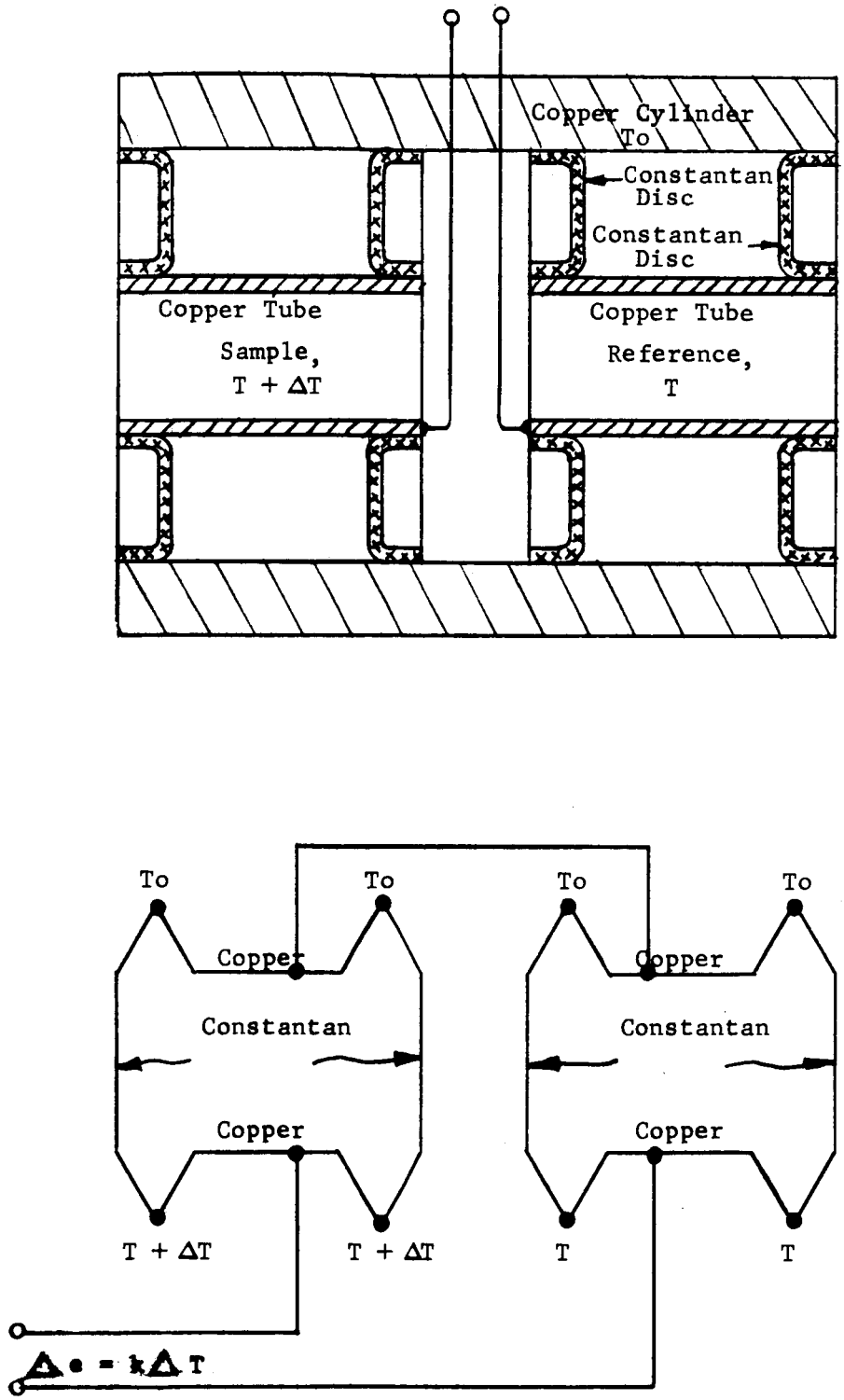


Figure 3-2. Electrical and Thermal Systems Configurations

as thick as constantan for equal thermal conductance. A possible advantage lies in the potential use of a number of very fine thermocouple wires connected in series electrically. If the combined thermal conductance of N such couples was small compared to that for the ceramic or glass end discs, the output voltage would be N times as great. As a practical matter, the thermal conductance of the glass ends and N thermocouples would probably be about equal for optimum conditions.

As an example, for a 1/4" diameter cell and a 3/4" diameter sink, a 0.05" thick glass header at each end, and 100 iron-constantan thermocouples of 0.0025" diameter wire mounted radially between the cell and sink walls, the following approximate values may be computed:

g (glass) $= 70 \times 10^{-4}$ cal/sec ^{o}C (for two ends).

g (iron) $= 0.05 \times 10^{-4}$ cal/sec ^{o}C

g (constantan) $= 0.015 \times 10^{-4}$ cal/sec ^{o}C

g (per couple) = g (iron) + g (constantan) $= 0.065 \times 10^{-4}$ cal/sec ^{o}C

g (N) = Ng (per couple) $= 0.065\ (N) \times 10^{-4}$ cal/sec ^{o}C

when N = 1200 g(N) is approximately g (glass), and

$\Delta T = 1.5 \times 10^{-4}\ ^{o}C/\mu$ cal/sec

Δe = 1 microvolts/μ cal/sec

If redundant thermopiles of 1200 couples each were connected in parallel electrically and thermally (i.e., one thermopile on each end cap of glass), then the output would be lowered by about 33%, but the reliability would be doubled. This could be an attractive trade-off.

Δe (redundant thermopiles) = 0.7 microvolts/μ cal/sec.

This approach is more nearly in keeping with the prior art, and hence has a high degree of scientific acceptability. A further improvement in sensitivity could be achieved by utilizing a larger number of thermocouples, but a factor of two is the most that could be accomplished unless the thermocouples were made of smaller wire, or with greater length. Wire smaller than 0.0025" diameter is feasible with difficulty and reduced reliability. In view of the higher conductance of iron than that of constantan, the iron elements might be made three times as long by spiraling and connecting a "staggared" constantan wire (radially mounted). In this case g (iron) = 0.015 = g (constantan), and g (per couple) would be 0.03, compared to 0.065. The sensitivity would be increased by 33% for the redundant thermopile arrangement if 1200 thermocouples per pile were employed, or by a factor of two if 2400 couples per pile were used in either the single pile or redundant pile configuration. The spiralled iron configuration is shown in Figure 3-3, but it should be understood that spiralling is not necessary.

3.2.3.4 Desired Electrical Characteristics of Thermopiles

In the paragraphs above an attempt has been made to estimate thermopile sensitivities in terms of output voltage per unit power dissipated in the microcalorimeter measuring cell. In each evaluation an additional criteria has been applied; namely, that a relatively large ΔT be maintained, even at expense of lowering Δe by a factor of two. This criteria arises from consideration of Equation 25, which dictates that as the number of thermocouples, N, increases the output voltage, Δe, becomes independent of N. The value of ΔT, however, becomes inversely proportional to N when N becomes large. Since the signal-to-noise ratio of each thermocouple is proportional to ΔT, the use

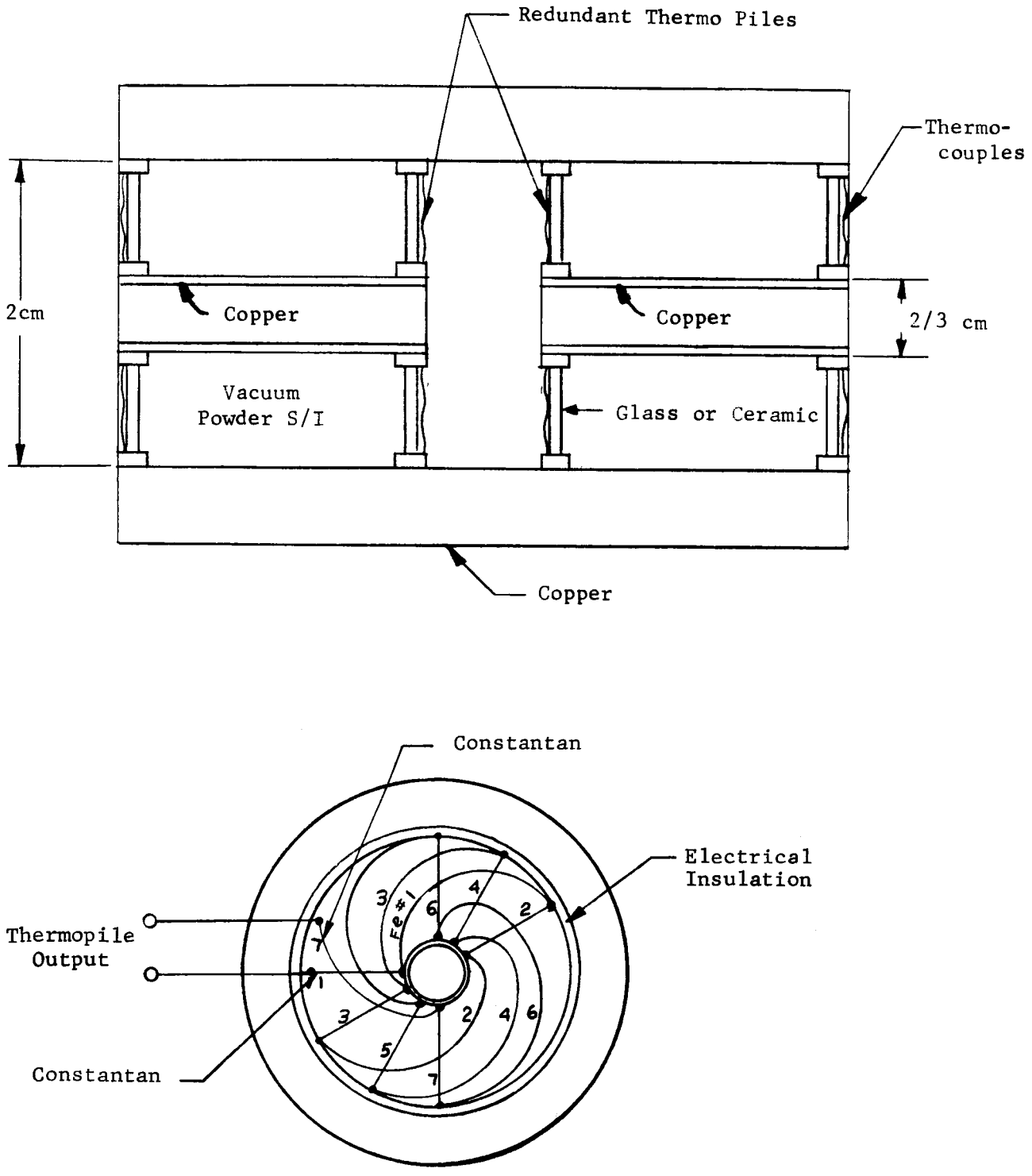


Figure 3-3. Spiralled Iron Configuration

of a very large number of couples will tend to reduce the signal-to-noise ratio of the thermopile output signal. The example calculations have been arbitrarily based upon utilization of a number of couples large enough to lower ΔT by only a factor of two. A more careful evaluation of the signal-to-noise ratio of thermocouples may reveal that a factor of ten or more reduction in ΔT could be tolerated from the standpoint of the thermopile signal-to-noise ratio. Other considerations, however, also indicate that a limited N is desirable.

Considering ease-of-fabrication and reliability of the end product, a limited number of thermocouples is definately indicated. A few relatively expensive but highly reliable couples are to be perferred over a large number of less reliable couples, even if less expensive. The mass, volume, power and reliability constraints placed upon extraterrestial equipment remove it from competition with commercial laboratory apparatus, and make radical departures in design possible and, perhaps, desirable.

From the standpoint of utilizing conventional semiconductor amplifiers throughout, the number of couples to be employed in the thermopile also has a definate limit. This is true because the noise level of transistor amplifiers, referred to the input, is roughly proportional to the source impedance for high source impedances. This characteristic of transistors arises from the fact that a principal source of noise is random variation in the collector-to-base leakage current, which current generates an input voltage proportional to the resistance through which it flows in returning to the power source. The best available differential amplifiers (1966) are specified to have less

than several microvolts/^{o}C input offset voltage (base-to-emmitter), but the collector-to-base leakage currents are a larger source of offset unless the input resistance is very low. In fact, the net offset voltage can be made to compensate by selection of the base resistors to make R_b (d I_{CB}/dT) + (dV_{BE}/dT) for one transistor equal to that for the other. The precision with which this can be accomplished is,in general, greater for smaller values of R_b, the base resistance. In connection with detecting very small voltages from thermopiles, these considerations indicate that the internal resistance of the thermopile should be as low as possible for a given output signal, Δe, to achieve an optimum signal-to-noise ratio. Considering only the transistor noise due to collector-to-base leakage current, an approximate relationship between input noise and source resistance may be written:

$$Se = DR_p = 2DNR_C = 2DNr_C \frac{L_c}{A_c} \qquad (34)$$

where: Se is the noise at the amplifier differential input,

D is a constant of the transistors in the input stages of the differential amplifier,

R_p is the thermopile resistance,

R_c is the resistance per couple,

r_c is the resistivity of the couple wires (average for two wires of different resistivity),

N is the number of couples,

L_c and A_c are length and area of the thermocouple wires.

By combining Equation 24 with Equation 28, the maximum signal-to-noise ratio will be:

$$\frac{e}{Se} = \frac{K \frac{dQ}{dt}}{NDr_C K_C} = \frac{1}{D} \frac{k}{Nr_C K_C} \frac{dQ}{dt} \tag{35}$$

Equation 35 is written in a manner which separates the expression into factors that represent figures of merit for the amplifier and for the thermopile. That is, 1/D should be as large as possible for the amplifier, and $k/r_C K_C$ should be as large as possible for the thermocouple to permit use of a small number, N, of thermocouples. It must also be borne in mind that this expression was derived using an equation for e which assumed that stray losses were negligable, and that only one source of transistor noise is considered. Within these limitations, Equation 35 may be used to determine the approximate maximum N for a given signal-to-noise ratio, if D is known.

3.2.3.5 Amplifier Characteristics

Consideration of several sources of thermocouple inefficiency indicates that the amplifier input resistance should be high. The first of these inefficiencies arises from the ohmic voltage drop due to the thermopile internal resistance. This voltage drop is, of course, minimized when the amplifier input resistance is maximized and the thermopile internal resistance is minimized. The second source of inefficiency arises from the Peltier effect, by which the hot junction is cooled and the cold junction is heated in proportion to the current drawn from each thermocouple. The Peltier effect is not highly efficient, but since it is proportional to the current drawn from the couple it may be minimized by maximizing the apparent input impedance of the amplifier.

In addition, the power dissipated in each wire of the thermopile is proportional to the square of the current drawn from the pile and to the resistance of the wire. The disturbing influence which this factor has upon the experiment can be minimized by minimizing the resistance of the thermopile, and by minimizing the current drawn from the thermopile by maximizing the apparent input impedance of the amplifier.

The apparent input impedance of the amplifier may be made very large in several ways. The most attractive approach is to utilize the fact that the thermopile is a potential source, and, consequently, if isolated from the amplifier supply, the feedback connection can be made in such a way that the apparent input impedance is the actual impedance multiplied by the loop gain of the amplifier. Alternately, the amplifier input may be nulled by heating the reference cell (assuming it is cooler than the sample cell) by application of the amplifier output to an appropriate electrical heater winding within the reference cell.

Another approach would be to utilize a second thermopile for equilibrating the temperature of the two cells by Peltier heating or cooling, (depending upon the direction of current flow), with a current supplied by the amplifier output. Either method of nulling the amplifier input would require an amplifier "on-time" of at least 10 minutes to establish equilibrium conditions, while the direct readout would require only sufficient time for the amplifier to stabilize.

If a five volt output is to be obtained for a one microvolt input (corresponding to about one microcalorie/sec heat input) the open loop gain of the

amplifier must be at least 5×10^6, and prefferably greater by a factor of 100 to permit a loop gain of 100 or more. State-of-the-art integrated circuit operational amplifiers would provide an open loop gain of 5×10^8 for a power consumption of about 0.4 watts, but as a practical matter the noise referred to the input is about one microvolt, making a full scale sensitivity of one microcalorie/sec impractical.

The ultimate limitation of system sensitivity is the sum of the amplifier input noise and the thermopile noise, since a further increase of open loop gain is of little benefit once the error signal is reduced to the noise level. In application, this means that the input noise must be 10% or less of the full scale sensitivity for 10% of scale output noise, regardless of amplifier gain, and that increasing the amplifier open loop gain beyond several hundred times the required closed loop gain is not worthwhile since only a small improvement is possible.

While the above signal-to-noise figures refer to an amplifier using integrated circuit operational amplifiers currently available, it may reasonably be expected that the state-of-the-art will advance in the next several years. Parametric amplifiers with peak-to-peak noise of less than one microvolt, and with very high input impedance, are now commercially available. It is entirely possible that a noise level of less than 0.1 microvolt, at very high input impedance, will be feasible within a matter of one or two years. This could also make the use of semi-conductor thermocouples feasible, and might make it possible to increase the sensitivity of the microcalorimeter by several orders of magnitude.

3.2.4 Resistance Thermometers as Detectors for a Microcalorimeter

3.2.4.1 Principle of Operation of Resistance Thermometers

The resistance thermometer utilizes the fact that an electrical conductor such as platinum has a thermal coefficient of resistivity of about 0.4%/^{o}C. Most pure metals have a resistivity which is reasonably linear with temperature over a wide range, and which extrapolates to zero at 0°K. Platinum is the most commonly used material because it is inert, has high resistivity, a linear coefficient, and a high melting point. The resistance of platinum wire may be measured directly, and is essentially directly proportional to the absolute temperature.

Differential resistance thermometers are also widely used in such devices as thermal conductivity bridges. The degree of acceptability within the scientic community is comparable to that of thermocouples. Consequently, consideration of utilizing this method of monitoring the thermal gradient within a microcalorimeter is warranted.

3.2.4.2 Design Parameters for a Differential Platinum Resistance Thermometer

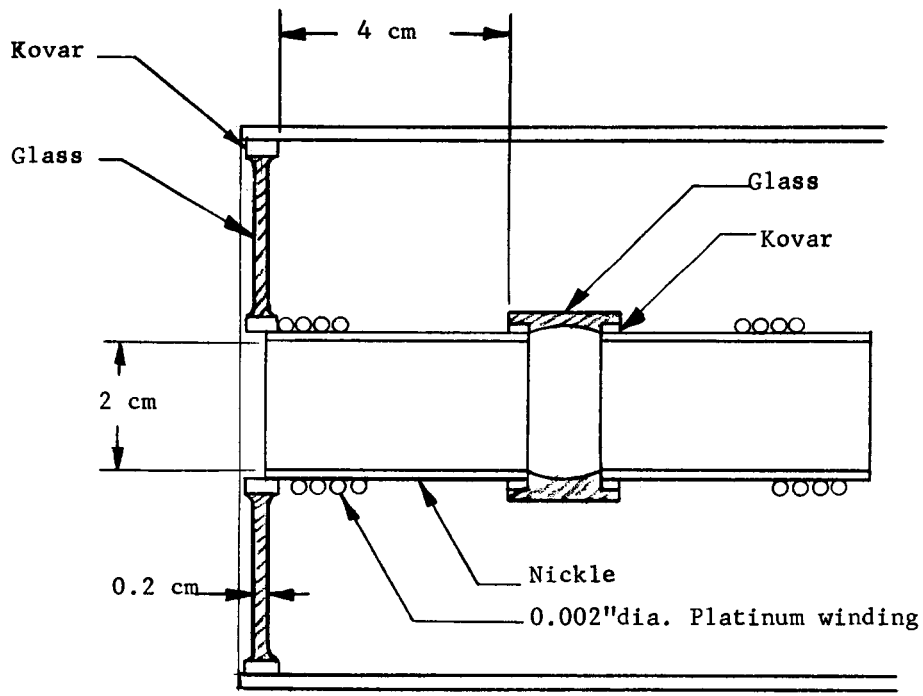
A platinum resistance element has a coefficient of resistivity of about 0.4%/^{o}C. If it is assumed that a 1200 ohm element is in good thermal contact with the wall of a culture tube within the microcalorimeter, then this element will change resistance by 2.4 ohms per degree centigrade. A one-half milliampere current through the element will produce a power of 300 microwatts (about 75 micro calories/sec). When operating under these conditions the change in voltage with temperature will be about 1200 micro volts/^{o}C. The

change in element temperature may be computed, for an assumed geometry, when a culture heat output of one microcalorie per second occurs.

The deminsions and materials of construction assumed in Figure 3-4 provide a heat conductance of 8×10^{-4} cal/sec ^{o}C for the two glass headers. With super insulation the other losses would be negligable. For an input of one microcalorie per second the thermal rise would be about 1.2×10^{-3} ^{o}C. From the above paragraph, the output voltage would be about 1.4 micro volts per microcalorie per second input. This theoretical sensitivity compares favorably to that of the thermopile method. This approach is, therefore, worthy of further consideration.

A reference cell (with resistance element) is shown in Figure 3-4. In application equal electrical power would be dissipated in each element. The thermal rise of each element would be 0.09^{o}C under the assumed conditions of one-half milliampere and 1200 ohms per element (75 microcalories/sec). The voltage drop across each element would be 0.6V, while the change in voltage for one microcalorie-per-second input would be 1.4×10^{-6} volts, or only about 2 parts per million (ppm) unbalance. This implies that the very best practices would be required in fabrication of the elements and in connecting them into a wheatstone bridge.

Assuming that the elements were connected in series so that the same energizing current passed through each, and that they were electrically and geometrically matched to within 0.1%, a noise level of one ppm is feasible. By way of supporting evidence, Beckman has produced experimental flow meters using nickle ribbon elements on a glass tube, which were self heated to 250 ^{o}C.



Design Notes

1. Resistance of 0.002" dia. Platinum wire = 0.55 ohms/cm
2. Length of wire per turn, about 6 cm.
3. 100 turns per cm for spacing equal to wire diameter
4. For 4 cm tube, wire length of 2400 cm is possible, providing a resistance of 1200 ohms for each element

Figure 3-4. Differential Platinum Resistance Thermometer

At least 50% of these elements had a noise level of less than 10 ppm, even when heated to 250°C. Most of the noise was found to result from assymetry of thermal capacity, which caused different thermal time constants for step function power supply noise. Because the two elements did not "track" thermally, the power supply noise resulted in bridge output noise.

3.2.4.3 Electronics for use with Resistance Bridge

If desired the microcalorimeter could be made to null by feeding back power to the reference element from the amplifier output. If the balancing power were to be applied to the sensing element, a non-linear calibration would result. In addition, the sensitivity would depend upon the "base" current passed through each element. The following expressions apply:

$$P = i_R^2 R_R \tag{36}$$

$$P+P_M = (i_R + i_f)^2 R_R \tag{37}$$

$$P_M = (2 i_R i_f + i_f^2) R_R = i_f R_R (2i_R + i_f) \tag{38}$$

In the above equations:

P is the "base" electrical power

P_M is the power due to metabolic processes

i_R is the "base" heating current

R_R is the element resistance

i_f is the feedback current

This is the equation of a parabola which has its vertex at the origin, but is rotated with respect to the axis of symmetry. Consequently, the

sensitivity decreases for higher power inputs. This could be advantageous, since maximum sensitivity at minimum input provides a wide range of useful response.

3.2.5 Sensing of Microcalorimeter Temperature by Infrared Radiation

A brief study was conducted of the feasibility of sensing the temperature rise within the sample cell of the microcalorimeter by use of an infrared radiation detector.

Initial consideration was given to the signal-to-noise ratio of available detectors. With a narrow band pass amplifier (several cycles/sec) the minimum detectable power for currently available detectors (operating at room temperature) is about 10^{-8} watts. Since a full scale input of 10^{-7} watts would represent a significant improvement over the sensitivity of currently available microcalorimeters, the study was continued.

To realize the potential advantage of the IR detector, it is necessary that a large percentage of the power dissipated within the cell due to biological activity be radiated to the detector. That is, the heat losses due to thermal conduction must not exceed the heat radiated to the IR detector if the IR detector approach is to provide any advantage over conventional detectors. To determine the relative merit of the two methods, consideration of the magnitude of heat transfer by the two mechanisms was necessary.

If an emissivity of one, and unit areas, are assumed for simplicity, the Stetan-Boltzman Law for radiation yields a coefficient of about 1.4×10^{-6} cal/sec^{o}C for emission under ideal conditions to a detector which is operating

at essentially the same temperature ($300^{o}K$ for these calculations). All of the microcalorimeter cell designs considered had thermal loss coefficients due to conduction which were approximately 100 times this figure, or about 10^{-4} cal/sec^{o}C. Consequently, it appears that at the present time no IR detectors are available which offer any improvement over the conventional thermopile microcalorimeter detector.

4.0 MICROCALORIMETER PRELIMINARY DESIGN

4.1 Design Requirements

As agreed in our meeting at NASA/Ames on Friday, March 25, 1966, Beckman agreed to conduct a feasibility and preliminary design study to delineate and specify the design parameters of a microcalorimetric system for the detection of Martian microorganisms. The system which Beckman designed is of minimum size and weight to allow maximum sensitivity, minimum power consumption and conforms to the following requirements:

1. All parts and materials appear on NASA List of Approved Materials.
2. Sample size shall not exceed 10 grams.
3. Internal temperatures can be held constant, at $5^{\circ}C$ increments, $\pm 2^{\circ}C$ between $5^{\circ}C$ and $30^{\circ}C$.
4. The system will accept liquid, solid, and slurry samples.
5. There will be two sets of sample and reference cells that can be operated and recorded simultaneously.
6. Data will be presented at the central data gathering interface continuously in an analog format.
7. A logic system, not to be defined in this report, will choose the data gathering rate. This rate will be dictated by the rate of change of the data presented at the interface.
8. The logic system will also dictate the sequence, rate and type of samples and nutrients that will be presented to the microcalorimetric system.

9. The solid samples presented to the system will be thirty mesh or finer.

10. The system will prepare samples for discard and present them to the central disposal interface.

11. The cell design will maintain a 1:1 gas to inoculum ratio to allow for possible future GC applications.

12. Environmental design considerations will be based on the assumption that the system will interface with the capsule's external environment as related to temperature, atmosphere, and radiation. Any commodity to adapt or regulate the environment will be internal to the system.

13. Structural and electrical design considerations will be based on the above mentioned environmental factors and also expected vibration levels, G-loading and sterilization temperatures.

14. All design considerations will be based on the latest information obtainable from the Philco ABL Report and JPL Voyager office.

A system interface diagram is shown in Figure 4-1.

4.2 Design Description

4.2.1 Functional Description of the Microcalorimeter (Figures 4-2 and 4-3)

It is assumed that after the landing on Mars the microcalorimeter will be properly oriented. Prior to lift off, the manipulator bar is driven through the support hole in the microcalorimeter heat sink and snugly fitted into the bearing support located at the opening in the outer housing. The manipulator bar is supported by bearings on each end and absorbs shock on launch and

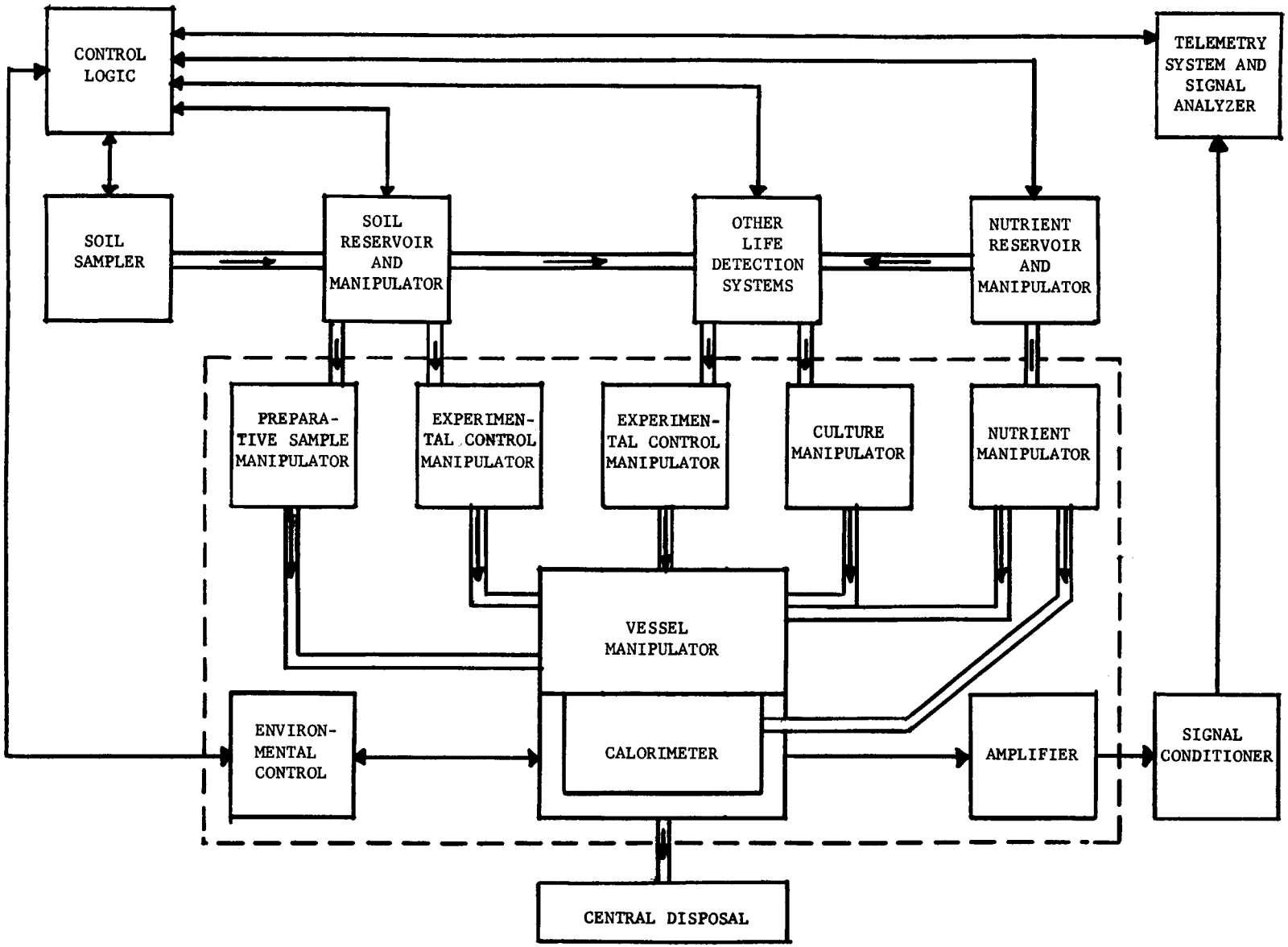


Figure 4-1. System Interface Diagram

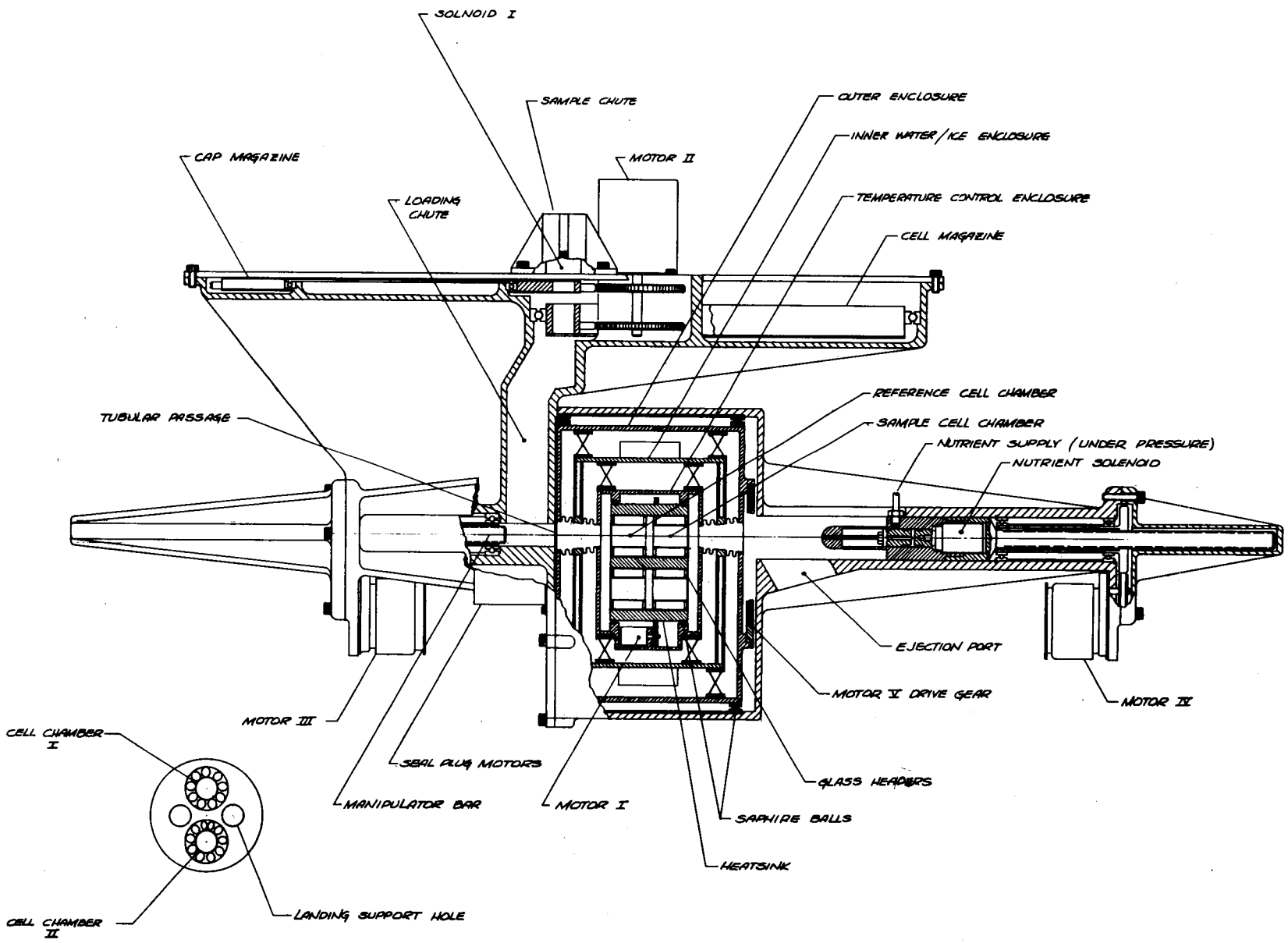


Figure 4-2. Microcalorimeter (Cutaway View)

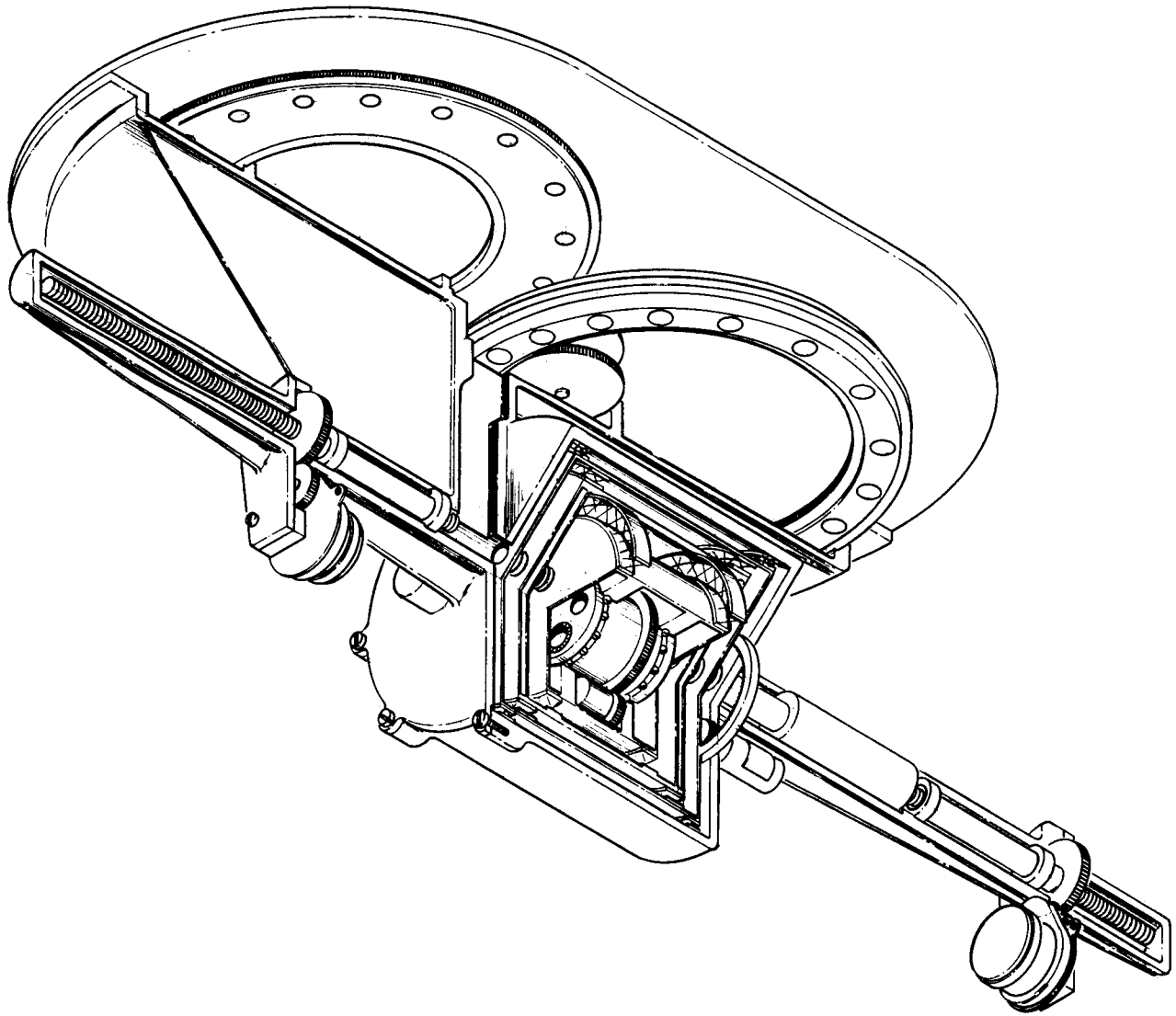


Figure 4-3. Microcalorimeter (Isometric View)

landing, for shock loading along the preferred axis. The manipulator operations are tabulated as follows:

1. Bearing support removal: Motor 3 is activated to unlock and retract the manipulator bar. The bar is driven through the microcalorimeter cell to disengage the bearing support used only in launch and landing. Upon retraction, the support bearing is disengaged and falls through the ejection slot.
2. Orientation of heat sink: Motor 1 is activated to rotate the sink, to align Cell Chamber I with the tubular passage.
3. Filling the sample cell: Motor 2 rotates the cell magazine into alignment with the sample chute. The sample collection system delivers a measured sample to the cell through a matching hole in the cap magazine.
4. Capping of the cell: Motor 2 rotates the two magazines until a hole containing a cap aligns vertically with the sample cell. When motor 2 stops, solenoid 1 inserts a cap into the filled cell.
5. Transfer of loaded cell: Motor 2 rotates the magazines to the position for loading the next cell. Simultaneously, the first cell drops into the loading chute and rolls into position to be inserted by the manipulator bar.
6. Insertion of the sample cell: Motor 3 drives the manipulator bar to insert the sample cell into the sample cell chamber.
7. Injection of nutrient: Motor 4 drives the nutrient syringe into a septum cap on the end of the sample cell and injects a predetermined

volume of nutrient. Injection is accomplished by energizing the nutrient solenoid. Motor 4 then reverses and retracts the nutrient syringe.

8. Loading of the reference cell: Steps 3 through 5 are repeated except that the second cell in the magazine contains an encapsulated inhibitor. The capsule is broken in the capping operation. Alternately the metered soil sample for the reference sample could be autoclaved prior to filling.

9. Insertion of reference cell: Motor 3 drives the manipulator bar to insert the reference cell into the reference cell chamber. Motor 3 then reverses and retracts the manipulator bar.

10. Alignment of Cell Chamber No. 2: Motor 1 rotates the heat sink as in operation Number 3 to align cell chamber Number 2 with the tubular passages. After repetition of Steps 3 through 9, Cell Chamber Number 2 is loaded and ready for an experiment.

11. Orientation of heat sink for experimental run: Motor 1 now rotates the heat sink into a position which places the landing support hole in alignment with the tubular passages and locates the cell chambers symetrically with respect to heat losses.

12. Rotation of enclosures: Motor 5 drives the microcalorimeter enclosures through the motor 5 drive gear to align the tubular passages with the seal plug insertion motors.

13. Insertion of sealing plugs: First one plug and then the other is inserted by the insertion drive motors. These plugs effectively

seal the microcalorimeter against changes in the outside environment. The motors are stopped once the seal plugs are inserted.

14. Experimental run: All manipulator power is now off and an experimental run is made. The length of the experiment will be determined by the results.

15. Removal of seal plugs: At the end of an experiment the seal plug insertion motors reverse and extract the seal plugs.

16. Rotation of enclosures to align manipulator bar with tubular passages: Motor 5 rotates the microcalorimeter enclosure back to the landing position.

17. Orientation of heat sink: Motor 1 rotates heat sink to align Cell Chamber I with the tubular passages.

18. Ejection of sample cells at end of experiment: Motor 3 drives the manipulator bar through the microcalorimeter heat sink ejecting the the sample and reference cells which fall through the ejection slot. Motor 3 retracts the manipulator bar.

19. Heat sink rotation: Motor 1 rotates the heat sink to align Cell Chamber Number 2 with the tubular passages.

20. Ejection of cells from chamber number 2: Repeat Step Number 18.

21. Recycling of nutrient injection: At any time during the performance of an experimental run additional nutrient may be injected into the sample cell by performing Steps 15, 16, 17 and/or 19, 7, 11, 12, 13.

4.2.2 Dimensions

4.2.2.1 Overall Dimensions

The overall dimensions of the apparatus shown in Figures 4-2 and 4-3 should be considered as typical examples only. No major effort was devoted to design of the manipulators, since this was an incidental requirement. It is probable that a considerable reduction in size and mass could be achieved.

Overall length: 34-5/8 inches

Overall width : 15-5/8 inches

Overall depth : 11-1/2 inches

4.2.2.2 Dimensions of Items Involved in Mechanical and Thermal Analysis

a. Glass headers used in microcalorimeter chambers:

Inner diameter: 1.4 cm
Outer diameter: 2.8 cm
Thickness : 0.08 cm

b. Heatsink:

Length : 5.6 cm
Diameter: 10.6 cm
Holes : 2 with 2.8 cm diameter and 2 with 1.4 cm diameter

c. Temperature controlled enclosure:

Length : 7.7 cm
Diameter : 12.9 cm
Wall thickness: 0.3 cm

d. Saphire balls in heat sink bearing:

Diameter: 0.3 cm

e. Inner enclosure (water/ice):

Length : 11.1 cm
Diameter : 15.3 cm
Copper thickness: 0.3 cm
Water/ice mass : 300 gm

f. Outer enclosure:

Length : 13.6 cm

Diameter : 20 cm

Wall thickness: 0.3 cm

g. Inner support wires (stainless steel):

Length : 1.7 cm

Diameter: 0.05 cm (48 wires total)

h. Outer support wires (stainless steel):

Length : 1.7 cm

Diameter: 0.05 cm (24 wires) and 0.1 cm (24 wires)

i. Tubular passage tubes (nickle, electro formed):

Diameter mean : 1.4 cm

Thickness : 0.01 cm

Effective length: 5 cm

j. Microcalorimeter cells:

Diameter (outer): 1.4 cm

Length overall : 2.5 cm, including caps

Volume : 3.2 cm^3

Wall thickness : 0.14 cm

4.2.2.3 Sample Size

The sample size utilized in the selected design was 3 gm of soil, assuming an average density of 2.5 gm/cm^3. The sample cell would also contain approximately 1.2 gm of nutrient in solution, and would provide a gas volume of approximately 30 to 50% of the cell volume.

4.2.3 Mass Estimate

Item	Description	Mass, Pounds
1	Housing, magnexium alloy casting	12.22
2	Shafts, stainless steel	1.34
3	Gears, aluminum and nylon	1.00

Item	Description	Mass, Pounds
4	Magazines, aluminum alloy	6.90
5	Heat sink, aluminum alloy	1.37
6	Enclosures, isothermal, copper (and water) and aluminum	5.14
7	Fasteners, stainless steel	0.50
8	Motors, (5)	1.25
9	Solenoids, (2)	0.75
10	Miscellaneous	0.50
	TOTAL	30.97

4.3 Power Requirements

4.3.1 Manipulator

It is estimated that each manipulation required could be performed by a 30 watt motor or solenoid. The total time for one complete manipulator cycle is probably about 10 minutes. The energy per cycle is, therefore, about 5 watt hours.

4.3.2 Temperature Control

The estimated average power would be 1.5 watts for control at +30°C against an average Martian ambient of -30°C. This average power level would control the critical amplifiers at 0°C, and assure that the controlled enclosure was surrounded by a 0°C enclosure at all times.

4.3.3 Amplification of Microcalorimeter Output

Using currently available components, the signal could be detected with amplifiers dissipating 0.3 watts each. For two simultaneous experiments, only 0.6 watts of power would be required. This power is included in the temperature control power estimate of 1.5 watts total, since the amplifier power dissipated is utilized.

for this purpose. If amplifiers requiring less power are available when required, it will be possible to improve the thermal resistance between the outer and inner enclosures and reduce the total power requirements by an equal amount.

4.4 Sensitivities

4.4.1 Amplifier

It was demonstrated that a conventional amplifier could provide an output of 0-5 V DC for an input of 0-20 microvolts from a source impedance of 1000 ohms. The signal-to-noise ratio was about 10 under these conditions. Thermal zero drifts were approximately 10 microvolts/^{o}C, with no special precautions. With proper technique this drift could be reduced to $\pm$ 2 micro volts/^{o}C.

4.4.2 Thermopile

The thermopile design selected has a theoretical sensitivity of 2 microvolts/-microwatt input of metabolic power. The theoretical noise is less than $\pm$ 0.06 microvolts.

4.4.3 Minimum Number of Bacteria Detectable

The microcalorimeter design selected could theoretically detect 2.8×10^{9} E. coli in the rest state, or 1.5×10^{6} B. coli in the most active state.

4.5 Thermal Analysis for Preliminary Design of Microcalorimeter

In this section, the feasibility of constructing a microcalorimeter which will provide acceptable sensitivity and stability under an assumed Martian environment of -80°C to +30°C (26 hour day), with a total power in the order of one watt, is demonstrated theoretically. The design equations and sample

calculations are presented in Section 3.0 of this report. Consequently, only the results obtained by similar analysis of the relatively complete model are given here. All of the parameters necessary for computation of the operating characteristics are tabulated to facilitate checking of the final results, and to permit rapid assessment of the overall effects of varying a given parameter. Most of the values tabulated are valid to within about 30%. Some notable exceptions are discussed in detail below.

It would be necessary to taper the enclosure end walls to reduce the thermal impedance at the junction of the enclosure ends with the tubular sample port. The junction thickness should be approximately three times that illustrated in the drawing in each case. The wall thickness should decrease as an exponential function of radius to approximately one-half of that shown. The cylindrical portions of the enclosure walls are approximately correct as illustrated. The water/ice volume should be increased by a factor of three.

The estimates of peak manipulator power and of energy required per manipulator cycle are relatively arbitrary. This is a consequence of the fact that manipulator requirements can not be sharply defined at present. The suggested apparatus is basically functional, but may be unsuitable if and when the total experiment is better defined. Consequently, it was assumed that 30 watt motors and solenoids (0.045 horsepower) would be adequate under all conditions. It was further assumed that only one manipulator drive would operate at any time, and that each of twenty separate manipulations would require 30 watts for 30 seconds.

The amplifier specifications are those actually obtained with a modified standard semi-conductor DC amplifier (see Appendix B). Consequently, these specifications do not rely upon possible improvements in performance with devices not yet available. It is quite probable that an improvement of at least a factor of five in signal-to-noise ratio could be made.

It should be noted that the auxillary heater is not shown in the illustration. This heater and the control electronics would be mounted on the water/ice enclosure. The sensing element would be mounted inside the enclosure. The control would introduce power into the water/ice enclosure only at times when all the water was frozen. This prevents the enclosure temperature from decreasing below $0^{o}C$ by more than a fraction of a degree centigrade. The power required to accomplish this would be 0.77 watts maximum if the environment is at $-80^{o}C$, and if a controlled enclosure temperature of $5^{o}C$ is maintained. If the controlled enclosure temperature were to be $30^{o}C$, then less auxillary power would be required, but the difference would be required for maintaining $30^{o}C$ in the controlled enclosure. The net effect is that a constant total power would be required regardless of the selected control temperature. This total would be an average of 1.5 watts for an average Martian temperature of $-30^{o}C$.

1. Summary of basic performance characteristics with amplifiers on water/ice enclosure:

   a. Average power required for $-30^{o}C$ average on Mars: 1.5 watts

   b. Minimum full scale metabolic power (20% noise): 10 microwatts

   c. Approximate time constant for metabolic activity: 0.8 hours

d. Approximate peak power for manipulations: 30 watts

e. Maximum energy required for one manipulator cycle: 5 watt hours

f. Minimum detectable number of E. coli in rest state: 2.8×10^9

g. Minimum detectable number of B. coli in highly active state: 1.5×10^6

h. Size of sample, assuming 2.5 gm/cm^3 density: 3 gm

2. Thermal conductances, controlled enclosure to calorimeter heat sink:

a. Thermal conductance of saphire balls (10 at each end): 0.04 watts/^oC

b. Thermal conductance of motor drive gears (nylon): 0.03 watts/^oC

c. Thermal conductance of gas (3 mm Hg, air) in cell cavity: 0.03 watts/^oC

3. Heat capacity of heat sink: 500 watts sec/^oC

4. Heat sink thermal response to variations in enclosure control temperature:

a. Time constant: 1.5 hours

b. Approximate ΔT for $\pm$ 1^oC control ripple having a 6 min period: $\pm$ 0.04^oC

c. Corresponding thermopile output ripple for 0.1% symmetry: $\pm 4 \times 10^{-5}$ ^oC (0.6 microvolts)

5. Heat sink thermal response to power input from metabolic activity:

a. Temperature rise: 10^{-5} ^oC/micro watt

b. Time constant: 40 hours

6. Microcalorimeter cell and thermopile parameters:

   a. Thermal conductance of glass headers: 3.5×10^{-3} watts/^{o}C

   b. Thermal conductance of super insulation: negligable

   c. Thermal conductance of each thermocouple: 1.2×10^{-5} watts/^{o}C

   d. Thermal conductance of each thermopile (300 couples): 3.5×10^{-3} watts/^{o}C

   e. Time constant (assuming 20 watts sec/^{o}C heat capacity): 0.8 hours

   f. Thermopile resistance: 730 ohms

   g. Temperature rise per unit power input: 1.5×10^{-4} ^{o}C/ micro watt

   h. Output voltage per unit power input: 2 micro volts/micro watt

   i. Thermopile noise due to temperature control variations: less than 0.06 micro volts

   j. Minimum detectable input power (simple amplifier): 2 micro watts

7. Water/ice enclosure parameters:

   a. Thermal conductance of tubular passages (2): 1.1×10^{-2} watts/^{o}C

   b. Thermal conductance of wire strut supports (48): 10^{-2} watts/^{o}C

   c. Thermal conductance through inner Super Insulation: 6×10^{-5} watts/^{o}C

   d. Thermal conductance through tube plugs (20% of tube): 0.22×10^{-2} watts/^{o}C

   e. Maximum power (to maintain controlled enclosure at 30°C): +0.75 watts

   f. Minimum power (to maintain controlled enclosure at 5°C): +0.125 watts

   g. Maximum continuous rate of melting ice (item e only, 30°C): -8 gm ice/hour

h. Minimum continuous rate of melting ice (item f only, $5^{o}C$): 1.3 gm ice/hour

i. Minimum quantity of water in enclosure wall: about 300 gm

j. Net minimum average rate of water freezing (sum of items 7.g, 8.h and 9.b): +1.6 gm ice/hour

k. Net maximum average rate of freezing water (sum of items 7.h, 8.h and 9.b): +8.3 gm ice/hour

l. Maximum auxillary heater power (to hold ice at $0^{o}C$): 0.77 watts

8. Outer enclosure parameters:

a. Thermal conductance of tubular passages (2): 1.1×10^{-2} watts/^{o}C

b. Thermal conductance of wire struts (24@ 0.02", 24@ 0.04"): 3.5×10^{-2} watts/^{o}C

c. Thermal conductance through outer Super Insulation: 12×10^{-5} watts/^{o}C

d. Thermal conductance through tube plugs (20% of tube): 0.22×10^{-2} watts/^{o}C

e. Maximum power to outer from inner enclosure ($-80^{o}C$):-5.0 watts

f. Maximum power from outer to inner enclosure ($+30^{o}C$): +1.5 watts

g. Average power to outer from inner enclosure ($-30^{o}C$ average): -1.5 watts

h. Average rate of freezing water (item g only, $-30^{o}C$): +16 gm ice/hour

i. Maximum rate of freezing water (item e only, $-80^{o}C$): +54 gm ice/hour

j. Maximum rate of melting ice (item f only, $+30^{o}C$): -16 gm ice/hour

9. Thermal balance parameters for amplifiers on water/ice enclosure:

   a. Power dissipated, two amplifier channels: 0.6 watts

   b. Continuous rate of melting ice (item a only, 0.6 watts): -6.4 gm ice/hour

   c. Proportional temperature control elements to be on enclosure controlled so that their heat dissipation is utilized as part of control power.

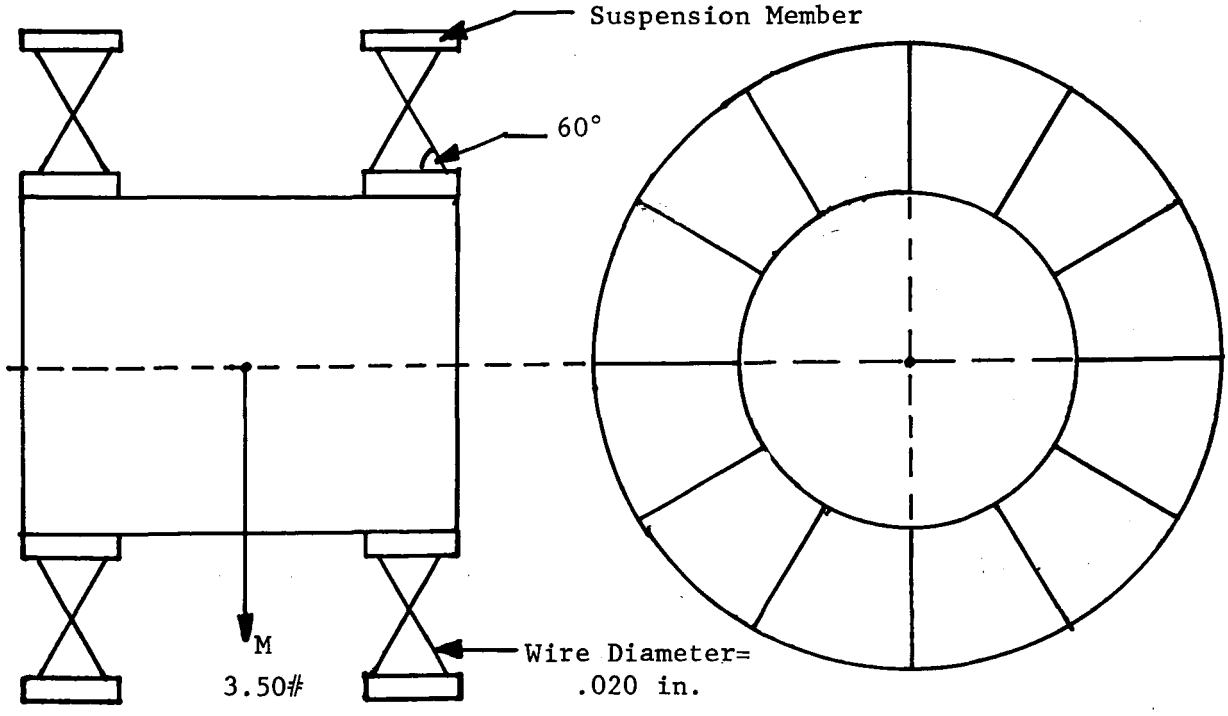
4.6 Structural Analysis

Assuming that landing impact would be in the order of 2000 g, a structural analysis was performed on the microcalorimeter system. It was decided that the analysis would be performed on the most sensitive portion of the system. This was determined to be the heart of the microcalorimeter. The areas of greatest stress would be on the manipulator rod that supports the heat sink at impact and the suspension wires supporting the ice/water enclosure and the temperature control enclosure.

It can be shown that all other portions of the system are much stronger structurally.

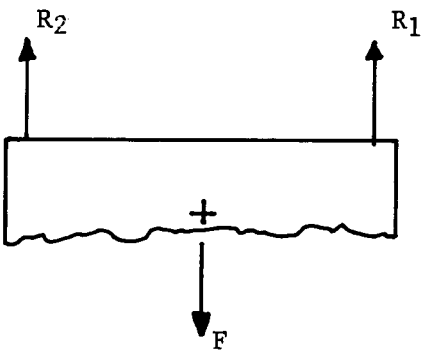
4.6.1 Analysis of Jacket Suspension

Method of Loading - 2000 g shock



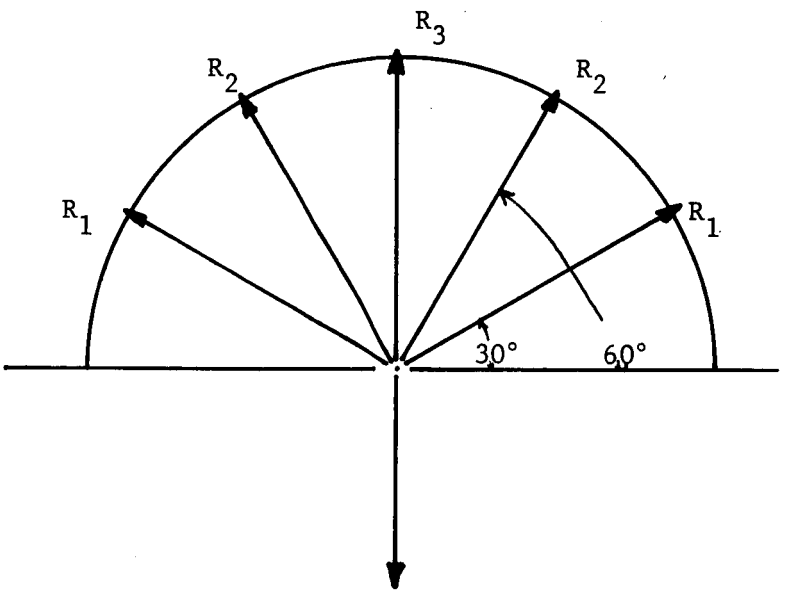
Suspension Arrangement

12 pairs of suspension wires per suspension member arranged equally spaced around a circle with each pair crossed as shown.



$F = 2000 \times 3.50 = 7000$ # F.

$R_1 = R_2 = 3500$ # F



F = 3500#

If we assume that all the load in one suspension member is taken up by those pairs of wires in tension as shown above, then:

$$S = \frac{F}{A\ E}$$

where:

S = deflection of suspended member (jackets)

F = load in #'s

A = cross section area of wires

E = Young's modulus of material used.

$$F = A\ E\ S = 2\ R_1 + 2\ R_2 + R_3$$
$$= A\ E\ (2\ S_1 + 2\ S_2 + S_3)$$

$S_2 = \text{Sin } 60^\circ$ $\qquad$ $S_3 = .866\ S_3$

$S_1 = \text{Sin } 30^\circ$ $\qquad$ $S_3 = .50\ \ S_3$

$$F = A\ E\ (S_3 + 2\ (.866)\ S_3 + S_3)$$

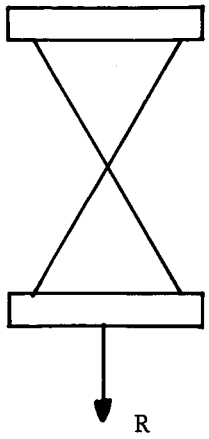
$$F = 3.732\ AE\ S_3$$

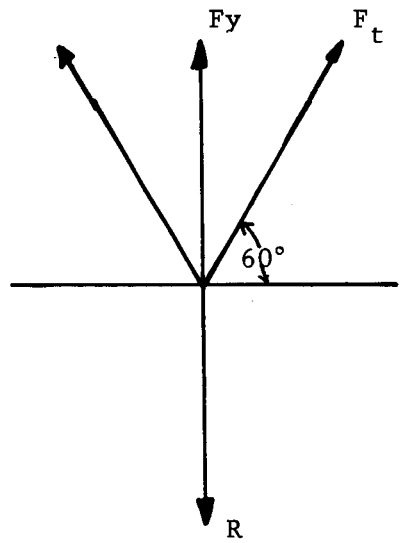
$$S_3 = \frac{3500}{3.732 \times A \times E}$$

$R_1 = A\ E\ S_1 = AE\ .50\ S_3$

$R_2 = A\ E\ S_2 = AE\ .866\ S_3$

$R_3 = A\ E\ S_3$





$$Fy = \frac{1}{2} R = F_t S \text{ in } 60^o$$

$$F_t = \frac{1}{2} R/S\text{in } 60°$$

where: F_t = tensile force in each wire.

From P. 3

For Wire Set 1

$$R_1 = .50 \text{ A E } S_3$$

$$F_t = \frac{1}{2} \frac{.50 \text{ A E S3}}{\text{Sin } 60^o}$$

Substitute for S_3

$$F_t = \frac{1}{2} \frac{.50 \cancel{AE}}{\text{Sin } 60^o} \frac{3500}{3.732 \cancel{A} \cancel{E}}$$

$$F_t = \frac{.250 \times 3500}{.866 \times 3.732} = \underline{\underline{271}} \#$$

For Wire Set 2

$$R_2 = .866\ A\ E\ S_3$$

$$F_t = \frac{1}{2}\ \frac{R}{\sin 60^o} = \frac{.866\ A\ E\ \ 3500}{2\ \ .866\ A\ E\ 3.732}$$

$$F_t = \underline{\underline{470}}\ \#$$

For Wire Set 3

$$R_3 = A\ E\ S_3$$

$$F_t = \frac{1}{2}\ \frac{A\ E\ S_3}{\sin 60^o} = \frac{1\ \ A\ E\ \ 3500}{2 \times .866 \times 3.732\ A\ E}$$

$$F_t = \underline{\underline{542}}\ \#$$

Stress in Wires:

$$S = \frac{F_t}{A}$$

A = Cross Sectional Area of Wires = .000314 spin

The worst condition exists in Wire Set #3 where:

$$F_t = 542\ \#$$

$$S = \frac{542 \times 10^4}{3.14} = 172.5 \times 10^4$$

1,725,000 <u>psi</u>

If we double the diameter of the wires in Set 3:

the stress will be <u>430,000 psi</u>

the stress in Set 2 is:

$$S = \frac{470 \times 10^4}{3.14} = 1{,}500{,}000 \text{ psi}$$

Doubling the diameter of these wires will reduce this stress to 374,000 psi.

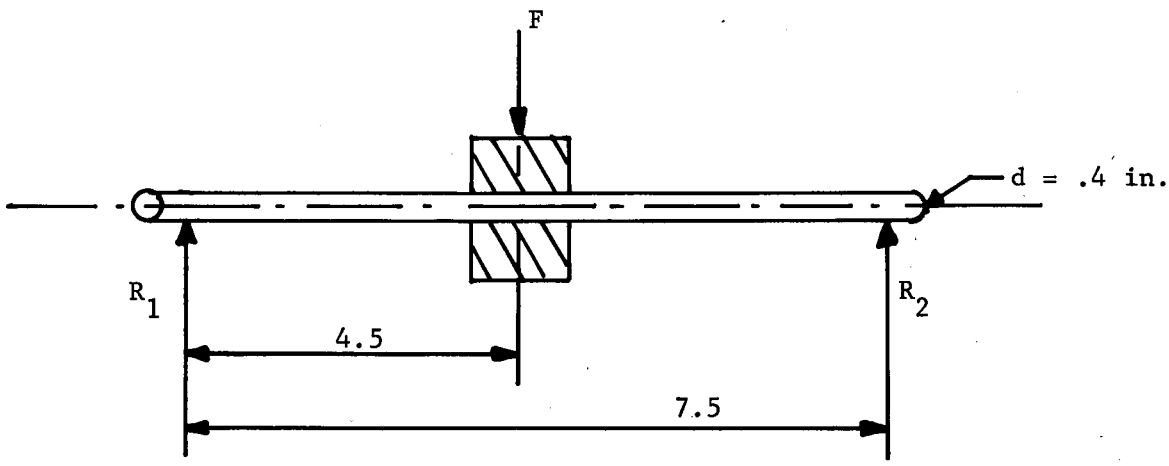
The stress in Set 1:

$$S = \frac{271 \times 10^4}{3.14} = \underline{865{,}000 \text{ psi}}$$

Yield Stress for SAE 9254 Wire ranges from 220,000 to 300,000 psi. Using a design stress of 250,000 psi, we would have to attenuate the shock load by a factor of:

$$Y = \frac{865}{250} = 3.46 \text{ or approximately } \underline{\underline{4}}$$

4.6.2 Analysis of Manipulator Bar Suspension



If F = KMa

and F = Force of G loading

M = Mass of heat sink = 1.41#

K = Constant for units = 1/g

a = Acceleration at impact = 2000 g

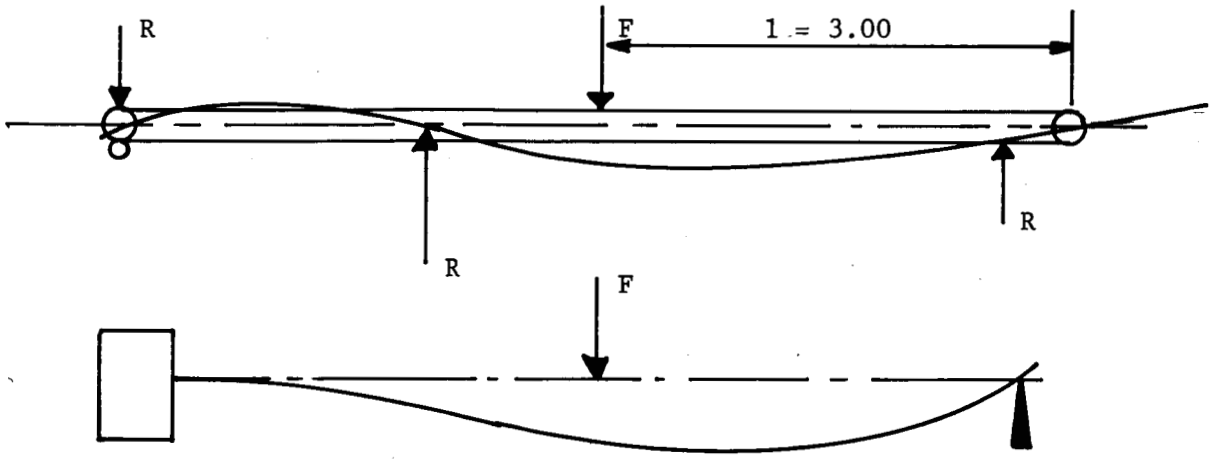
Then F = 2,820#

$R_1 = \frac{1}{2} F = 1410\#$

Shear Area = .79 (d^2) = .12

Shear Stress = R_1/Shear Area = 111,000 psi.

Bending Stress



$$S = \frac{Mc}{I}$$

where:

S = Bending Stress

M = Bending Moment

C = Shape Factor

I = Moment of Inertia

Since $M = 3/16\ Fl$ and $\frac{C}{I} = 32/\pi\ d^3$

$$S = (3/16\ Fl)\ 32/\pi\ d^3 = 254{,}000 \text{ psi}$$

If high strength steel is used, S yields as high as 230,000 psi can be realized. Using a safety factor of 2 we have a Sy = 115,000 psi. With this in mind it can be seen that at 2000 g impact, the g loading must be attenuated by 60 percent to avoid failure due to bending stress.

5.0 SUMMARY AND RECOMMENDATIONS

Hypothesis: Remote detection sensors must be developed to detect attributes of extraterrestrial life.

Justification for Microcalorimetry:

- The microcalorimeter monitors metabolism, a fundamental attribute of life.
- The detection of life by microcalorimetry is an in situ experiment.
- The detection of life by microcalorimetry does not depend on chemical analysis.
- Detection of life by microcalorimetry is independent of the life system's chemical base.

Study Basis: The aim of this study is to investigate the feasibility of using microcalorimetry in the detection of Martian microorganisms. The basic assumption is that if life exists on Mars, it exhibits heat of metabolism.

Study Results:

- The detection of Martian microorganisms is feasible under the assumed conditions.
- A completed preliminary microcalorimeter design to operate in the Martian environment.

Design Results: For clarity the design will be compared to the Beckman Model 190 Laboratory Microcalorimeter.

Parameter	Model 190	Flight Model
Weight	≃200 lb.	≃31 lb.*
Volume	≃35 $ft.^3$	≃3 $ft.^3$ *
Power	Several Hundred Watts	≃1.5 watts (nominal, continuous) ≃30 watts (maximum)*
Sensitivity	2×10^{10} E. coli**	2.8×10^{9} E. coli**
Ambient Temperature	±2°C variation	+30°C to -80°C
Shock	N/A	500g

* Including manipulating equipment

** Rest State

Tradeoffs:

- Increase available power → decrease size and increase strength.
- Increase size → decrease power.

Recommendations:

- Omit requirement for multiple experiments to:

  Increase Reliability

  Decrease Weight

  Decrease Complexity

  Decrease Cost

  Increase Strength

- Further laboratory study in semiconductor thermopile design.
- Further study in solid state electronic amplifier design.
- Fabrication of a laboratory breadboard based on the results of further study.

- Final design and fabrication of manipulation system and environmental enclosures should be attempted only after the satisfactory completion of a more sensitive detector.

It is possible that an additional factor of ten in sensitivity can be realized with further study and laboratory experimentation leading to a breadboard design.

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APPENDIX A

The inclusion of the following material was felt to be important because it is the systems approach to the conceptual design of a life detection experiment. This experiment uses a collection of sensors in a life detection system. These sensors are used in a logical experimental sequence so that the data obtained is more than just a yes or no answer. An integrated experiment must be developed before the problem of extraterrestrial life detection can be solved.

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C.	FUTURE EXPERIMENTATION INDICATED	A-27

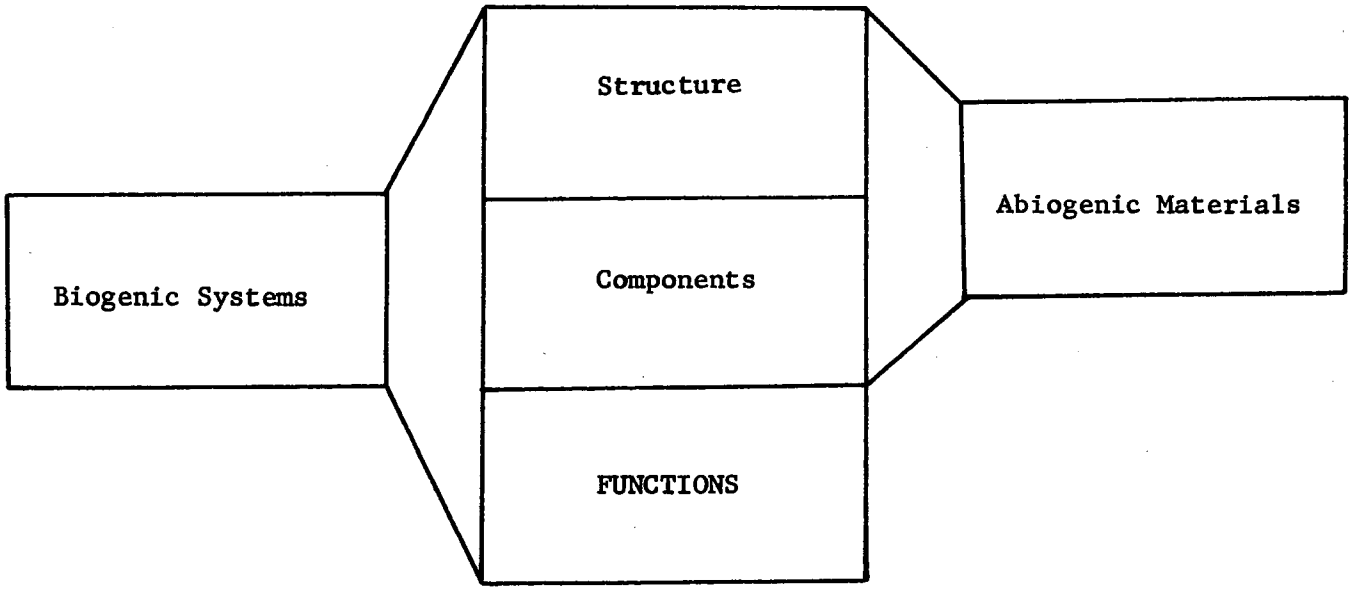
A. RATIONALE

DISCRIMINATION (Figure A-1)

Discrimination between biogenic and abiogenic phenomena cannot be characterized by either structure or components, since both are based on chemical and physical processes, but can only be discriminated on the basis of function. The characteristic response of the two systems, biogenic and abiogenic, remains essentially different since in living systems the interactions between chemical components take place according to the organizational intelligence (managed program) of the system and proceed as defined by past history and according to the objectives and requirements of the living system. For example, the processing of precursors within a cell is performed in a schedule as established by genitic code, nutritional requirements, and environmental availability. An abiogenic material will interact with other materials in its environment and produce heat of interaction, but the response will be immediate and complete, without long-term objectives such as the propagation of itself.

Figure A-1

DISCRIMINATION

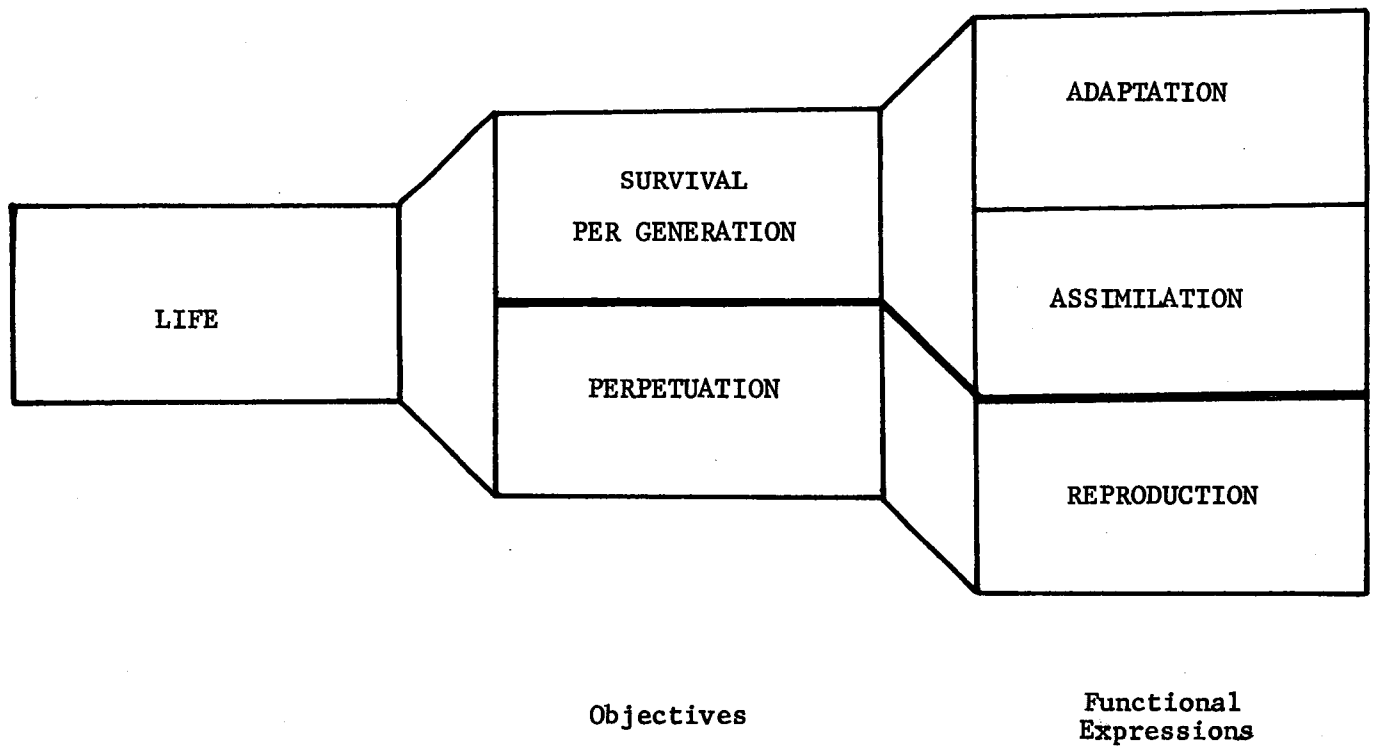


LIFE CRITERIA (Figure A-2)

Life has the objectives of survival per generation and perpetuation through successive generations. The organism, or biogenic system, functionally expresses the objective of survival per generation through adaptation and assimilation. The organism functionally expresses the objective of perpetuation through successive generations through reproduction.

Figure A-2

LIFE CRITERIA



AVAILABLE MEASUREMENT APPROACHES

Measurement approaches available are a) direct measurements and b) conditioned measurements. Conditioned measurements may, in turn, be categorized as either activation or inactivation procedures.

DIRECT measurement is a primary measurement since it does not require manipulation of the environmental conditions surrounding the specimen with the objective of achieving a given response, but takes advantage of the existing conditions surrounding the specimen. Direct measurements, therefore, require a minimum assumption in connection with the examination on the nature, e.g., requirements, of a biogenic system. Whenever a direct measurement is performed and whenever the specimen contains a microorganism in a growing state of activity, then a direct measurement will provide significant data in terms of life function of the microorganisms.

CONDITIONED measurement, on the other hand, requires that specific influences be brought to bear on the specimen which will predictably activate, accelerate, inhibit, or inactivate the biogenic system to produce a characteristic, anticipated response. Conditioned measurements have the disadvantage that more assumptions and more specific assumptions need be made concerning the nature of the specimen. This presents a particularly difficult problem in the design of an extraterrestrial life detection system for detection of microorganisms of unknown requirements and sensitivities.

Performance of conditioned measurements fall into two categories: activation and inactivation measurements. Activation procedures require the acceleration of metabolic activity of the biogenic system, eventually leading to increase in the protoplasmic mass and cell numbers. Inactivation procedures provide data which is significant from the standpoint of elucidation and identification of life in terms of chemical components of the life system (reaction of the killing agent and specific, target chemical compounds within the life system) and the termination of a functional activity by the biogenic system.

A greater number of presumptions are required in connection with activation procedures than with inactivation procedures; i.e., it is easier to select universal, broad-spectrum, killing agents (e.g., chemical agents and antimetabolites) or killing conditions (e.g., thermal sterilization and radiation) than it is to select universal media or culture conditions.

Conditioned experiments are significant by virtue of the fact that the experiments may be planned and utilized to call forth or manipulate a specific managed function of the life system.

MEASUREMENT APPROACHES			
MEASUREMENT	Environmental Manipulation Required	Presumptions Required	Life Functions Expressed
Direct Measurements	No	No	Yes/No
Conditioned Measurements			
Activation Procedures	Yes	Yes	Yes
Inactivation Procedures	Yes	Yes	No

Table A-1

MARS EXPERIMENT

1. Performance of a DIRECT MEASUREMENT which takes full advantage of information gained from a naturally growing culture within the specimen of soil. This is a preliminary life estimate.

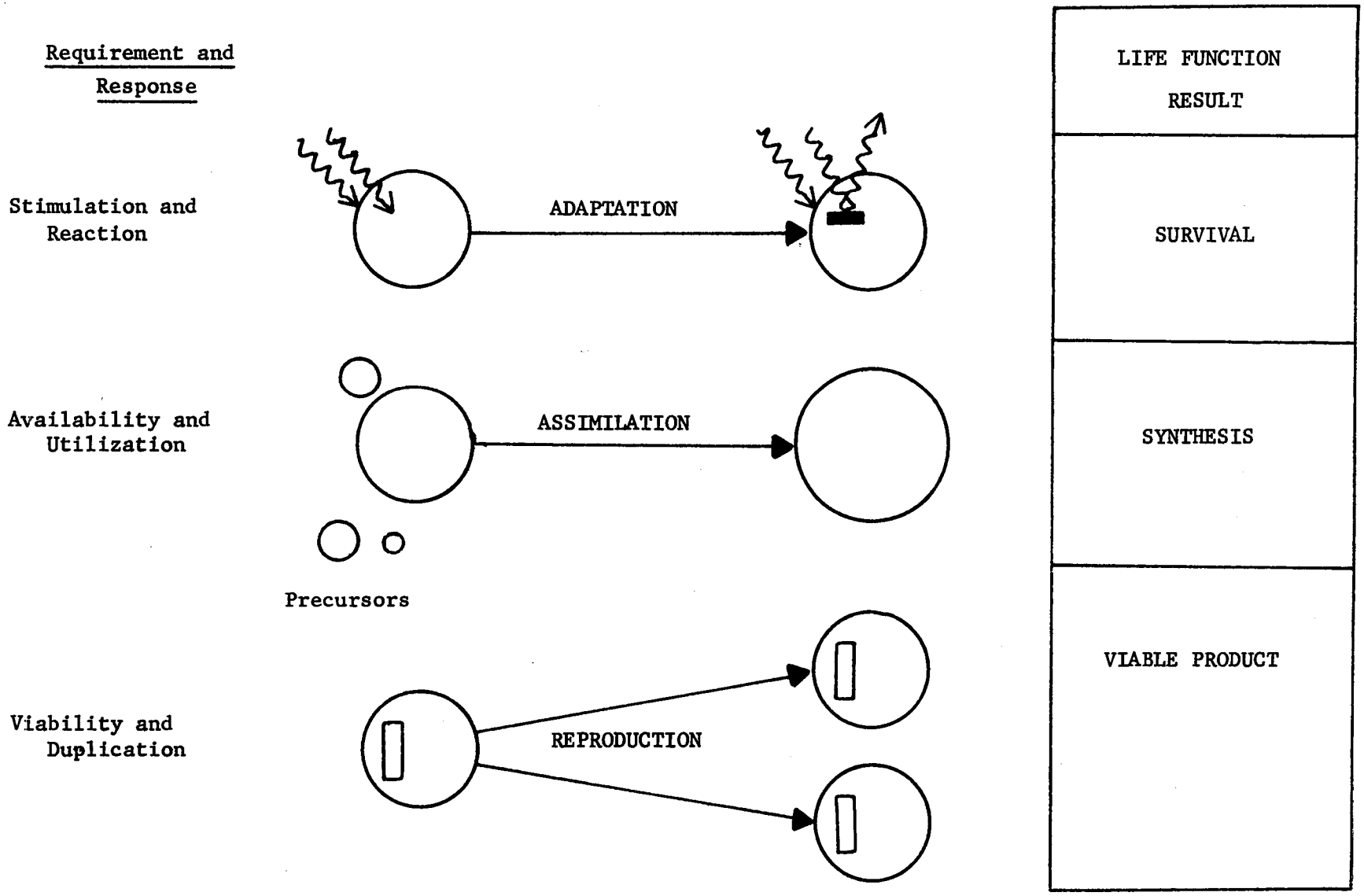
2. Performance of CONDITIONED MEASUREMENTS to permit functional evaluations of life. This is a conclusive demonstration of function.

LIFE FUNCTIONS (Figure A-3)

Life functions may be described in terms of requirements, responses, and results. Adaptation is reaction to stimulation resulting in survival. Assimilation is utilization of available basic compounds resulting in synthesis. Reproduction is duplication of a viable entity.

Figure A-3

LIFE FUNCTIONS



EXPERIMENTAL CRITERIA (Table A-2)

For the purpose of measurement of the functional activity of a biogenic system, fundamental criteria of interpretation are selected. These criteria are: change in the activity rate, increase in cellular content, and geometric population increase.

EXPERIMENTAL CRITERIA	
Functional Activity	Basis of Interpretation
SURVIVAL	INDUCED TEMPORARY CHANGE IN THE ACTIVITY RATE
SYNTHESIS	INCREASE IN CELLULAR CONTENT
VIABLE PRODUCT	GEOMETRIC POPULATION INCREASE

Table A-2

CHARACTERISTICS OF MEASUREMENT SYSTEMS

All proposed life detection systems give direct indication of adaptation and reproduction. Only the Microcalorimeter and the Gulliver give direct indication of assimilation.

CONCLUSIONS

EXTRATERRESTRIAL LIFE DETECTOR

If all systems are capable of direct survival measurement and the expression of life in terms of the function of adaptation, and

if only the u-Calorimeter and the Gulliver are capable of direct synthesis measurements and the expression of life in terms of the function of assimilation, and

if only the Vidicon Microscope is capable of direct viable product measurement and the expression of life in terms of the function of reproduction, then

an extraterrestrial life detection system which identifies life in terms of the functions of adaptation, assimilation, and reproduction must be made of a combination of either

a. μ-Calorimeter* + Vidicon Microscope, or

b. Gulliver* + Vidicon Microscope.

It should be noted that all systems have the capacity for performing direct viable product measurement provided two or more experiments (cultures) are performed. If two or more experiments are feasible, then an extraterrestrial life detection system made up of the u-Calorimeter <u>or</u> the Gulliver is adequate. All other systems, if aboard, would function to provide collaborative and confirmatory information (and also more detailed information on the nature of the biogenic system, if one were detected) but none would provide the information presented directly by either the u-Calorimeter or Gulliver systems.

* Microcalorimeter measures heat production from (a) production of protoplasm, (b) specific dynamic action, and (c) basal metabolism. Gulliver measures CO_2 produced by these activities.

1. Aerobic Activity: Food + Oxygen + Organisms $\longrightarrow$ New Cells + CO_2 + NH_3 + H_2O + HEAT

2. Anerobic Activity: Food + Organisms $\longrightarrow$ New Cells + CH_4 + CO_2 + H_2S + NH_3 + H_2O + HEAT

CHARACTERISTICS OF MEASUREMENT SYSTEMS*						
System	Measurements of Functional Activities					
	Survival		Synthesis		Viable Product	
	Direct	Indirect	Direct	Indirect	Direct	Indirect
Vidicon Microscope	X			X	X	
Gas Chromatograph	X			X		X**
U. V. Spectrophotometer	X			X		X**
J-Band Detector	X			X		X**
Optical Rotation Detector	X			X		X**
CO_2-Radioisotope Probe (Gulliver)	X		X			X**
Microcalorimeter	X		X			X**
pH-Detector (Wolf Trap)	X			X		X**
Multivator Detector (Enzymatic)	X			X		X**
Optical Density Detector	X			X		X**

* Basis: one experiment with multiple measurements.

** All become direct measurements if two or more experiments are conducted.

Table A-3

DESIGN OF LIFE DETECTION SYSTEMS (Table A-4)

Identification of functional requirements and systems requirements permits design and development of Life Detection Systems.

DESIGN OF LIFE DETECTION SYSTEMS

Functional Requirements

- Monitor Survival
- Monitor Synthesis
- Monitor Viable Product

Systems Requirements

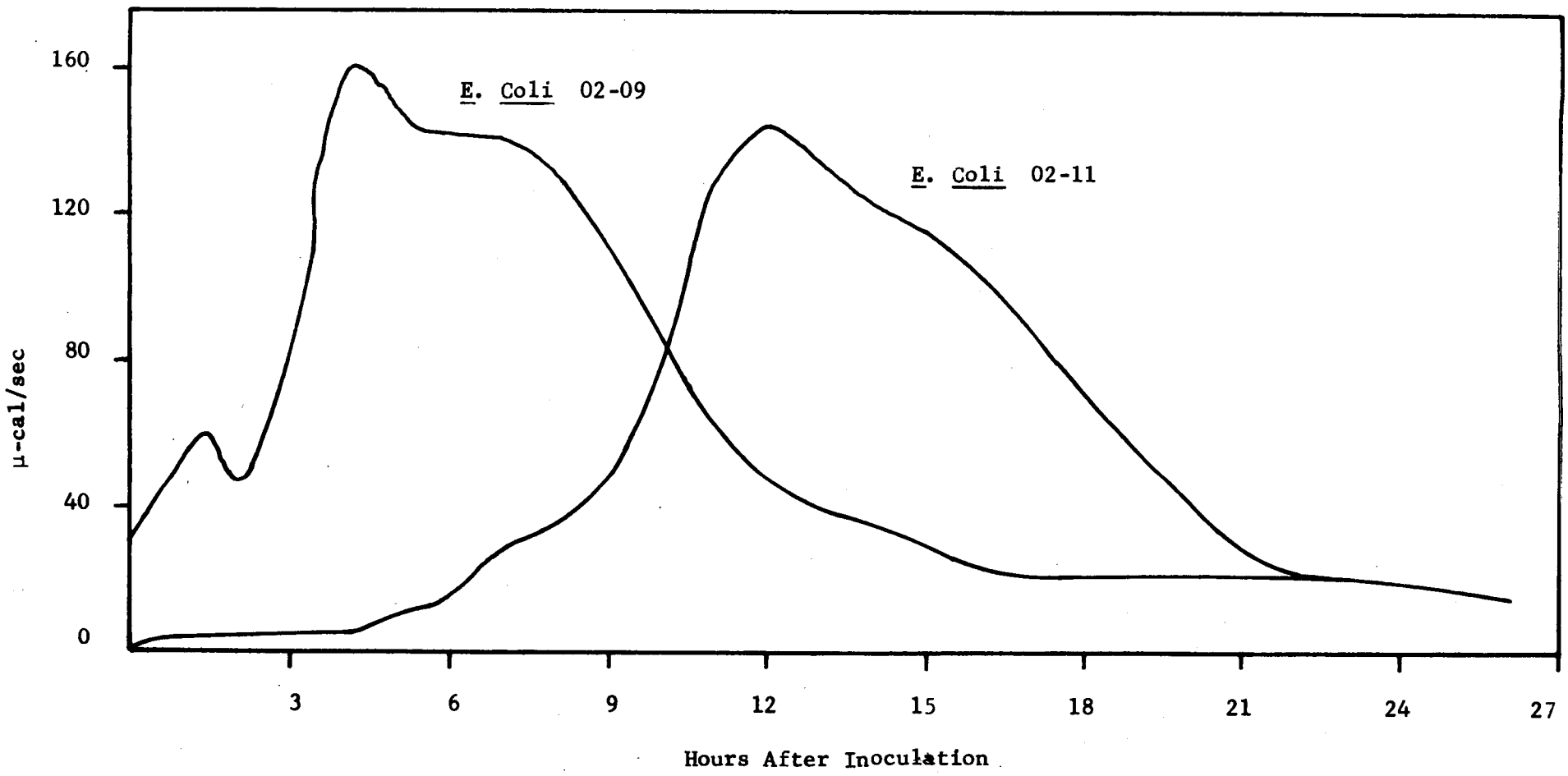
- Automatic
- Sensitivity and Specificity
- Reliability
- Low Power, Weight, Volume
- Compatability with Vehicle
- Other

Table A-4

B. EVALUATION OF EXPERIMENTAL RESULTS

CHANGE IN ACTIVITY RATE

Recession of the minor peak of E. coli subcultured from a maintenance medium of Heart Infusion directly into a maintenance medium of Brain Heart Infusion has been described. Phenomenon is illustrated in relationship to the characteristic thermogram of E. coli in Figure A-4 and detailed in Figure A-5.



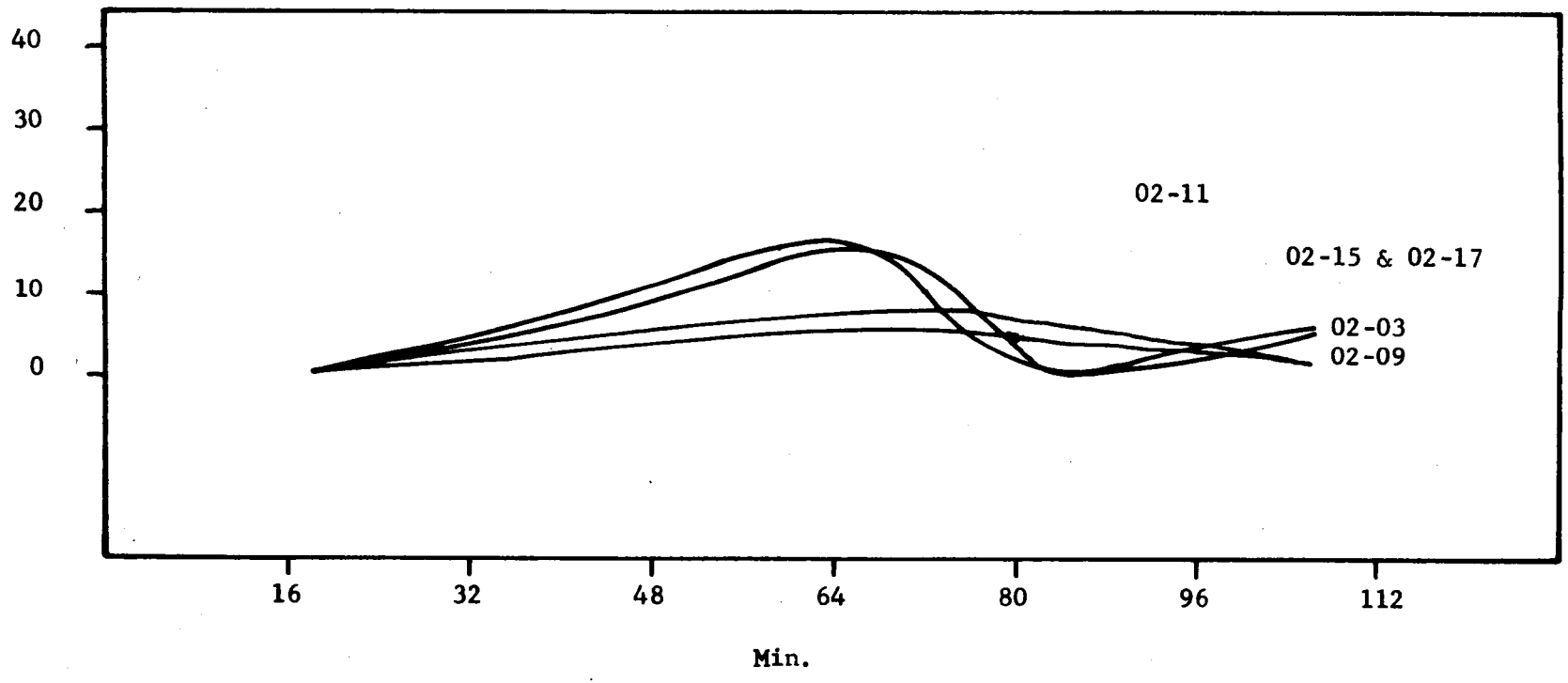
	02-09	02-11
Inoculum - Escherichia Coli		
Maintenance Medium	Difco HI	Difco BHI
Harvest Time	6-1/2 hours	4-1/2 hours
Suspension Solution	Water	Water
Control Inactivation	Thermal (60°C for 40 min.)	Thermal (60°C for 40 min)

Medium

5 mls. 3.7% (w/v) Difco Brain-Heart Infusion, Code 0037-02

Microcal. Cell Temp. Approx. 25°C

FIGURE A-4 EFFECT ON THERMOGRAM OF INOCULUM CONCENTRATION

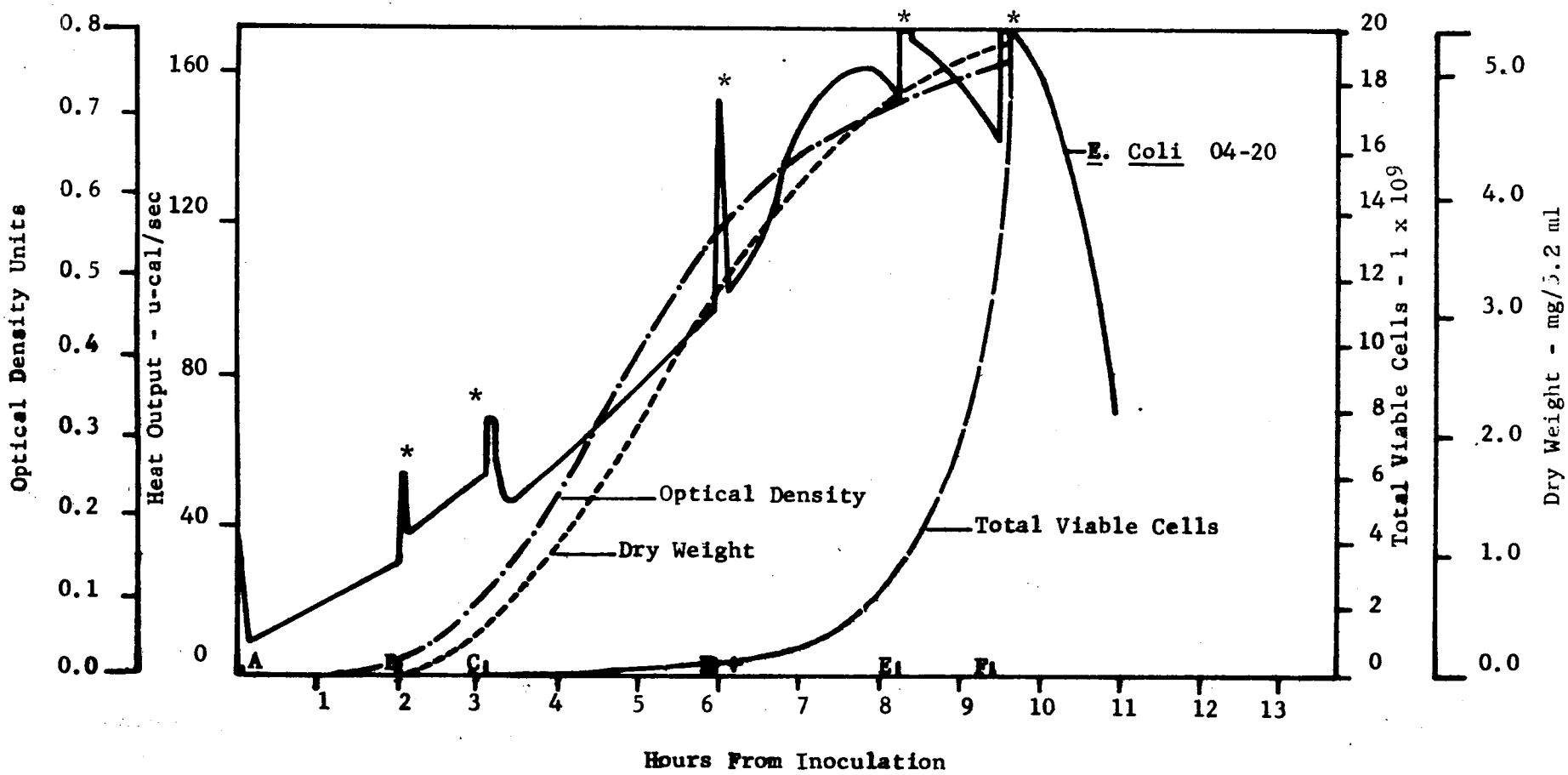


* Direct Trace From Thermograms

FIGURE A-5 RECESSION OF THE MINOR PEAK OF ESCHERICHIA COLI*

INCREASE IN CELLULAR CONTENT

Increase in cellular content on culture of E. coli has been described. This phenomenon is illustrated in Figure A-6. Heat output in the early portion of the developing peak appeared to be associated with increase of total protoplasmic mass, with cell division rate being relatively low. On appearance of the peak, rate of increase of protoplasmic mass was diminishing, while cell count increased abruptly. Following the heat peak, the heat output fell rapidly as the rate of increase of total cell mass approached zero.



Inoculum - Escherichia Coli
Maintenance Medium -Difco BHI
Harvest Time -4-1/2 hours
Suspension Solution -Water
Control Inactivation-Thermal
(60°C for 30 min.)

Medium
Difco Brain-Heart Infusion, Code 0037-02
(3.7% w/v)

Microcal. Cell Temp. Approx. 25°C

*Disturbances in the thermogram caused by mixing operations applied concurrently with mixing on external cultures.

External cultures mixed and sampled at designated times: A - F

+Total viable counts between points A and F:
A: 0.10×10^9, B: 0.14×10^9, C: 0.33×10^9,
D: 0.48×10^9, E: $2.[illegible] \times 10^9$, F: 19.8×10^9

FIGURE A-6 RELATION OF THERMOGRAM TO GROWTH AND COUNT

GEOMETRIC POPULATION INCREASE

Geometric population increase has been demonstrated. Effect on the thermogram of an inoculum reduction of from 3.3×10^8 to 3.3×10^5 organisms of E. coli is illustrated in Figure A-4. Results indicate a greater time required for exhibition of minor and major peaks; however, the general shape and area of both thermograms are similar, i.e., they exhibit mainly a time displacement.

C. FUTURE EXPERIMENTATION INDICATED

ADAPTATION EXPERIMENTS (Figure A-7)

A. Characterization of Biological Challenging Agents.

1. Determine characteristic thermograms for a number of media.

2. Determine the change in the thermograms on subculture into another medium.

3. Identify changes exhibited, including:

   a. Change on Challenge
   b. Change on Adaptation
   c. Change on Reversion to Standard Conditions

B. Characterization of Physical Challenging Agents

1. Identification of optimal Physical Challenging Agents.

2. Determine characteristic thermograms for a number of agents.

3. Identify optimal challenging conditions.

4. Identify optimal challenging times.

C. Characterization of Chemical Challenging Agents

1. Identification of optimal Chemical Challenging Agents.

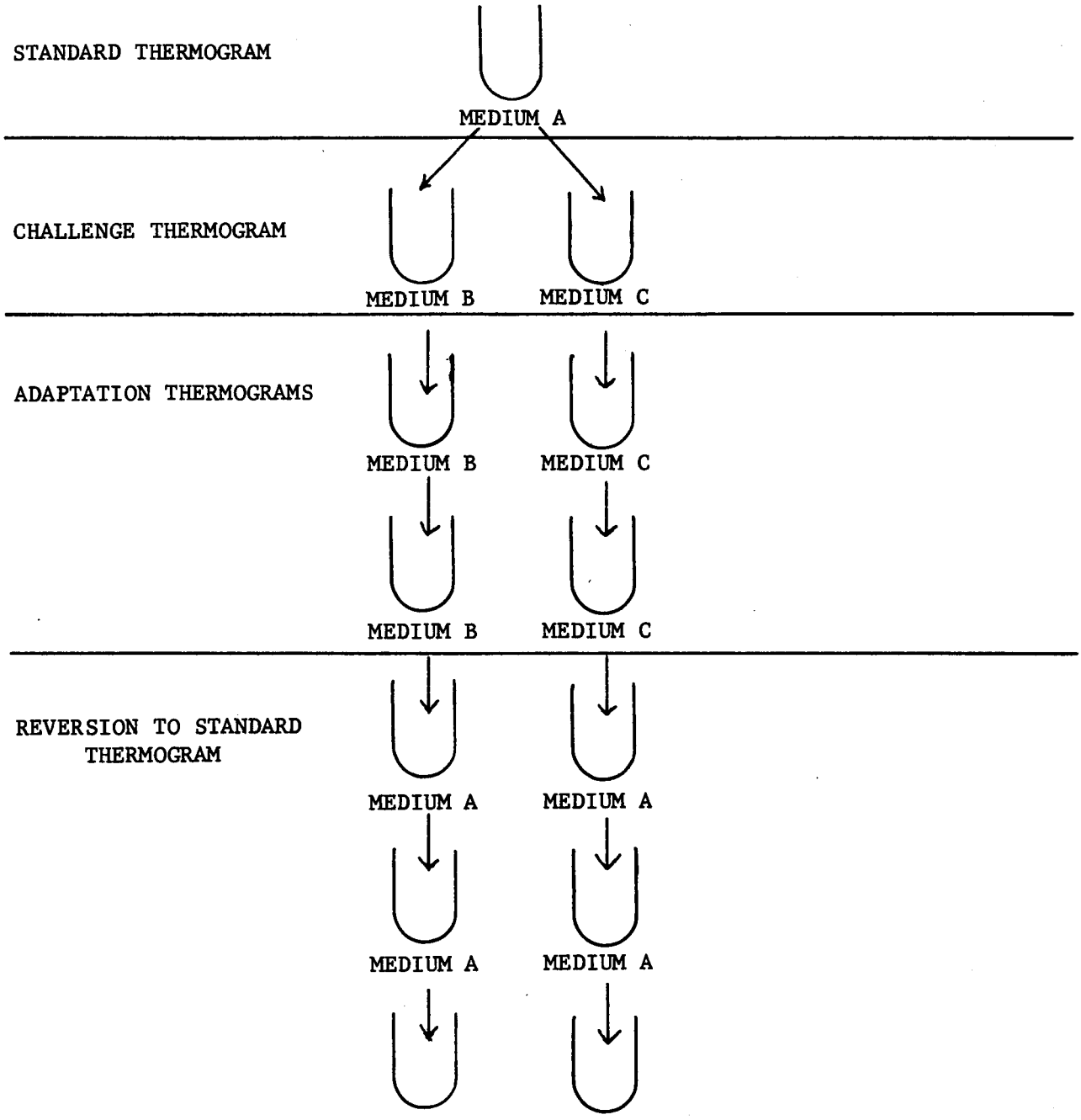
2. Determine characteristic thermograms for a number of agents.

3. Identify optimal challenging concentrations.

4. Identify optimal challenging times.

Figure A-7

ADAPTATION EXPERIMENTS



REPRODUCTION EXPERIMENTS (Figure A-8)

A. Identify geometric increase in population by the relationship of concentration of the inoculum and time required for exhibition of the thermogram.

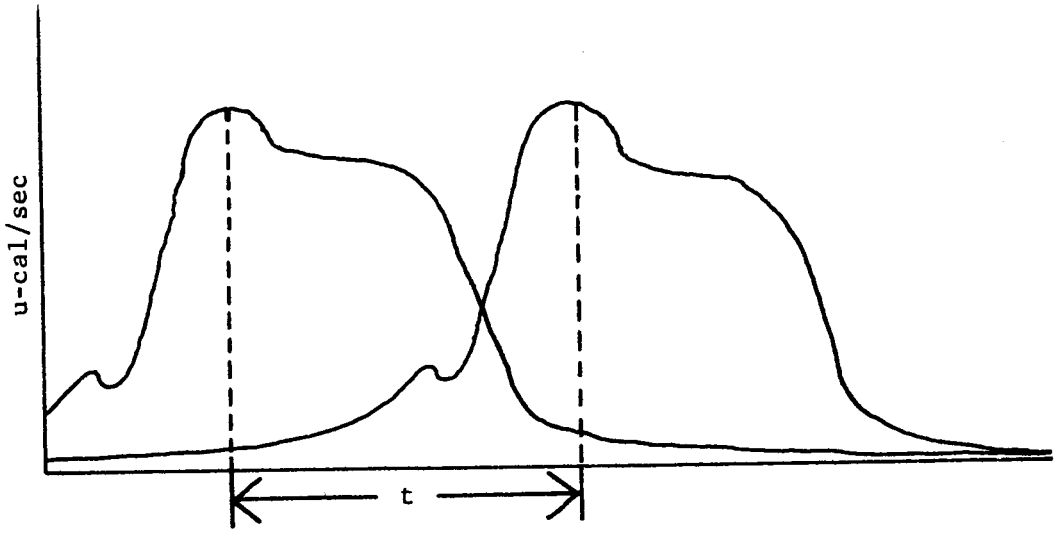
B. Identify generation time.

C. Determine a viable end product by subculture after one generation.

D. Determine duplication of the species by subculture after one generation.

Figure A-8

REPRODUCTION EXPERIMENTS



n = No. generations
t = Time
g = Generation time, or the time for one complete cellular division to take place
d = Dilution of inoculum

$$n = 3.3 \log d$$

$$g = \frac{t}{n}$$

ASSIMILATION EXPERIMENT (Figure A-9)

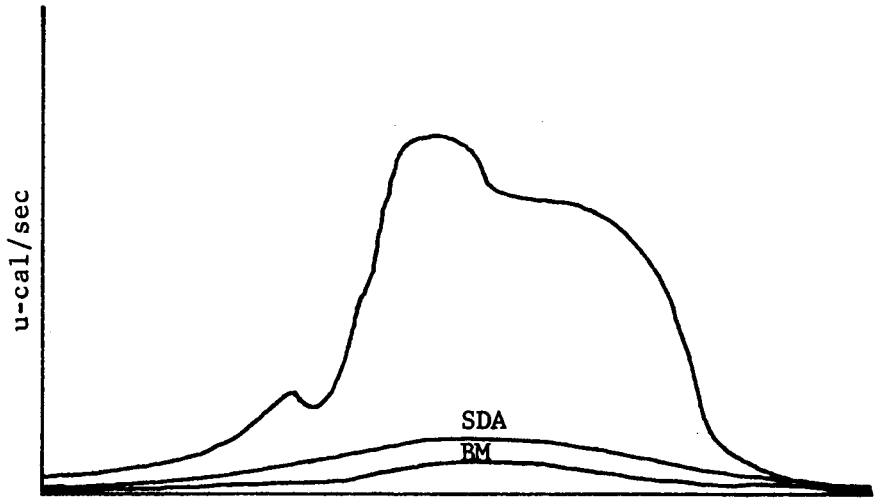
A. Determine the total integrated heat output during a culture originating from basal metabolism.

B. Determine the total integrated heat output during a culture originating from specific dynamic action.

C. Determine the total integrated heat output during a culture originating from assimilation.

Figure A-9

ASSIMILATION EXPERIMENTS



Assimilation: Precursors $\longrightarrow CO_2 + H_2O$ + New Protoplasm

S.D.A.: Precursors $\longrightarrow CO_2 + H_2O$ + Metabolized Precursors

Basal Metabolism: Precursors $\longrightarrow CO_2 + H_2O$ + Body Maintenance

APPENDIX B - MATERIALS REPORT

This report consists of observations and experiments performed on the Beckman 190 calorimeter to determine the systems basic sensitivity. Studies were also performed to determine what factors would best aid in optimizing the systems operation.

Since the existing laboratory model is too large to be used for extraterrestrial life detection, the experiments were conducted with an eye towards miniaturizing the system in order to make it flyable.

The first series of tests were conducted to measure peak or burst response. The method of testing began by charging up a ten microfarad capacitor to the desired voltage, then discharging it into a commercial 10 ohm wire wound resistor taped to the wall of the sample chamber of the microcalorimeter. The test was then repeated, only this time the sample chambers of the microcalorimeter were separated by an insulating plug of polyurithane foam. Figure B-1 gives the circuit schematic for this test and Table B-1 gives the tabulated results. From the tabulated results in Table B-1, it can be seen that there is little or no difference in the output caused by isolating the chambers.

A second series of tests were conducted with constant power being applied to the resistance element. The test was run first without the insulating plug. The test was then re-run with the insulating plug in the chamber. The results of this test are tabulated in Table B-2. It can be seen from Table B-2 that

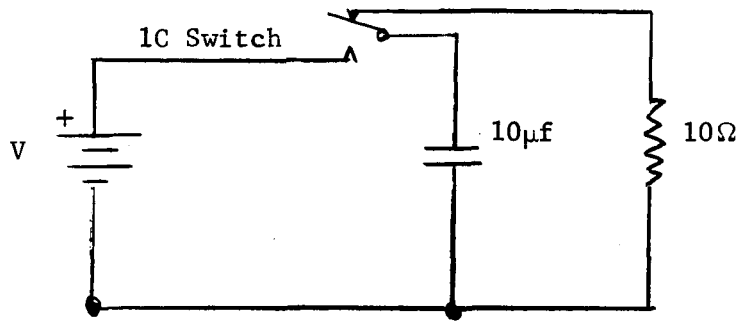


Figure B-1

Voltage	Heat Burst	Peak Sensitivity	Remarks
20.0V	.479 m cal	1.300 mv/cal	There was no noticeable difference in Peak with or without insulation between the two cells.
30.0V	1.100 m cal	1.130 mv/cal	
30.0V	1.100 m cal	1.135 mv/cal	
39.7V	1.910 m cal	1.110 mv/cal	
100.0V	11.950 m cal	1.130 mv/cal	Time Constant ≈ 140 sec
200.0V	47.900 m cal	1.130 mv/cal	

Commercial 10Ω Wire Wound Resistor

Table B-1

there is now a difference in the output resulting from thermal separation of the two chambers.

The error in the one milliamp test sensitivity is due in part to the accuracy in reading small changes on the chart paper. The low reading at four milliamps without insulation is the result of heating the air volume between the sample and the reference cell. If the heat is generated slowly enough, and applied over a long length of time, such as culturing bacteria, then it is possible that the calorimeter loses its sensitivity because of the natural equilibration between the two cells.

Because of the small area of contact between the commercial 10 ohm resistor and the wall of the cell, it was decided to make a larger resistor that would give a larger area of contact. At this time, some spools of black carbon-filled nylon were machined to a 1.4 inch diameter by 1.5 inch length. .030 inches were removed from the center and #30 even ohm wire was bifilar wound until the resistance equaled 10 ohm. The wire has a resistance of 8.16 ohms per foot. The final resistance measured 9.82 ohms. The outside of the wire and spool were then covered with black plastic insulating tape. An identical spool without the wire and tape was placed in the reference chamber. This was done to eliminate the possibility of thermal gradients and asymetry. A series of tests were then made with this new resistor. The results of these tests can be seen tabulated in Table B-3. Some differences appeared immediately.

1. The peak sensitivity had increased by about a factor of five.

Current	Heat	Sensitivity W/Insulation	Sensitivity W/Insulation
1 ma	2.39 μcal/sec	.2300V sec/cal	.209V sec/cal
2 ma	9.55 μcal/sec	.2100V sec/cal	.209V sec/cal
4 ma	38.20 μcal/sec	.2150V sec/cal	.177V sec/cal
8 ma	153.00 μcal/sec	.2160V sec/cal	------

Commercial 10Ω Wire Wound Resistor

Table B-2

Voltage	Heat Burst	Peak Sensitivity	Remarks
10V	120.00 μcal	6.00 mv/cal	Time constant varies during discharge. A TC of about 100 sec was average.
20V	478.00 μcal	5.75 mv/cal	
30V	1.07 m cal	5.81 mv/cal	
50V	2.98 m cal	5.95 mv/cal	
100V	11.90 m cal	5.98 mv/cal	
200V	47.60 m cal	5.99 mv/cal	

10Ω Hand Wound on 1 1/2" Nylon Spool

Table B-3

2. The charge constant change from 60 seconds to approximately 4 seconds.

3. The discharge time constant appeared to be composed of two or more time constants.

The increase in peak sensitivity can be explained by showing that the wire wound resistor is uniformly spaced only a few thousands of an inch from the inside surface of the microcalorimeter chamber. Whereas the 10 ohm commercially available resistor was touching the shell at only one point with its own outside shell of insulating material.

The increase in the discharge time constant would be due in part to the absorption of the liberated heat by the black nylon spool. The spool would then slowly release the heat to its environment.

A second set of tests were then conducted with the same 10 ohm hand wound resistor. These tests were constant power being applied to the resistance element. The results of this test can be found in Table B-4. It can be seen that by comparing Table B-4 and Table B-2, the sensitivity between the 10 ohm hand resistor and the commercial 10 ohm resistor is very similar. A further comparison between Table B-1 and Table B-3 indicates a rather large difference between the peak sensitivity of the 10 ohm hand wound resistor.

These findings tend to confirm the fact that for heat burst type microcalorimetry cell design is very critical. The cell must contain as little mass as possible and be located as tightly to the innersurface of the thermocouples as possible. However, when heat is being given off at a continuous rate or

Current	Heat	Sensitivity	Remarks
2 ma	9.52 μcal/sec	.210V sec/cal	
2 ma	9.60 μcal/sec	.208V sec/cal	
4 ma	38.20 μcal/sec	.216V sec/cal	
8 ma	153.00 μcal/sec	.235V sec/cal	TC $\approx$ 220 sec

10Ω Resister Hand Wound on 1 1/2" Nylon Spool

Table B-4

a very slowly rising rate, the cell design is of less importance. An increased mass only serves to change the time constant. With this in mind, another set of nylon spools was fabricated. This time, the center section was cut down .300 inch, then wound with enough even ohm to make a resistor of 100 ohms. As one would expect from the previous experiments, the peak sensitivity under heat burst was quite poor, .57 millivolts per calorie. This is a factor of ten poorer than the previous experiment. The charge time constant increased to 300 seconds and the discharge time constant increased to 815 seconds.

The Bristol recorder used to record the measurements was equipped with a disc integrator. Although there was some variation in the number of microcalories per integrator unit, measurements remained essentially constant. The range for the commercial 10 ohm resistor was 91.5 microcalories per integrator unit to 100 microcalories per integrator unit. The range for the 10 ohm hand wound resistor was 91 microcalories per integrator unit to 110 microcalories per integrator unit. Only large variations were observed during continuous input power. For low values of input, that is 10 microcalories per second, the sensitivity was about 90 microcalories per integrator unit. As the input power was increased to 153 microcalories per second, the integrator had dropped to 77 microcalories per integrator unit. This indicates that for high input power, i.e. 153 microcalories per second, the effect of the high heat input is to elevate the temperature of the heat sink, thus lowering the ΔT across the thermopiles and decreasing the sensitivity.

The experiments that were conducted tend to show that for the problem of extraterrestrial life detection, where the heat given off will be in a continuous log function, the cell design would only be critical if the rate of

growth of any microorganisms was extremely rapid or the heat from metabolism was inordinately high. However, the cell should fit tightly in the chamber so as to prevent any energy loss due to convection. It should also have ends that are very poor thermal conductors to decrease any losses through the ends of the cell. A cell of little mass would be advised if the possibility exists that the rate of growth or changing rate of heat output for extra-terrestrial microorganisms is very high. The reason for this is that a cell of large mass would have a large thermal inertia and with a long charge or discharge time constant would not allow the microcalorimeter to follow a rapidly changing heat output.

Since the Beckman model 190 microcalorimeter, in its laboratory configuration, utilizes a passive heat sink with a mass of approximately 16 killograms, it was felt that an active heat with less mass and a heater be substituted for the large mass of the existing heat sink.

For a first experiment the large heat sink was removed and only the existing metal surrounding the thermopile was retained as a heat sink. A 50 ohm heater fabricated of #30 Even Ohm wire was wound on each cell of the microcalorimeter. A thermistor which formed a part of the bridge was placed in the center between the two cells. Figure B-2 gives a schematic diagram of the proportional heater. After reaching temperature, the output of the microcalorimeter, as recorded on the Bristol recorder, cycled through a variation of approximately 100 microvolts with a time constant of approximately three minutes. Dividing the time constant by the thermopile sensitivity showed a heater unbalance of one part in 500 or .2%. This was a good balance; a balance of .001% was needed.

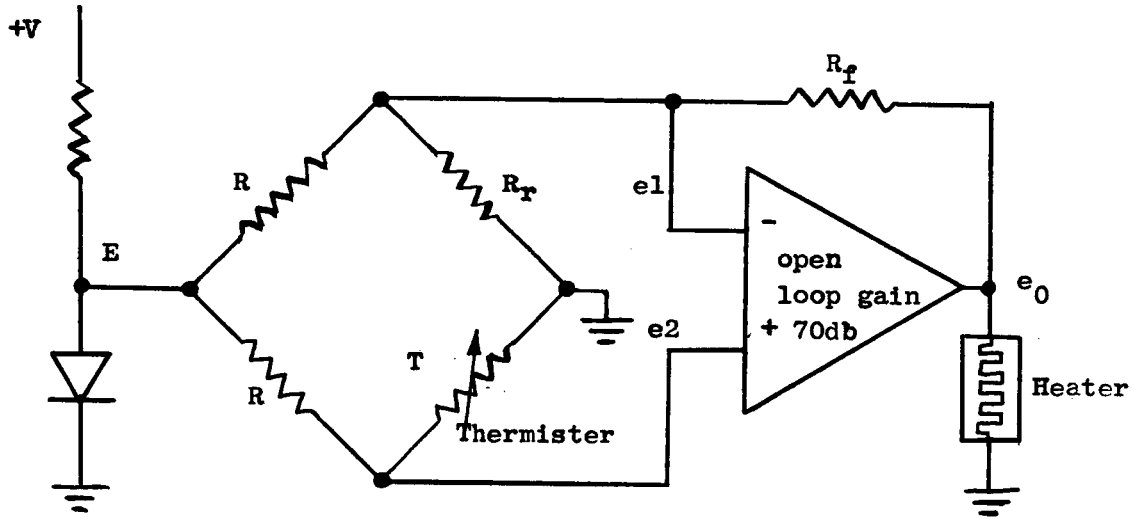


Figure B-2

Derivation of the Transfer Function
for Fig. B-2

let k = gain of amplifier

T = Thermistor resistance

R_r = Reference resistance

R_f = Feedback resistance

R = Bridge resistance

$$e_o = e_2 k - e_1 k$$

$$e_2 = \frac{T}{R+T} E$$

$$e_1 = \frac{\frac{E}{R} + \frac{e_o}{R_f}}{\frac{1}{R} + \frac{1}{R_r} + \frac{1}{R_f}}$$

$$\text{let} \left[\frac{1}{R} + \frac{1}{R_r} + \frac{1}{R_f}\right] = \frac{1}{Z}$$

$$\text{Then } e_o = \frac{TEk}{R+T} - \frac{EZk}{R} - \frac{e_o Zk}{R_f}$$

$$e_o = \frac{TEk\, R_f}{(R+T)(R_f+Zk)} - \frac{EZk\, R_f}{R\,(R_f+Zk)}$$

if $k \longrightarrow \infty$

$$e_o = \left(\frac{T}{R+T}\right)\left(\frac{R_f}{Z}\right) E - \frac{R_f}{R} E \qquad \frac{e_o}{E} = G = \left(\frac{T}{R+T}\right)\left(\frac{R_f}{Z}\right) - \frac{R_f}{R}$$

$$\frac{dG}{dT} = \left(\frac{R_f}{Z}\right) \frac{R}{(R+T)^2}$$

The next approach was to put a layer of foam over the twin cells. A new heater of 100 ohms was then wound over the foam with the thermistor allowed to float in the dead air space. The air space was relied upon to distribute the heat evenly. Although the results were a factor of ten better, the balance was not yet good enough.

In the next experiment, aluminum foil was wrapped several layers deep over the heater. It was felt that the aluminum would give a more even distribution of heat over the surface area of the sink. The thermistor was placed in good contact with the foil and the entire surface area was wrapped again with foam. The results of this experiment brought the output to ±3%. Since the heater is capable of putting out one watt or 0.239 calories per second, 3% is equal to 0.75 microvolts or seven microcalories per 0.239 calories. This is equal to a temperature balance of 0.003%. The next step was to reduce the cycling. Thus, with a 510K ohm resistor in the feedback, the best possible run was made.

Over a seventeen hour run, after temperature stabilization, the base line deviated only 1% for a stability of 0.0005%. This balance was a factor of 2 better than that which was felt would be needed.

Before leaving the subject of heaters, it would be well to look at the speed of response. With the amplifier operating at its maximum ouput, it took several hours to bring the unit to equilibrium. With the ambient temperature at 24°C, two megohms in feedback regulated at 31°C and 510K ohm in feedback regulated at 29.2°C. This would indicate that the heater was applying power at the same rate at which it was leaking from the system. It would be desirable to

speed up the response of the heaters to bring the system to equilibration more rapidly. This could be done quite easily with a two heater system. A first heater would dump a large amount of power into the system to bring it up near the equilibrium point quite rapidly. Then the primary heater would be switched off and the regulating heater switched on to hold the system at its equilibrium point.

A series of tests were run at the elevated temperature and no difference could be noted in sensitivity or time constant. From a theoretical point there should have been a .3% improvement in sensitivity, but this order of magnitude was hard to measure. From the preceding experiments, it is felt that good thermal regulation can be attained by use of an active heat sink that would weigh much less than the passive heat sink that is used in the present laboratory microcalorimeter. It is also felt that a gain can be made in the efficiency of the instrument if care is taken to keep thermal leaks to a minimum and the two chambers that contain the reaction cells thermally separated to keep to a minimum any possible crosstalk.

Bacteria Sensitivity

If it is assumed that a 5% deflection is needed to be certain that there is an exothermic reaction then;

$$\frac{(5\%)\ (\text{full scale in volts})}{\text{microcalorimeter sensitivity in volts sec/cal}} = \text{rate of heat output to determine an exothermic reaction}$$

For the Beckman model 190 Laboratory Microcalorimeter, the amount of heat output for a 5% deflection on the most sensitive scale (25 μV full scale) is;

$$\frac{(.05)(25\mu V)}{.21V \text{ sec/cal}} = 6\,\mu\text{cal/sec}$$

According to Calvet, a single bacterium of B. coli liberates 5.4×10^{-13} cal/sec at the height of activity. From the Phase I final report on Detection of Extraterrestrial Microorganisms by Microcalorimetry prepared for the National Aeronautics and Space Administration by the Advanced Technology Operations of Beckman Instruments, Inc. The heat output of a single bacterium E. coli in the resting phase is 2.8×10^{-16} cal/sec. Thus, the laboratory instrument can detect $\frac{6 \times 10^{-6}}{5.4 \times 10^{-13}} = 1.1 \times 10^{7}$ to $\frac{6 \times 10^{-6}}{2.8 \times 10^{-16}} = 2.1 \times 10^{10}$ bacteria.

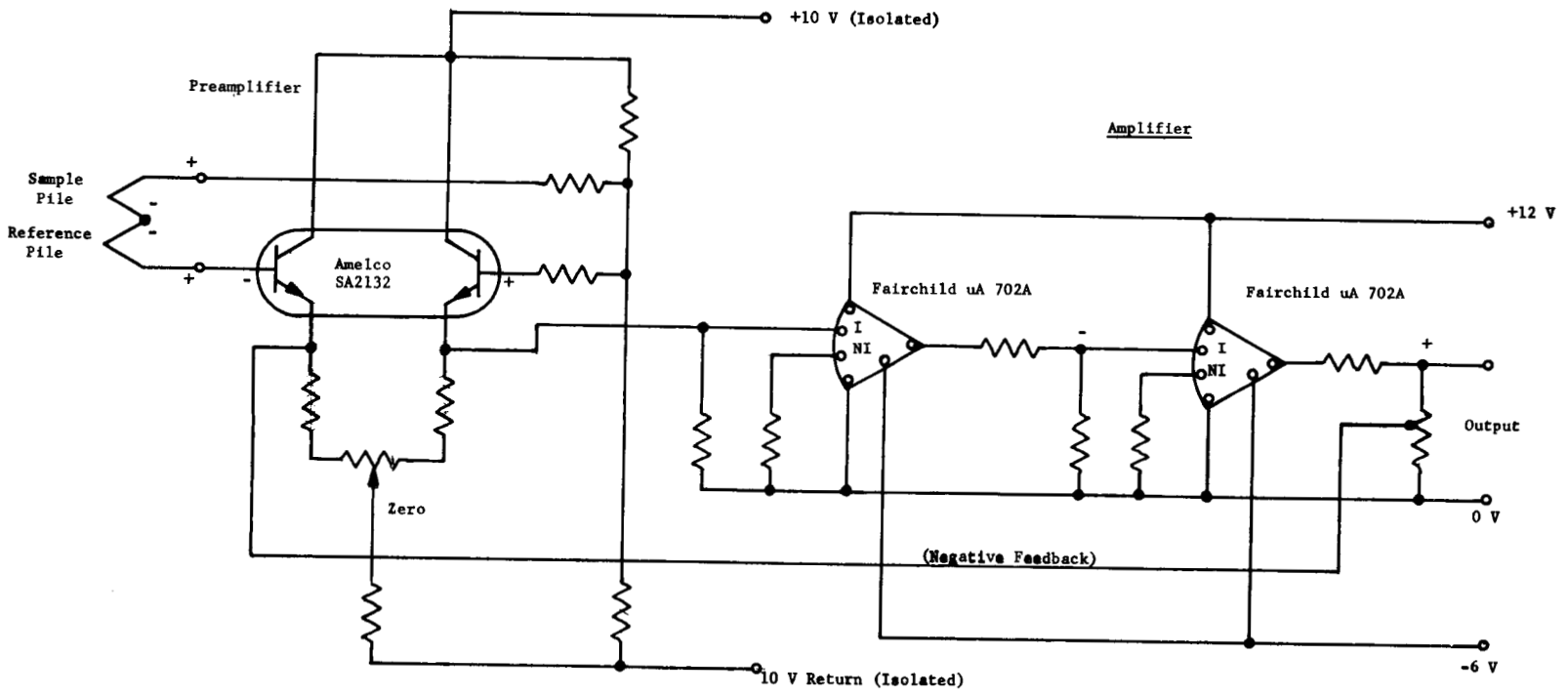
Laboratory Tests Performed with a Standard Beckman Amplifier Modified for a 0-20 Microvolt Range

A component test apparatus which contained a circuit for monitoring the output of a pressure transducer was available. The pressure amplifier was originally designed for a 0-25 mv input and a 5 v output. This circuit was modified slightly to increase the gain for a 0-20 microvolt input range. The modified form of the circuit is shown in the simplified schematic diagram of Figure B-3. Referring to this figure, it should be noted that the Amelco differential amplifier, SA2132, has very high performance specifications. The base-emitter voltage difference is guaranteed to change less than 3 microvolts per degree C. The transistors have high gain at low collector current, which is necessary in applications permitting use of limited power. Differential amplifiers with comparable specifications are now available at approximately 1/10 of what the SA2132 cost one year ago (September 1965). This fact is indicative of the rapid improvements in the art of transistor fabrication.

The amplifier gain is provided by two Fairchild 702A integrated circuit amplifiers. These units have a minimum guaranteed gain of 2,000, but units with gain in excess of 6,000 may be selected. The open loop gain of the two operational amplifiers, therefore, may be made to exceed 2.5×10^7. Operation with a closed loop gain of 2.5×10^5 is quite feasible.

Figure B-3 also contains a listing of important specifications based upon use of selected components. The ± 2 microvolt noise figure given in the specifications is actual. This noise figure is based upon the recorder chart reproduced as Figure B-4. From this chart it may be seen that the theoretical 20 microvolt full scale calibration is essentially valid, and that the noise is about ± 2 microvolts. Some of the larger transients spikes shown on the record were due to stray pickup caused by incomplete shielding. Superimposed upon this relatively rapid noise, there are slow thermal drifts. The specification on thermal dependence of the amplifier zero given in Figure B-3 assumes that by properly matching components the thermal drift could be as small as ± 2 microvolts/^{o}C (referred to the input). As the circuit was when tested, however, the temperature dependence was about -10 microvolts/^{o}C. No major effort was made to improve the signal-to-noise ratio of this amplifier. It is anticipated that with the components shown in the schematic diagram of Figure B-3, the noise could probably be reduced by a factor of 2 to 4 by application of standard circuit techniques.

The tests were performed with a simulated thermo-pile input. The source impedance was 1,000 ohms, and the microvolt signal was obtained from an adjustable 0-1 v supply with a suitable large voltage dropping resistor. The principal reason for performing these tests was to establish the signal-to-noise ratio of an amplifier presently available. It should be understood that this particular amplifier is not recommended as the most suitable, but was merely used as an example.



SPECIFICATIONS (Selected Components):

Power Requirements:

a) 10^{-3} watts from 10 V isolated supply (Preamplifier)

b) 0.3 watts from +12 V and -6 V Supply (Amplifier)

Voltage Gain, DC:

a) Open Loop: 2.5×10^{7} minimum

b) Closed Loop: 2.5×10^{5} for 0.25 volt output/microvolt input.

Thermal Dependence of Amplifier Zero:

By matching components, may be less than ± 2 microvolts/°C (referred to input). (As tested, about -10 microvolts/°C).

Noise, Referred to Input:

$\pm$ 2 microvolts

Figure B-3 DC Amplifier, Simplified Schematic
Tested 9-23-66 through 9-27-66

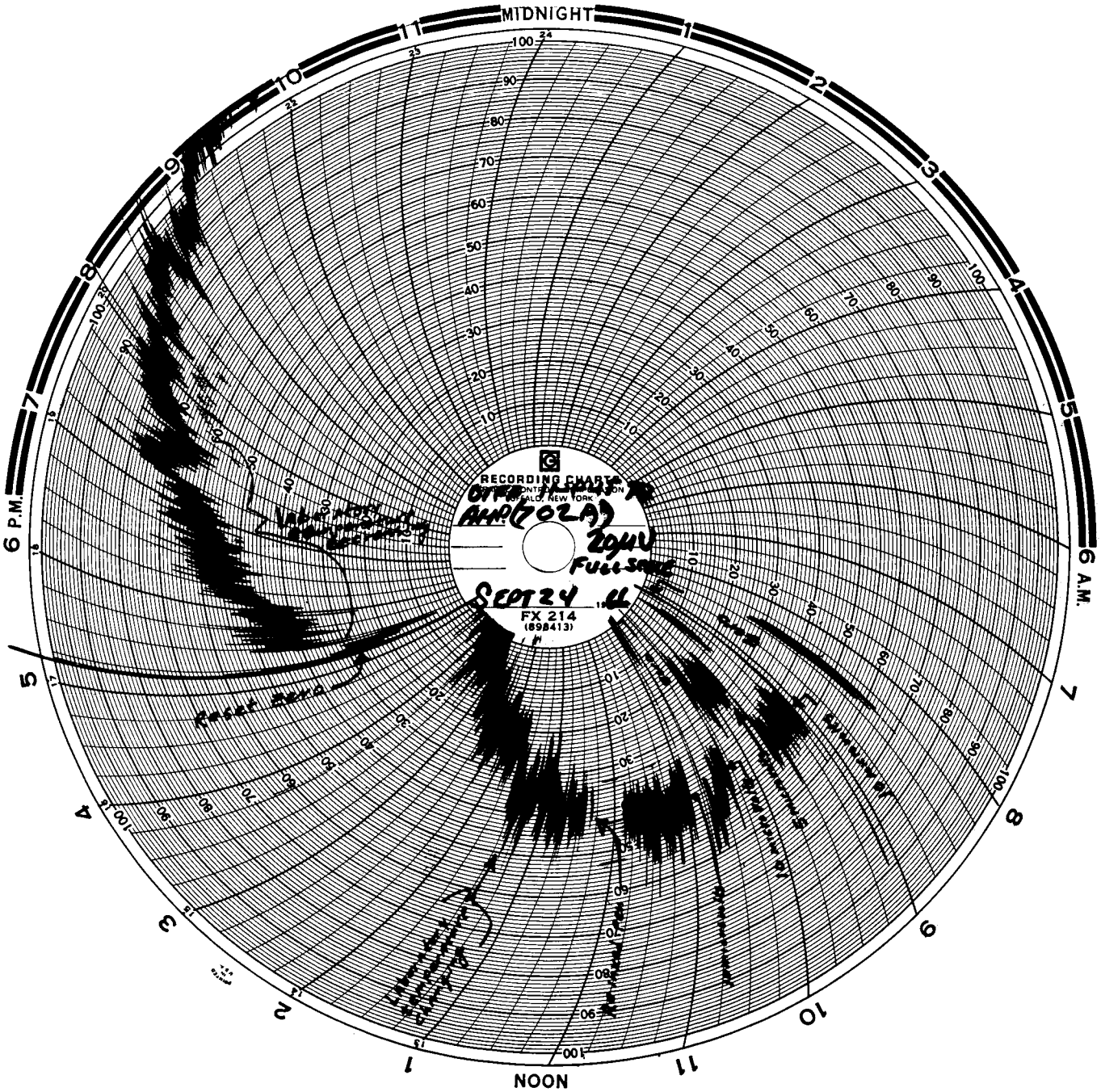


Figure B-4 Noise Figure Measurements