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(NASA-CR-143997) CONVECTION MEASUREMENT PACKAGE FOR SPACE PROCESSING SOUNDING ROCKET FLIGHTS Summary Report (Lockheed Missiles and Space Co.) 60 p HC $4.25 CSCL 16B

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Cummings Research Park
4800 Bradford Drive,
Huntsville, Alabama

CONVECTION MEASUREMENT PACKAGE FOR SPACE PROCESSING SOUNDING ROCKET FLIGHTS

SUMMARY REPORT

April 1975

Contract NAS8-27015

Prepared for National Aeronautics and Space Administration
Marshall Space Flight Center, Alabama 35812

by

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FOREWORD

This report was prepared for the National Aeronautics and Space Administration, Marshall Space Flight Center, as a summary report on Contract NAS8-27015, "Convection in Space Processing." This report describes a convection measurement package for sounding rocket flights. The work was performed in the Space Processing Group of the Huntsville Research & Engineering Center.

The NASA Contracting Officer's Representatives for this task were B. S. Blake and G. M. Arnett, MSFC Space Sciences Laboratory.

ACKNOWLEDGMENT

The work described in this report represents the cooperative efforts of persons at NASA-MSFC Space Sciences Laboratory and at Lockheed-Huntsville. The contribution of all of these people is hereby gratefully acknowledged.

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Section 1
INTRODUCTION AND SUMMARY

This report summarizes the results of a study whose objectives are to analyze, design, fabricate and check out a convection measurement package for sounding rocket flights. The study was motivated by NASA's current plans to utilize these rockets for performing materials processing experiments in a low-gravity environment.

The use of sounding rockets provides an opportunity for the space processing community to gain knowledge and experience in low-g experimentation in the time period between manned space missions. The low-accelerations experienced during the coast phase of the rockets allows more experiment time than drop towers or aircraft free-fall maneuvers. The low-gravity environment of space should have important advantages in materials processing due to reduced sedimentation and natural convection. However, the suitability of the sounding rocket environment for performing these experiments is not known. In particular, the effects on heated fluids of non-constant accelerations, rocket vibrations, spin rates, etc., is not defined. The need thus arises for a system to be flown on the rockets to determine the influence of the convective effects on fluid experiments, and the general suitability of the rockets for performing these experiments.

The initial phase of this study consisted of an analytical investigation of convection in an enclosure which is heated in low gravity. The gravitational body force was taken as a time-varying function using anticipated sounding rocket accelerations, since accelerometer flight data were not available. A computer program was used to calculate the flow rates and heat transfer in fluids with geometries and boundary conditions typical of space processing configurations. Calculations were made for both a constant acceleration and for time varying accelerations (termed "g-jitter").

Comparisons of the convection effects allows a measure of the contribution of g-jitter to the flow circulation and heat transfer.

Results of the analytical investigation have identified the configurations, fluids and boundary values which are most suitable for measuring the convective environment of sounding rockets. Two configurations were selected for the system: (1) a rectangular cell, with water or the fluid, which is heated along a wall, and (2) a cylindrical cell, with mercury as the fluid, which is heated on one end of the cylinder. These two fluid cell modules were designed, fabricated and bench tested for proper operation.

The rectangular configuration, termed the water cell, consists of a plexiglass enclosure with a dc powered heater mounted on one wall. Thermocouples are mounted on the container walls and in the fluid to record the thermal history as the water is heated. The cylindrical configuration, termed the mercury cell, consists of an RTV rubber cylinder filled with mercury. A dc powered heater is provided at one end of the cylinder to supply the thermal input. Thermocouples mounted in the fluid and on the heater plate are used to record the thermal history. Electronic control modules are provided to regulate the power input, supply the needed voltage to the heaters and to interface with the rocket telemetry system. The fluid cells were selected on the basis of: (1) sensitivity to low-g accelerations, and (2) their resemblance to typical space processing configurations. These two fluid cells were delivered to MSFC for integration.

This report summarizes the study of the Convection Measurement Package. Section 2 presents the analytical investigation of g-jitter convection, the results of the sensitivity analysis and the recommended concepts. A short description of the fabricated fluid cells and the complete measurement package is given in Section 3. The procedure of analyzing the data from the convection package including the evaluation of the rocket environment constitute Section 4. Appendix A summarizes the test procedures for the flight apparatus. Details of the hardware can be obtained from the master blueprints at the MSFC Space Sciences Laboratory.

Section 2
ANALYTICAL INVESTIGATION

2.1 BACKGROUND AND PERSPECTIVE

Natural convection and its effects on heat and mass transfer processes in fluids is a major concern in most space manufacturing processes. Density gradients in a fluid, induced by temperature or concentration changes, in the presence of gravity gives rise to buoyancy forces. This gravity-driven convection can be the dominant mechanism affecting fluids processing in a ground-based laboratory. One of the major advantages foreseen in manufacturing products in space concerns the reduction of this buoyancy-driven fluid flow. Moreover, the ability to control the magnitude of convection in a low-g environment offers advantages in materials processing which cannot be achieved on earth. When convection is suppressed, precise knowledge of diffusion rates of mass or heat become critical as many processes become diffusion controlled. Prediction of accurate diffusion rates by theory is often intractable. Thus, a means of measuring concentration and temperature gradients during low-g processing is very desirable.

However, it is erroneous to conclude a priori that natural convection will be totally absent in a low-g laboratory. Gravity levels of even 10^{-6} g can cause significant convection if the temperature or concentration gradients are very large. Results of the Heat Flow and Convection Demonstration (Refs. 1 and 2) which were flown aboard Apollo 14 and 17 indicate that low-g convection can be an important factor in determining fluid behavior and heat transfer. Changes in the magnitude and/or direction of accelerations can also be an important factor. Termed "g-jitter" convection, this may be significant, especially aboard sounding rockets. Convection driving mechanisms other than gravity must also be considered. Results of several Skylab experiments have indicated that surface tension-driven flow may have affected the processes

significantly. Accurate knowledge of the magnitude and pattern of convection is essential because many promising space manufacturing processes (i.e., fiber eutectics for optical communications, uniformly doped semiconductors, vapor grown single crystals) depend upon the elimination of natural convection.

Among the processes most likely to be drastically affected by convection are various crystal growth procedures and material separation techniques such as electrophoresis and Soret methods. These phenomena must be understood and explained if any significant process of this type is to be designed for space manufacturing. The sounding rocket program offers an excellent opportunity for this type of investigation. However, it is possible on these rocket flights that vibration (g-jitter) levels will be of the same magnitude as the residual, steady state gravity level on the payloads. Recent theoretical analyses of g-jitter induced convection in the configurations similar to the Skylab multi-purpose furnace (Ref. 3) indicate that small vibrations (10^{-3} g in amplitude) can stimulate significant flow and temperature oscillations in heated melts. Thus significant banding and other deleterious effects could occur during space processing if g-jitter is not taken into account and experiments are not designed to suppress it.

The effects of vibrations on convective heat and mass transfer are reported in the literature (see for example Refs. 4 through 11). However, little work has been reported on these effects in a low-gravity environment. The study performed at Lockheed-Huntsville (Ref. 3) was directed toward determining the effects of vibrations on convection in enclosures at low gravity conditions. The term "g-jitter" convection is coined to describe fluid flow and associated transport phenomena caused by any time varying accelerations imparted on a container of fluid. G-jitter may result from a non-constant gravitational acceleration, spacecraft control maneuvers, vibrations, equipment disturbances and even astronaut movements. The study has revealed that g-jitter convection can cause significant changes in flow structure and temperature distributions in confined fluids which are heated in a low-g environment.

The possibility of g-jitter or other types of convection occurring in fluids processing experiments aboard sounding rockets provides justification for investigating these effects. The study described in this summary report was directed toward:

- Determining the potential influence of g-jitter convection on fluids in low-g
- Defining the configurations and boundary conditions which are most sensitive to g-jitter, and
- Designing, fabricating and checking out appropriate fluid cells for use in a Convection Measurement Package for sounding rocket flights.

The subsections which follow describe the analytical investigation which was performed, summarizes the sensitivity analysis and presents a flight concept for the Convection Measurement Package.

2.2 DIMENSIONAL ANALYSIS

The first part of the analytical investigation was directed toward identifying candidate fluids for studying low-g convection. The technique of dimensional analysis was used to provide the pertinent information. The fluids initially considered included:

- Air
- Helium gas
- Krytox oil
- Water
- Mercury
- Carbon dioxide, and
- Sucrose solutions

The fluids for use in a sounding rocket convection measurement system should (1) be somewhat typical of space processing materials; (2) be readily available for use in a variety of geometric configurations; and (3) have thermal property values which render the fluids sensitive to low-g convection.

An important property of fluids for convective analysis is the Prandtl number

$$Pr = \nu / \alpha \tag{1}$$

which is the ratio of momentum diffusivity, ν, to thermal diffusivity, α. This dimensionless parameter was used to aid in selecting three fluids for further study. Mercury has a low Prandtl number (~ 0.01) which is typical of liquid metals used in space processing experiments. The Prandtl number for most gases is an order of 1.0 (helium ~ 0.68) and provides a mid-range Prandtl number fluid. Water, with a Prandtl number greater than 1.0, was selected for its simplicity of use and to provide a larger Prandtl number fluid. These three fluids were selected for further study based on similarity to fluids used in space processing and because they span the range of Prandtl numbers from ~ 0.01 to 10.0. Table 1 is a summary of the material properties of water, helium gas and mercury. The remainder of the dimensional analysis is carried out for these three fluids.

Another governing dimensionless group in gravity driven natural convection is the Grashof number,

$$Gr = \frac{g \beta \Delta T L^3}{\nu^2} \tag{2}$$

where g is the acceleration of gravity, β is the thermal expansion coefficient, ΔT is the temperature gradient imposed on fluid, L is the characteristic dimension of fluid container, and ν is the kinematic viscosity. This quantity represents the ratio of buoyancy forces to viscous forces. Experimental and theoretical analyses of convection have determined that the heat transfer by buoyancy driven natural convection correlates with the product of Prandtl number and Grashof number. This dimensionless group, termed

Table 1

MATERIAL PROPERTIES OF WATER, HELIUM GAS, MERCURY

Temp. (^{o}C)	Thermal Conductivity k ($\frac{cal}{sec\text{-}cm\text{-}^{o}C}$)	Dynamic Viscosity μ (poise)	Density ρ ($\frac{gm}{cm^3}$)	Specific Heat C_P ($\frac{cal}{gm\text{-}^{o}C}$)	Thermal Expansion Coeff. β ($1/^{o}C$)	Thermal Diffusivity α ($\frac{cm^2}{sec}$)	Kinematic Viscosity ν ($\frac{cm^2}{sec}$)	Prandtl Number Pr -
(Water)								
10	1.37E-3	1.31E-2	0.998	1.00	8.82E-5	4.97	1.31E-2	9.55
38	1.50E-3	6.82E-3	0.992	0.998	3.60E-4	5.48	6.90E-3	4.52
94	1.62E-3	3.05E-3	0.961	1.00	7.20E-4	6.11	3.17E-3	1.88
204	1.57E-3	1.35E-3	0.857	1.08	1.44E-3	6.12	1.58E-3	0.927
(Helium gas)								
-18	3.22E-4	1.69E-4	1.92E-4	1.24	5.01E-3	4.90E-3	8.86E-1	0.67
94	4.00E-4	2.21E-4	1.33E-4	1.24	2.74E-3	8.73E+3	1.65E+0	0.686
204	4.75E-4	2.65E-4	1.02E-4	1.24	2.10E-3	1.35E+4	2.59E+0	0.70
427	5.69E-4	3.39E-4	6.97E-5	1.24	1.43E-3	2.38E+4	4.88E+0	0.73
(Mercury)								
10	1.94E-2	1.59E-2	13.55	3.3E-2	1.8E-4	1.58E+2	1.12E-3	0.027
94	2.47E-2	1.25E-2	13.34	3.3E-2	1.8E-4	2.05E+2	9.33E-4	0.016
204	2.97E-2	9.98E-3	13.07	3.2E-2	1.8E-4	2.52E+2	7.46E-4	0.011
315	3.34E-2	8.64E-3	12.83	3.2E-2	1.8E-4	2.89E+2	6.53E-4	0.008

the Rayleigh number, is

$$Ra = Gr\ Pr \tag{5}$$

In general, the larger the Rayleigh number, the more vigorous the convective flow and heat transfer. In addition, for "heating-from-below" situations, a critical value of Rayleigh number must be reached for the buoyancy forces to overcome the viscous forces and produce convective flow. Thus an initial estimate of the sensitivity of a configuration to gravity driven convection can be obtained by examining the Rayleigh number.

Figure 1 is a plot of Rayleigh number versus temperature gradient for the three selected fluids. A characteristic container dimension L = 1.27 cm was used for a 1-g environment. For low-g situations, the ordinate can be multiplied by the gravity level in g's to obtain the corresponding Rayleigh number. The fluid properties contained in the Rayleigh number equation were evaluated at an average temperature of the fluid. This figure shows that, for a fixed ΔT, water has the largest Rayleigh number, mercury the mid-range value, and helium the lowest value. The "critical" value of Rayleigh number depends on the geometric configuration, the heating direction and other factors. Because of this, and since the g-levels that will be experienced on the rockets is not quantified as yet, no attempt was made to identify critical Rayleigh numbers for the rocket flights. This simple dimensional analysis was carried out to identify candidate fluids for the computer analysis of g-jitter convection which is discussed subsequently.

A measure of the effects of natural convection on heat transfer is provided by the dimensionless group termed the Nusselt number:

$$Nu = \frac{hL}{h}$$

where h is the local heat transfer coefficient, L is the characteristic dimension of the container, and k is the thermal conductivity. The group represents the ratio of the total heat transfer to the pure conduction heat transfer. A magnitude of Nu near 1.0 indicates little convection effects, while Nusselt number values above 1.0 provide a measure of percent

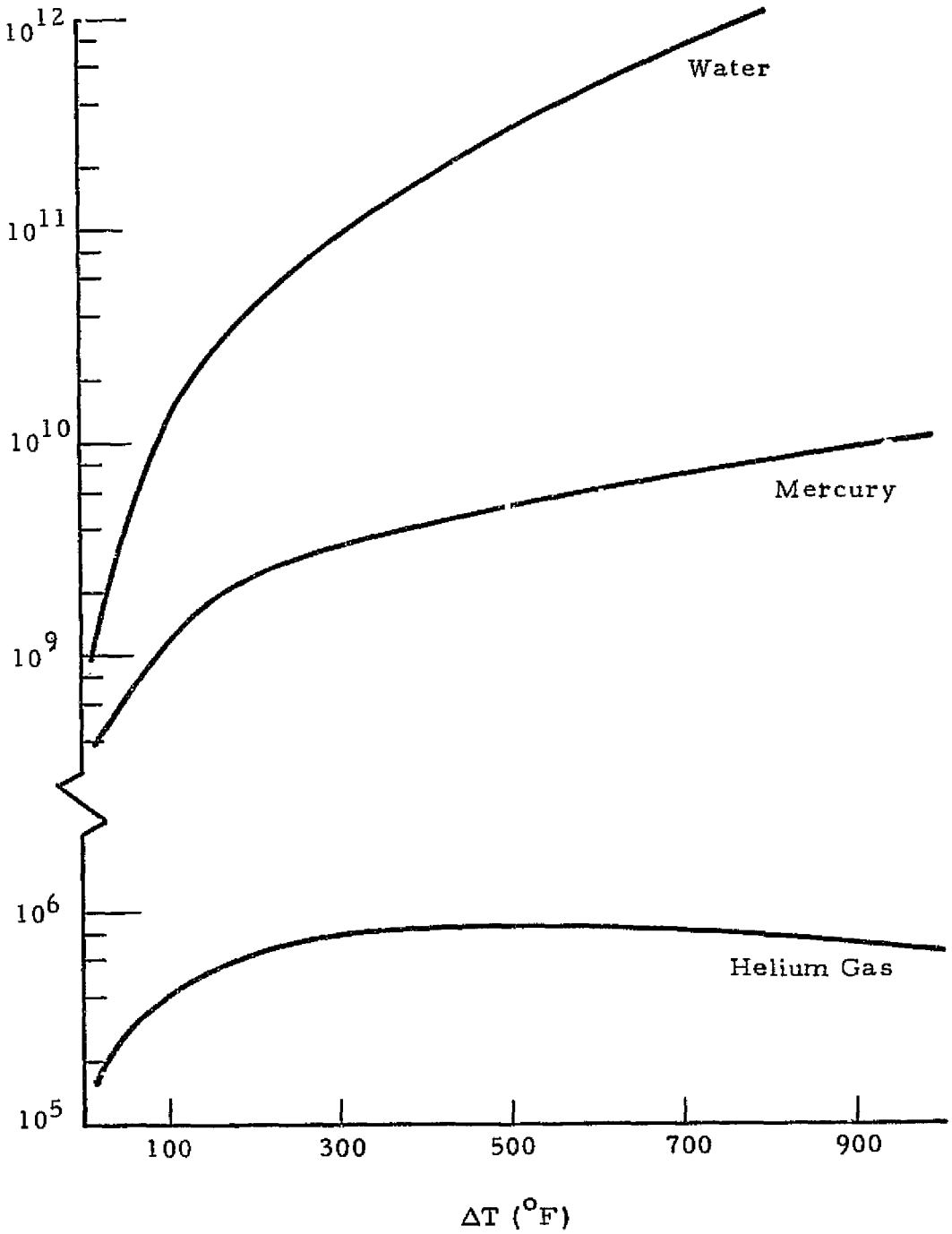


Fig. 1 - Rayleigh Number vs Temperature Gradient for Water, Mercury, Helium Gas (T_o = 20° C, 1 g)

increase in heat transfer due to convective flow. Accurate calculation of Nusselt numbers must be made from the thermal profiles in the fluid. This requires a computer analysis such as the one discussed in the following section.

2.3 COMPUTER MODELS

A factor which potentially can cause deleterious effects aboard the rockets is g-jitter convection. This phrase is coined to describe the fluid flow induced by any time-varying accelerations imparted on a container of fluid. An analytical investigation was made to determine the potential influence of g-jitter on confined fluids which are heated in low-g.

The basis of this investigation is the Lockheed Convection Analysis (LCA) Computer Program. The LCA program utilizes a finite-difference numerical solution of the Navier-Stokes equations to calculate the convective flow and heat transfer in confined fluids. The following are among the capabilities of this program:

- Rectangular or cylindrical geometries
- Gases or liquids
- Two-dimensional or axisymmetric flow
- Temperature-dependent material properties
- Constant gravity level or time varying magnitude and direction
- Combinations of heat flux and temperature boundary conditions
- Transient and steady state analyses
- Free surface flows
- Compressibility effects in gases, and
- Heating from the side or heating from below (two dimensional)

The LCA program has been checked out and verified by comparison with experimental data. The reader is referred to Refs. 12, 13 and 14 for details of the program, numerical method and data verification.

The approach used in this analysis is to select geometric configurations, with the three test fluids, and perform a series of calculations with the LCA program. Figure 2 shows the four selected configurations for the analysis. They consist of (a) a rectangular cell heated from the side; (b) a rectangular cell heated from below; (c) a cylindrical cell heated from below; and (d) a point heat source in a "large" (rectangular) container. The flow in the heating-from-below cases was initiated by a temperature perturbation. The mode of flow was forced to be a single two-dimensional roll cell in order to avoid three-dimensional effects. The g-jitter cases were started using the established flow patterns from the constant-g solutions. The effects of g-jitter can then be determined by the degree of perturbation from the constant-g mode.

The actual g versus time that is experienced on the rocket flights was not available at the time of this analysis. A parametric study was done using three models of the g-jitter shown in Fig. 3. The mean g, the amplitude, and the period were parameters in the solutions. Parametric values were selected to span the range of anticipated acceleration levels on the rockets

The computer models thus consist of combinations of the four configurations, the three test fluids, the three g-jitter models and a range of amplitudes and periods. The computer runs were generally made from heat-up ($t = 0$) to approximately $t = 360$ seconds.

Figures 4 and 5 are typical of the results obtained with the computer models. These are shown for illustration of the effects of g-jitter on temperature profiles and flow patterns. A summary of the entire analysis is given in Section 2.4.

Figure 4 shows isotherm maps (lines of constant temperature) for four cases: (a) rectangular box of water heated from the side; (b) rectangular box of water heated from below; (c) cylindrical container of mercury heated from below; and (d) point heat source in a pool of mercury. The constant-g cases are for 10^{-3}g, and the g-jitter cases are for Model 3 with $\bar{g} = 10^{-3}$,

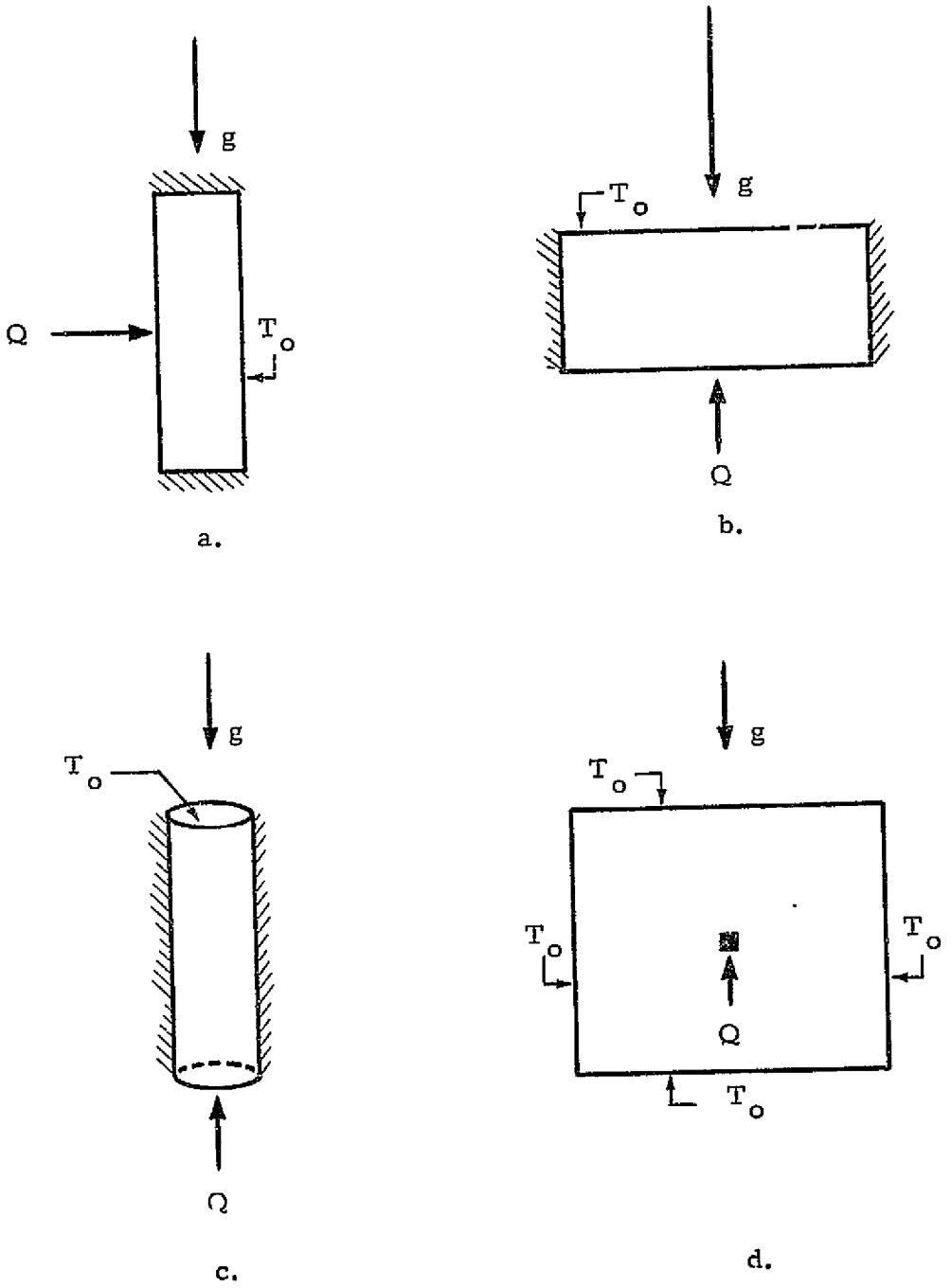
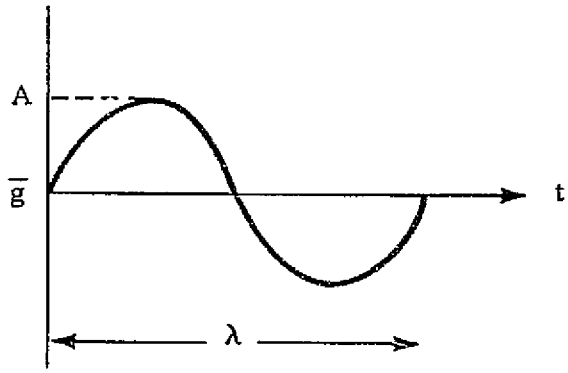
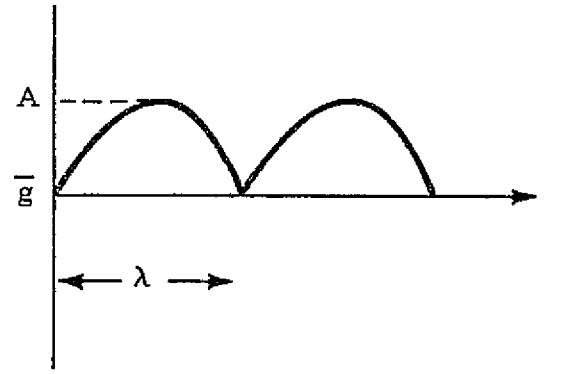


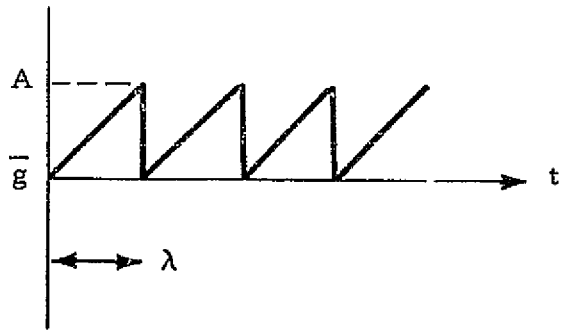
Fig. 2 - Configurations Used in Computer Models of g-Jitter Convection



Model 1
(Sinusodial)



Model 2
(Absolute Value Sinusoid)



Model 3
(Linear Periodic)

$\bar{g}$ = mean gravity level
A = amplitude of jitter
λ = period of jitter
t = time

Fig. 3 - G-Jitter Models Used for Parametric Study

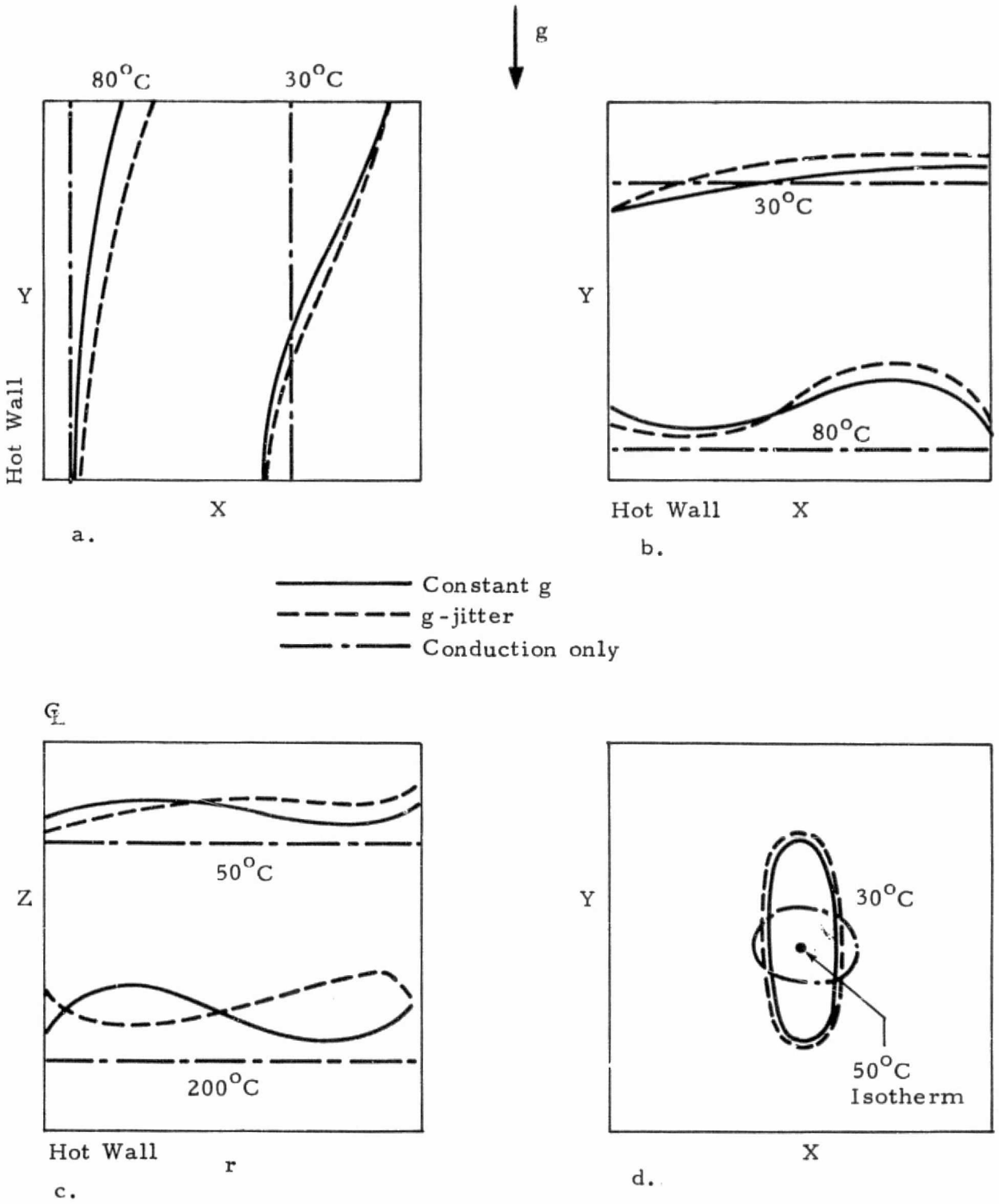
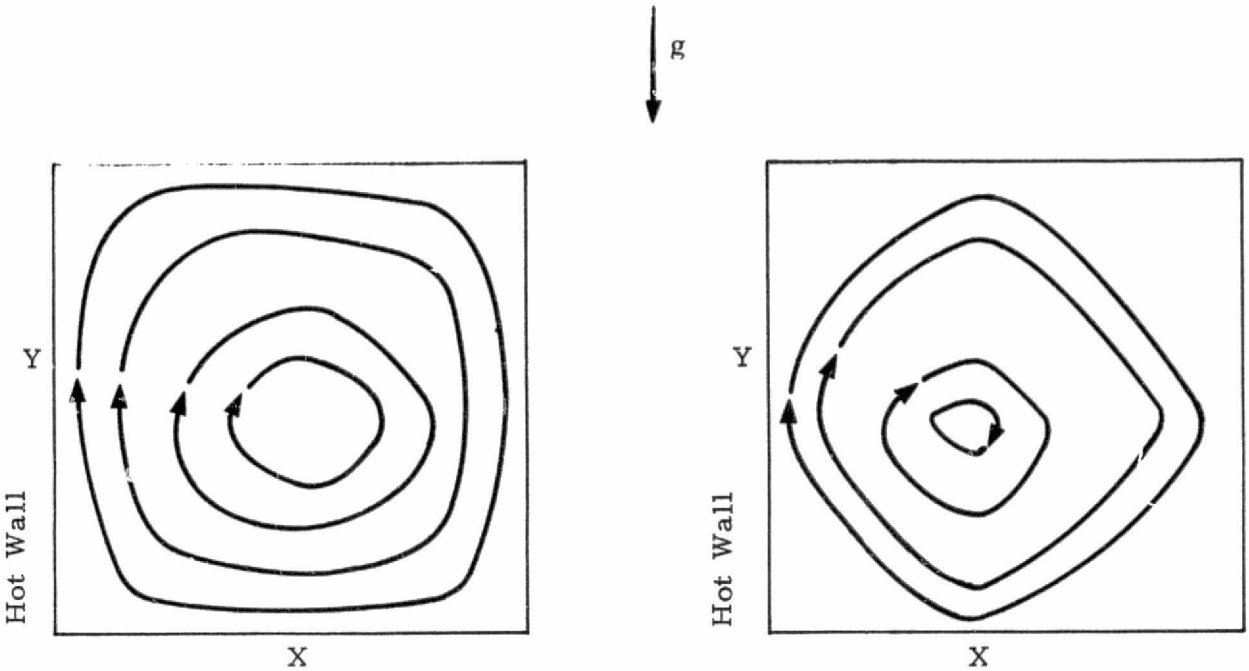


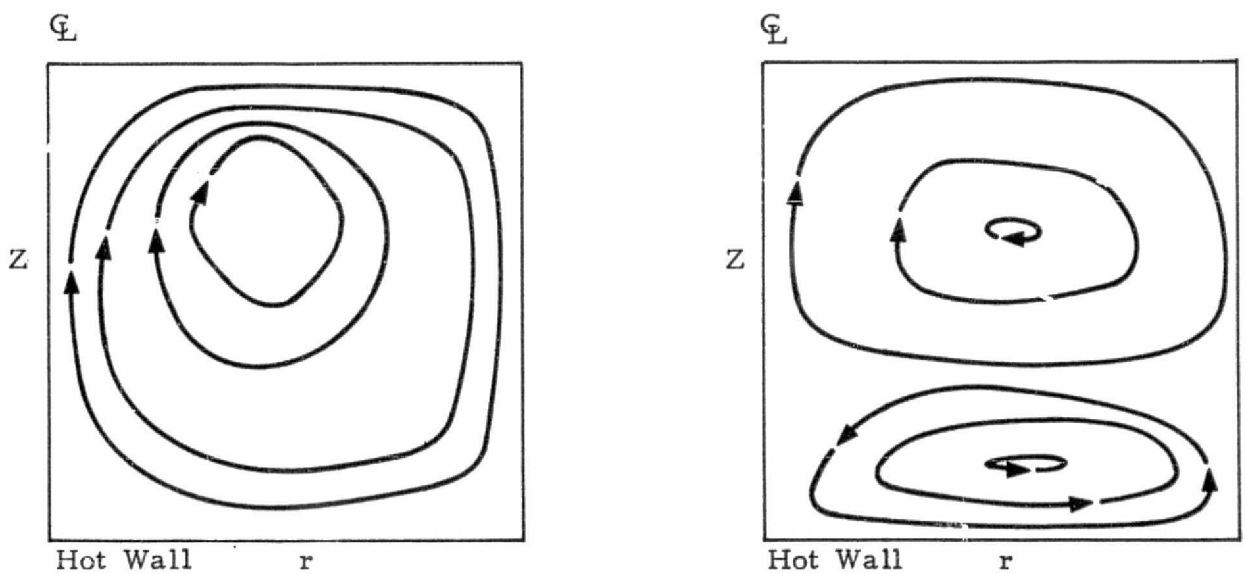
Fig. 4 - Isotherms at t = 3 Minutes for Four Configurations Showing Effect of g-Jitter



Water, g = Constant (10^{-3}
Rectangle, Side Heating

Water, g = g(t) Model 3
Rectangle, Side Heating

a.



Mercury, g = Constant (10^{-3})
Cylinder, Below Heating

Mercury, g = g(t) Model 3
Cylinder, Below Heating

b.

Fig. 5 - Streamlines at t = 3 Minutes for Water and Mercury Showing Effects of g-Jitter on Flow Patterns

$A = 10^{-3}$, $\lambda = 1$ sec. Cases (a) and (b) use a constant hot wall temperature $T_h = 95^{\circ}C$, cold wall $T_c = 25^{\circ}C$, with the other walls adiabatic. Figure 4a shows that the $80^{\circ}C$ isotherm is located farther into the water for the g-jitter case than for constant-g. The basic shape remains the same. Figure 4b shows the $80^{\circ}C$ isotherm has also penetrated somewhat farther for the g-jitter case. These plots show that g-jitter can effect the temperature profiles and potentially influence space processing experiments which rely on flat isotherms.

Case 4c is for mercury in a cylinder heated from below. The hot wall temperature is $T_h = 200^{\circ}C$, cold wall $T_c = 25^{\circ}C$ with the adiabatic side wall condition. This figure shows a more drastic effect. The $200^{\circ}C$ isotherm for the g-jitter case has changed shape, i. e., somewhat the inverse of the constant g isotherm. This behavior results from a change in mode of the convection from a single cell to a double cell (as seen later in Fig. 5). The point heat source case, 4d, shows the relative shape of the isotherms is the same with and without jitter, but with the g-jitter isotherm penetrating slightly farther into the fluid.

Figure 4 illustrates the type of results obtained. The numerous cases which were run show similar behavior, and are not shown in this report. A measure of the sensitivity to g-jitter, given in terms of temperature-difference, is discussed in Section 2.4.

Figure 5 provides another measure of the effects of g-jitter. These are streamlines plotted in the x-y (r-z) plane for two configurations. Figure 5a is the rectangular box of water heated from the side (same conditions on Fig. 4a). The constant-g streamlines are the usual single roll seen in most investigations. The corresponding streamlines for the g-jitter case shows a skewness toward the hot wall and also a change in shape. The general circular patterns for constant-g are more elliptic for the case of g-jitter. Figure 5b shows an even more pronounced effect. This case is the cylinder of mercury heated from below (same conditions as Fig. 4c). The

single two-dimensional roll cell has broken off into a two-cell pattern. The flow pattern in this cell was found to oscillate between the single cell and the multiple cell. The period of oscillation could not easily be determined from the calculations. These flow patterns do show a significant influence of an oscillatory g profile. The streamlines for other cases analyzed showed similar behavior, but with each case having its own pecularities.

The above results, in conjunction with the other cases studied, showed the following interesting facts and trends:

- The effect of g-jitter on fluid flow and heat transfer is more pronounced at low gravity levels ($\leq 10^{-3}$ g) than at 1-g conditions for comparable amplitude of oscillation.
- The flow streamlines can be altered from the circularized patterns produced by constant accelerations.
- The calculated temperature-time profiles tend to match the corresponding g-jitter model profile but has a lower frequency and is out of phase due to thermal lag.
- The calculated Nusselt number ratios are strong functions of the amplitude of the jitter and much weaker functions of frequency.
- The sine-wave model produces the least effect on the flow profiles and heat transfer and the linear periodic model produces the largest effects.
- Fluids with Prandtl numbers near 0.01 and 10.0 show significant g-jitter effects while Prandtl numbers near 1.0 exhibit very little changes in heat transfer.
- Temperature gradients of 20°C/sec are calculated at periodic steady state for the cases which exhibit maximum g-jitter influence.
- The maximum Nusselt number ratio calculated for any of the cases is 1.2 for g-jitter convection as compared to 1.0 for constant g conditions. This maximum is attained for the rectangular box heated from the side at a mean g-level of 10^{-3} g using model 3 with Pr = 6.0.

The results of the present study have shown that, for the models considered, g-jitter convection can have significant effects on fluid flow and heat transfer in confined fluids in low gravity. More precise calculations can be made on the nature and magnitude of actual g-jitter when quantitative flight data become available.

2.4 SENSITIVITY CALCULATIONS

A sensitivity parameter was selected to provide a means of comparing the numerous computer models which were run. This parameter consists of the maximum temperature difference between the g-jitter case and the corresponding constant-g case. This temperature difference was obtained regardless of the position in the container, or the time point in the oscillation cycle where it occurred. This approach was necessary because of the complex nature of the isotherms, the differing geometries and boundary conditions, and the different g-jitter models. This ΔT_{max} should provide an adequate measure of the sensitivity of the configurations to g-jitter convection.

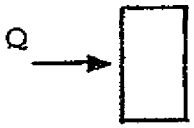
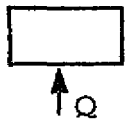
Table 2 summarizes the results of the analysis. The left-most entries in the matrix show the configuration, fluid and heated wall maximum temperature. Note that different values were used for water ($90^{\circ}C$) than for the other fluids. The gravity parameter entry in the matrix consists of the mean $\bar{g}$, the amplitude A, and period λ for g-jitter Model 3, the linear periodic profile. This model is used to summarize the results since it produced the maximum convective effect and is probably most typical of actual g-jitter. The calculated ΔT_{max} is shown for each case in the matrix. A sensitivity rating is assigned based on the magnitude of ΔT_{max}. The last entry in Table 2 shows the smallest mean $\bar{g}$ level at which any appreciable convection occurred.

The rectangular cell "heated from the side" has the largest ΔT_{max} i.e., most sensitive. The cylinder "heated from below" rates number 2, the box "heated below" is third and the point source case is poorest. The analysis also shows that, for a fixed configuration, water is the fluid most sensitive of those tested, with mercury next and helium gas the least sensitive. Note the agreement of this finding with the dimensional analysis of Fig. 1. As a result of this analysis, the following fluids were chosen:

- Water
- Mercury.

Table 2

SUMMARY OF SENSITIVITY ANALYSIS

Configuration	Fluid	Wall Temp. (°C)	Mean g	A, λ	ΔT_{max}(°C) ($T_g - T_{jitter}$)	Sensitivity Rating	Minimum Sensitivity of Config.
 Rectangular	H_2O	90	10^{-3}	10^{-3}, .1 sec 10^{-3}, 1 sec	20 20	Excellent	10^{-5}g
	Hg	260	10^{-3}	10^{-3}, .1 sec 10^{-3}, 1 sec	16 16	Excellent	10^{-5}g
 Rectangular	H_2O	90	10^{-3}	10^{-3}, 1 sec	8	Good	10^{-4}g
	Hg	260	10^{-3}	10^{-3}, 1 sec	6	Good	10^{-4}g
Cylindrical	H_2O	90	10^{-3}	10^{-3}, 1 sec	12	Good	10^{-5}g
	Hg	260	10^{-3}	10^{-3}, 1 sec	10	Good	10^{-5}g
	He	260	10^{-2}	10^{-2}, 1 sec	3	Fair	10^{-3}g
Point Source	Hg	Power .001 W	10^{-2}	10^{-2}, 1 sec	0	Poor	10^{-2}g
	Hg	Power 0.1 W	10^{-2}	10^{-2}, 1 sec	< 1	Poor	10^{-2}g

The container geometries selected are:

- Rectangular box (7.62 x 10.16 x 1.27 cm)
- Cylinder (1.91 cm diameter, 18.1 cm length)

The dimensions of the containers, aspect ratios, and heating requirements for the fluid cells were determined from the analysis and from practical limitations. The combinations of fluids, containers and heating directions are numerous. Various concepts are now discussed and a recommended flight concept is presented.

2.5 FLIGHT CONCEPTS

The sensitivity analysis has identified the fluids and configurations which are most sensitive to low-g convection. A convection measuring package for sounding rocket flights could utilize these results in a number of combinations. The orientation of the fluid cells with respect to the heating direction is critical to analyzing the convection itself. The actual direction of the acceleration vector on the rockets will most likely be changing with time. However, it appears likely that there will be a maximum g in one primary direction during the coast phase of the flight. The convection measuring package recommended here provides for altering the orientation of the fluid cells in the rocket payload area.

Figure 6 summarizes the flight concepts which are recommended and also provides an alternate. Three flights are recommended to obtain maximum information and to define the rocket convective environment. Flight 1 contains the two fluid cells mounted "vertically" with respect to the long axis of the rocket. This provides for two different heating directions regardless of the direction of the primary acceleration component. Flight 2 rotates the cell 90 degrees to produce a "horizontal" orientation with respect to the long axis of the rocket. Flight 3 is a repeat of flight 1 with the exception that the cylindrical cell is to be heated before launch. This will provide a measure of the effects of large accelerations on the

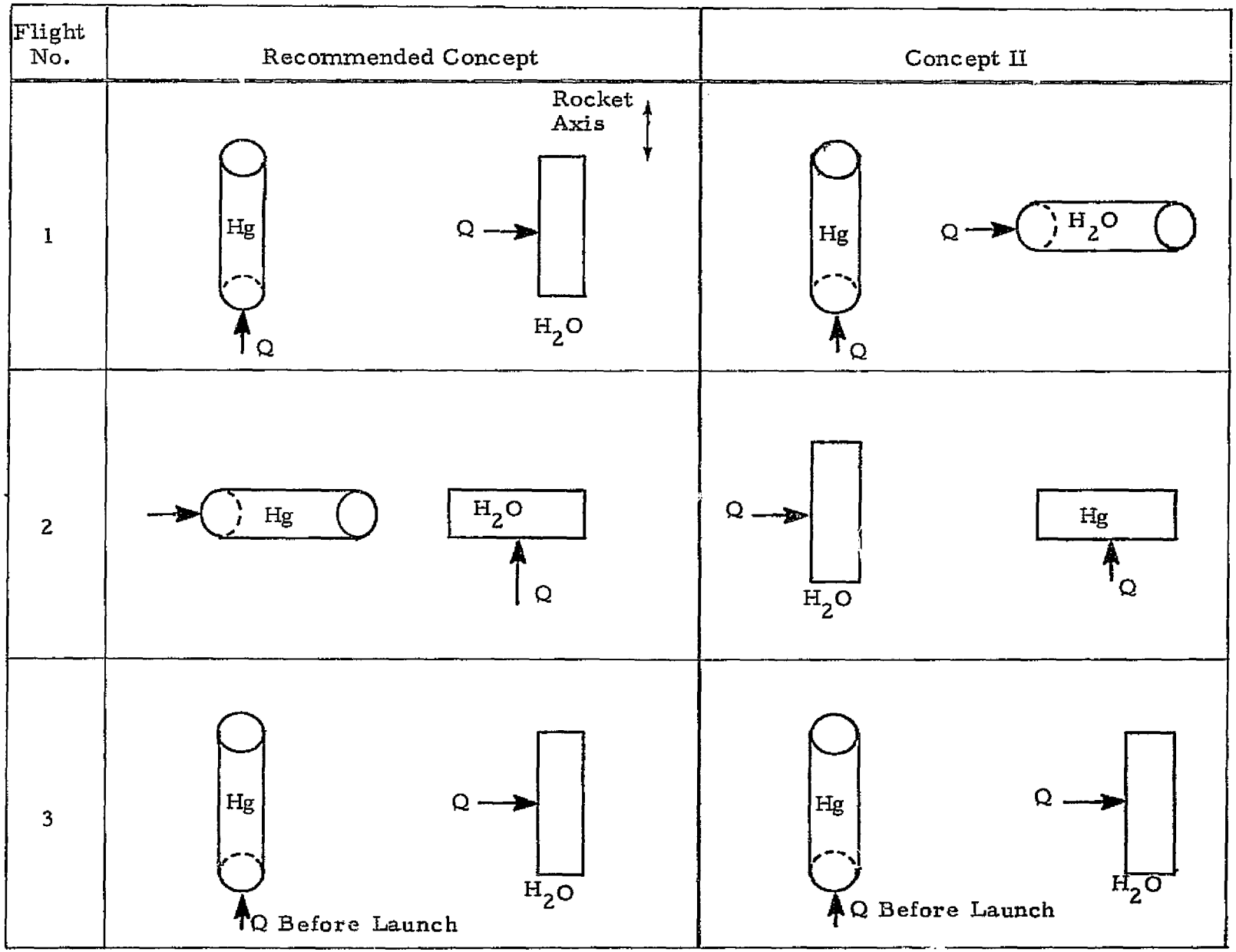


Fig. 6 - Flight Concepts for Convection Measurement Package

settling time, spindown, etc., of fluids aboard the rockets. Flight 3 will also provide redundant data on the rectangular cell for verification of the measured environment.

There are obviously many other combinations which could be flown, for example, concept II in Fig. 6. It is believed however, from the results of this study, that the recommended flight concept will provide the maximum amount of information for the fewest number of flights and the lowest cost.

Section 3
FLIGHT APPARATUS

This section presents a summary of the apparatus which was fabricated for measuring convection effects on sounding rockets. The hardware for the water cell, the mercury cell and the electronic modules are summarized including the interface with the rocket payload area. A discussion is also given of the bench tests which were performed to verify the operation of the hardware.

The reader interested in details of the mechanical and electrical design of the apparatus is referred to NASA-MSFC drawings available at the Space Sciences Laboratory, ES34.

A summary of the test procedure for the convection measurement package is given in the appendix.

3.1 THE WATER CELL

The water cell hardware consists of a plexiglass rectangular box 7.62 x 10.16 x 1.27 cm which contains the fluid. An aluminum plate constitutes one of the walls of the container. A schematic of the water cell is given in Fig. 7 to illustrate the various components. A thermofoil heater, 7.62 x 10.16 cm (Minco HK-6060-04, R = 7.64 ohms) is mounted behind the plate to supply the required thermal input to heat the water. Thermal insulation is placed behind the heater to reduce the heat losses out the back of the container.

A mechanism for relieving thermal expansion is provided. These chambers are shown in the sketch in Fig. 7. Two cylinders, 1.27 cm diameter, 7.62 cm in length, with a plunger mechanism are mounted at the top and bottom of the cell. As the water expands upon heating the plungers

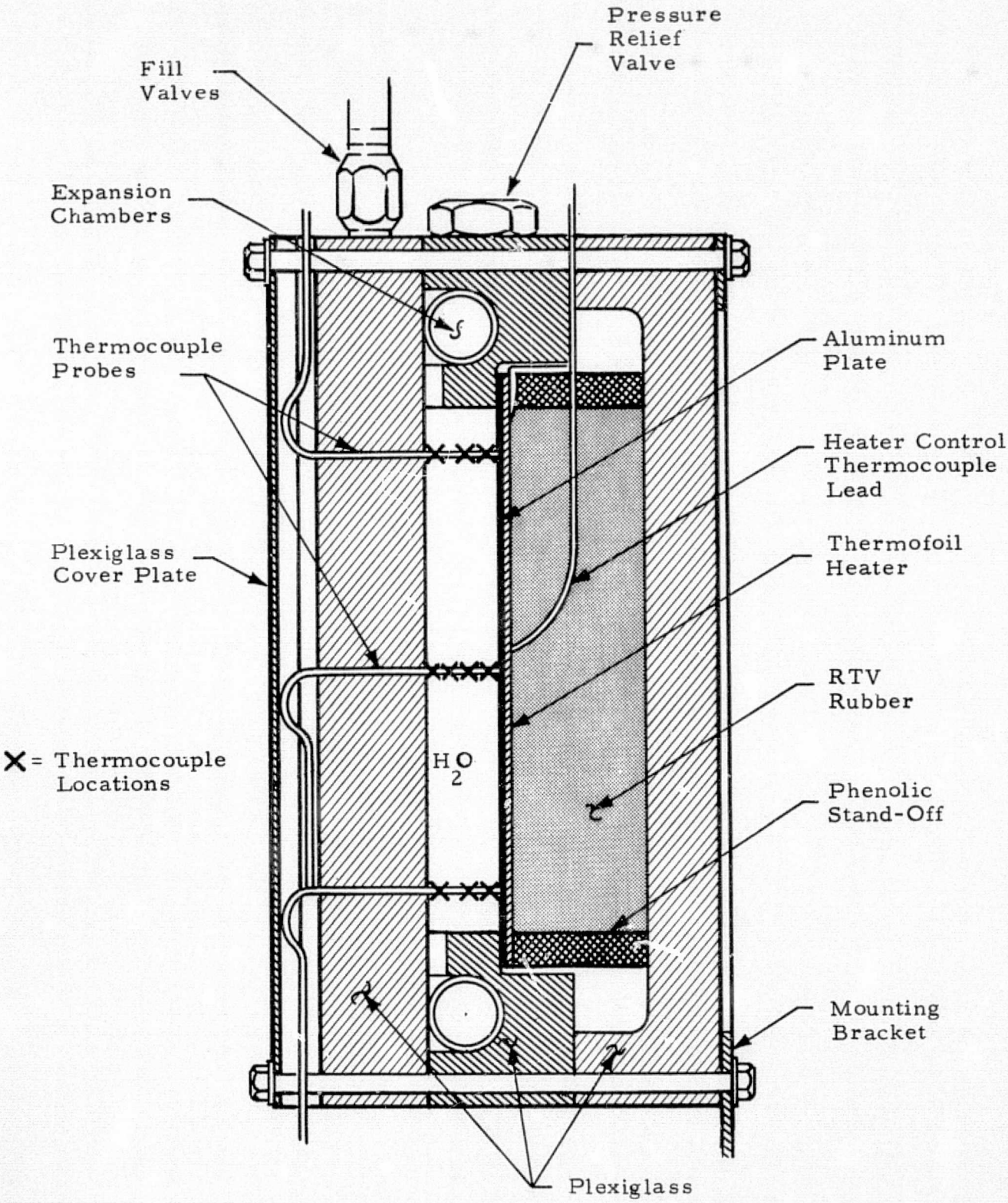


Fig. 7 - Schematic Side View of Water Cell Module

are forced in the cylinders, compressing the air and providing a larger volume for the water. As the water cools and the pressure is equalized, the plungers return to their original position for repeated use. This mechanism was verified by bench tests of the unit.

A copper-constantan thermocouple (Omega SCPSS-0206-6) is attached to the heater back face for use by the heater controller circuits to regulate the heater temperature. Ten other sheathed thermocouples of the same type are mounted on the front face of the heater plate and also in the water to record the temperature history. The response time of the thermocouples is of the order of 0.1 second. Calculations were made to determine the effect of conduction in the thermocouple sheaths on the measurement of temperature at the junction. These calculations indicate that the conduction in the water is approximately 1000 times the conduction in the thin wires. The temperature at the thermocouple junction will thus be very close to the temperature of the medium to which it is connected.

The remainder of the hardware consists of a pressure relief valve (35 psid), thermocouple connector brackets, fill valves and a mounting bracket. The completed apparatus comprising the water cell module is shown in the photograph of Fig. 8.

3.2 THE MERCURY CELL

The mercury cell hardware consists of a cylindrical container, 1.91 cm inside diameter and 18.1 cm length which contains the fluid. The cylinder material is RTV rubber (Dow Corning 3116) which is chemically compatible with the mercury. One end of the rubber cylinder contains a stainless steel plate with a heater button (Minco H6A20W28) behind it to supply the thermal input. Figure 9 is a schematic of the cell to illustrate the components. The heater assembly is sealed in place with RTV rubber which also minimizes the heat leaks out the back of the container. The rubber cylinder is contained inside a 3.175 cm diameter stainless steel sheath for rigidity. The entire package is then contained inside a 5.59 cm inside diameter fiberglass cylinder and the annulus filled with Microquartz felt thermal insulation.

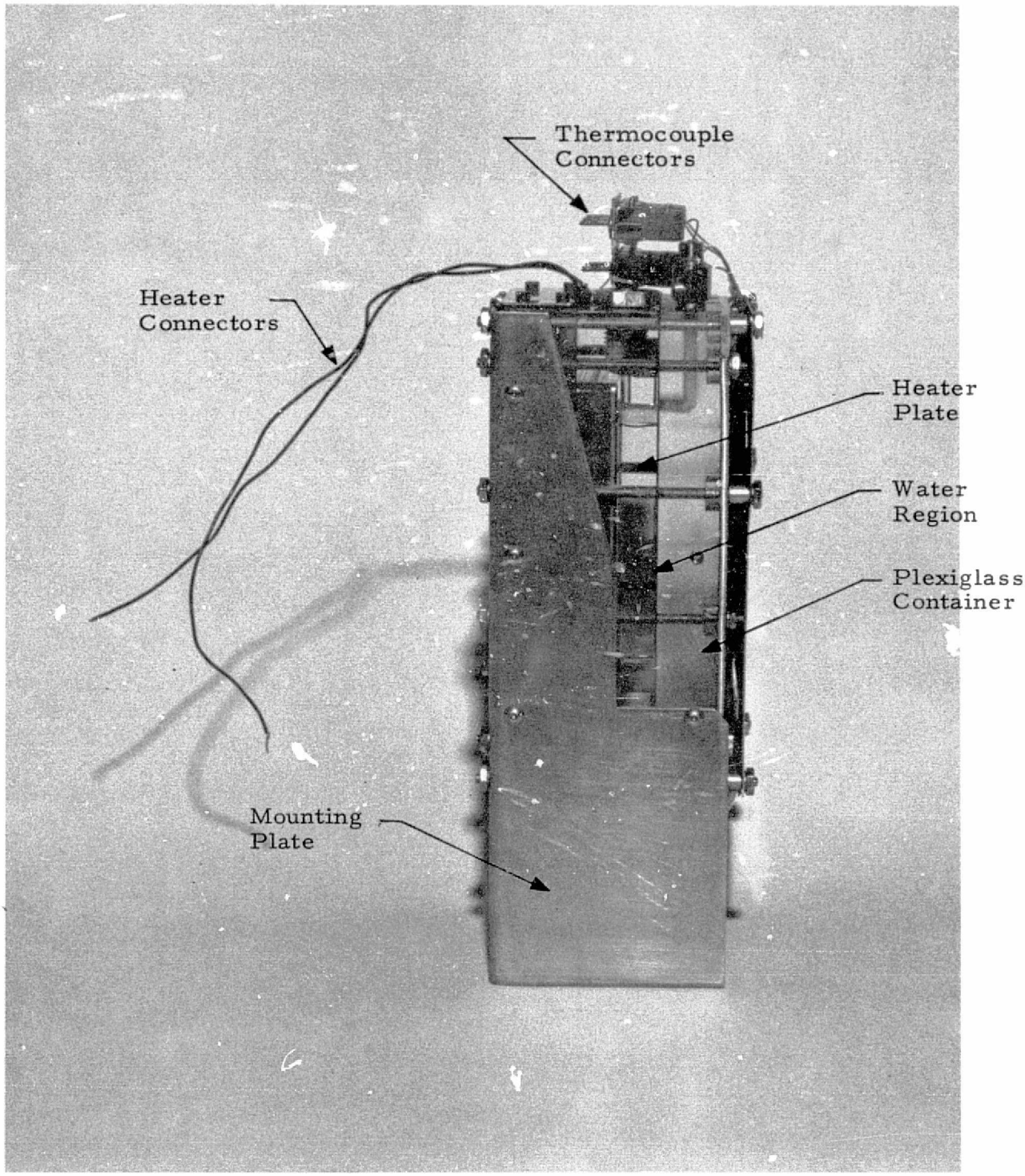


Fig. 8 - Photograph of Water Cell Module

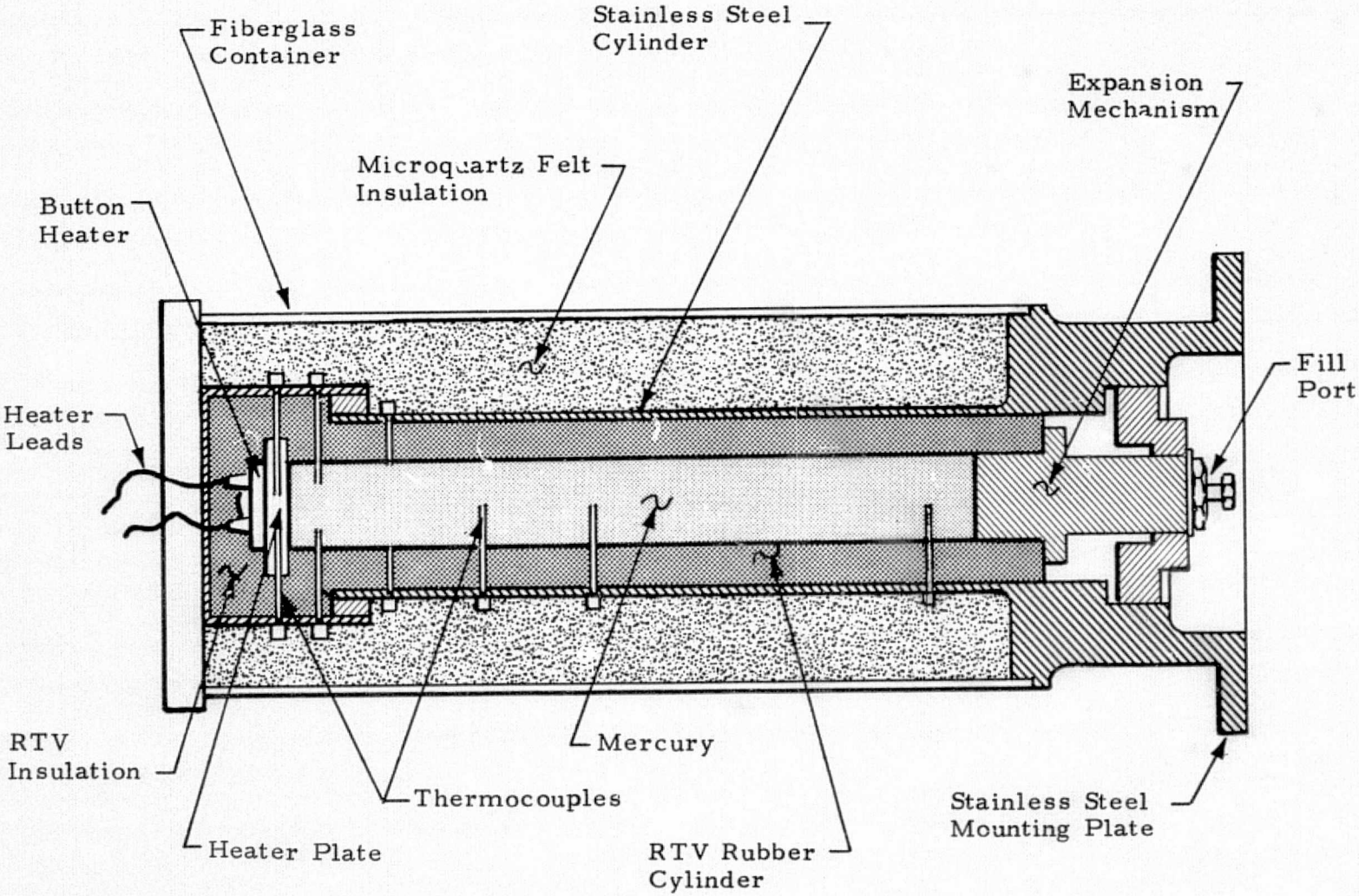


Fig. 9 - Schematic of Mercury Cell Module

The end of the cylinder opposite the heater contains a thermal expansion mechanism consisting of a spring-loaded plunger which contracts as the heated mercury expands. This system can be used repeatedly without refilling since the spring mechanism retracts as the mercury cools down. This expansion system was verified by repeated bench tests of the unit.

A copper-constantan thermocouple (Omega SCPSS-0206-6) is attached to the back of the heater face for use by the heater controller to regulate the heater temperature. Ten other sheathed thermocouples are mounted in the mercury and in the heater plate to record the temperature histories. The optimum locations of these thermocouples were determined from the theoretical analysis discussed in Section 2.

The remainder of the mercury cell hardware consists of thermocouple connectors, an end plate and mounting bracket. The completed apparatus comprising the mercury cell module is shown in the photograph of Fig. 10.

3.3 ELECTRONIC MODULES

The fluid test cells just described are operated via two electronic modules. Figures 11a and 11b are photographs showing two views of the measurement apparatus. Figure 11a is a view showing the position of the two fluid cells in the total package. Figure 11b shows the two enclosed electronic modules (front and back) with the water cell, interface plugs and thermocouple connectors. The mounting plate allows direct interface with the payload area of the rocket.

The electronic modules are divided into three basic elements: (1) power regulation and conversion; (2) amplifiers, and: (3) heater controller. Ten thermocouples with battery powered reference junctions provide input signals to the high gain (1000) amplifiers. These amplifiers output a 0 to 5 V signal to interface with the telemetry system. The amplifiers are initially adjusted by using an ice bath for zero output voltage representing $0^{\circ}C$ and boiling water for 4.27 V output correlated to $100^{\circ}C$. A two-step electrical

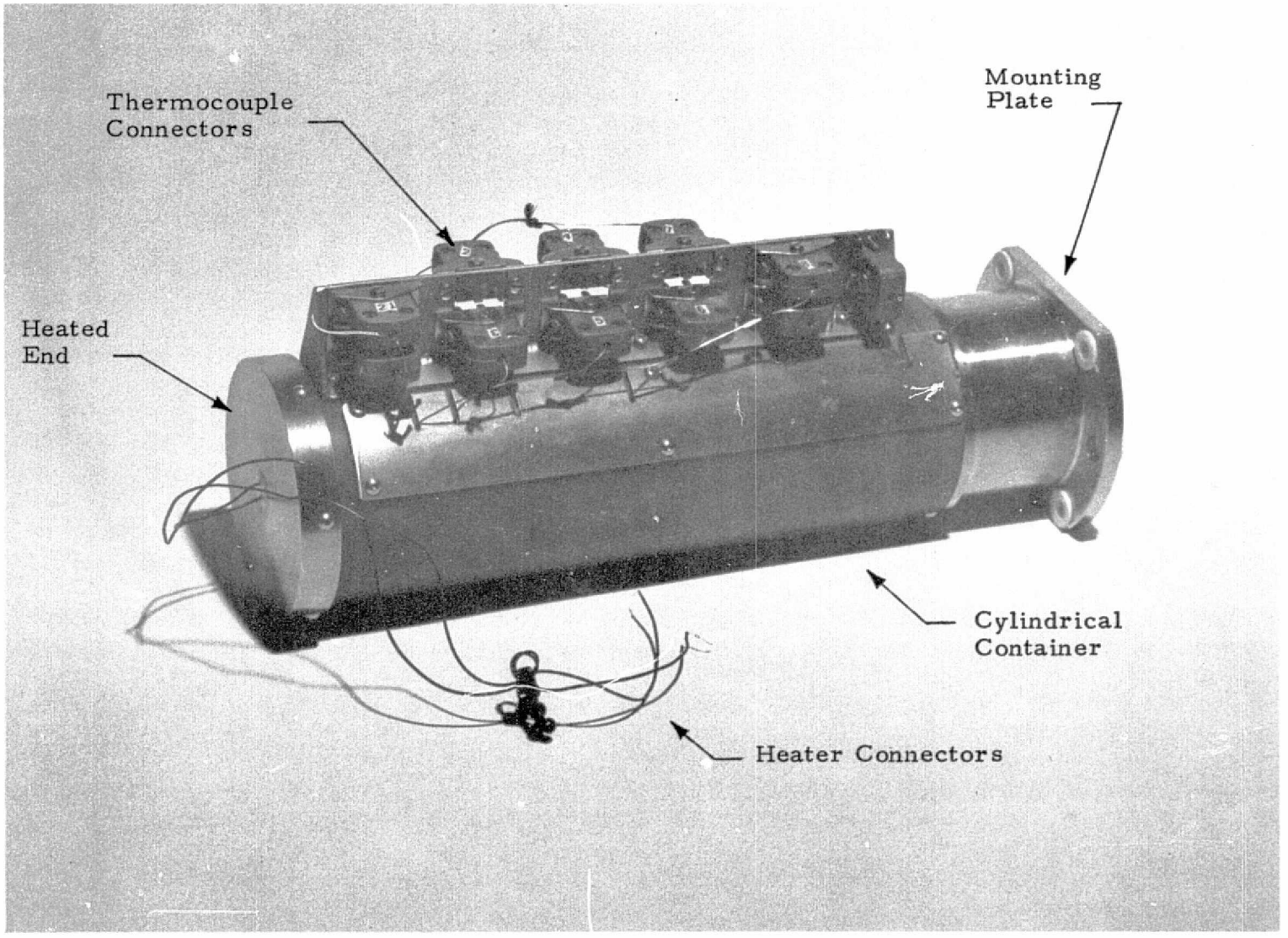


Fig. 10 - Photograph of Mercury Cell Module

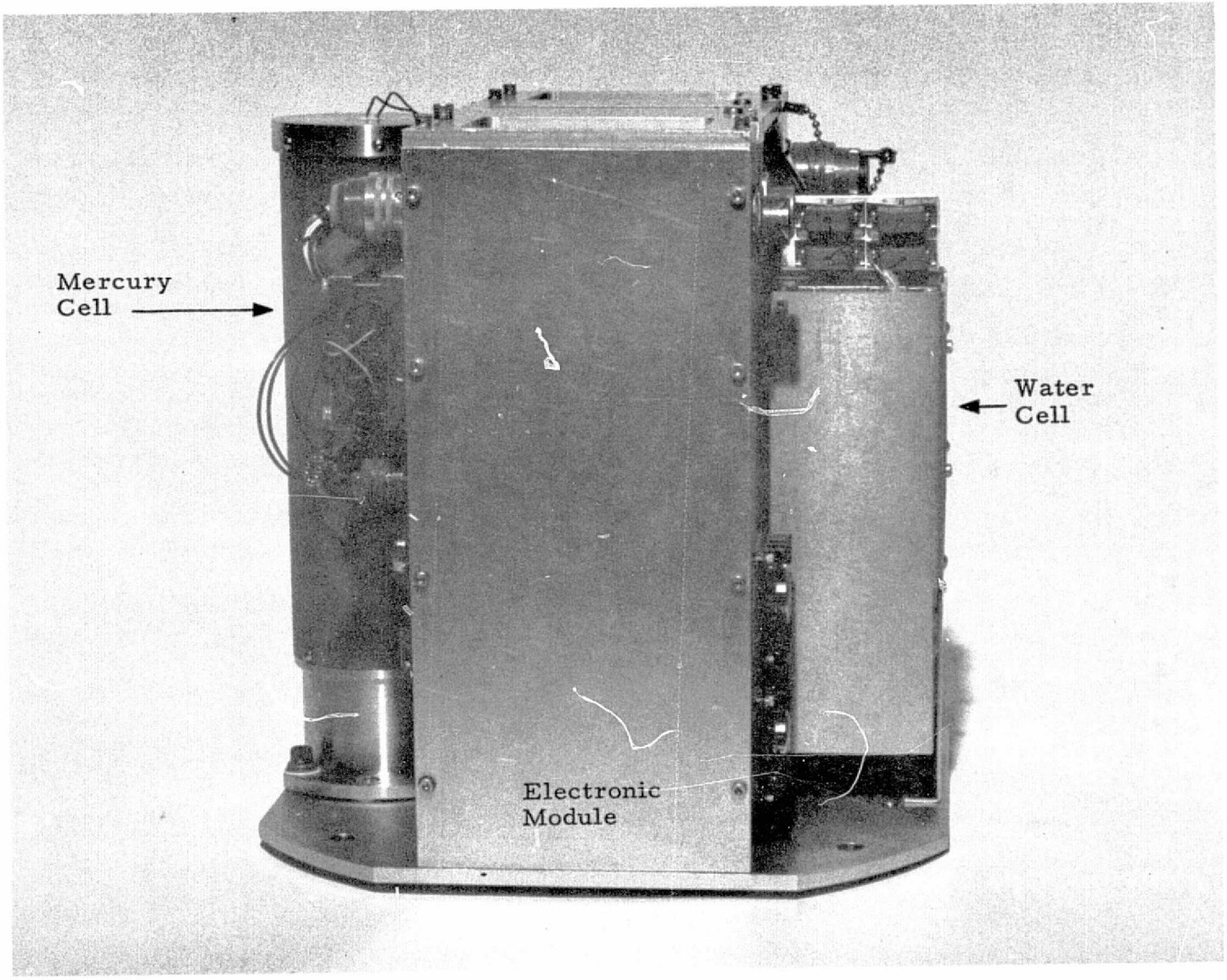


Fig. 11a - Photograph of Convection Measurement Apparatus

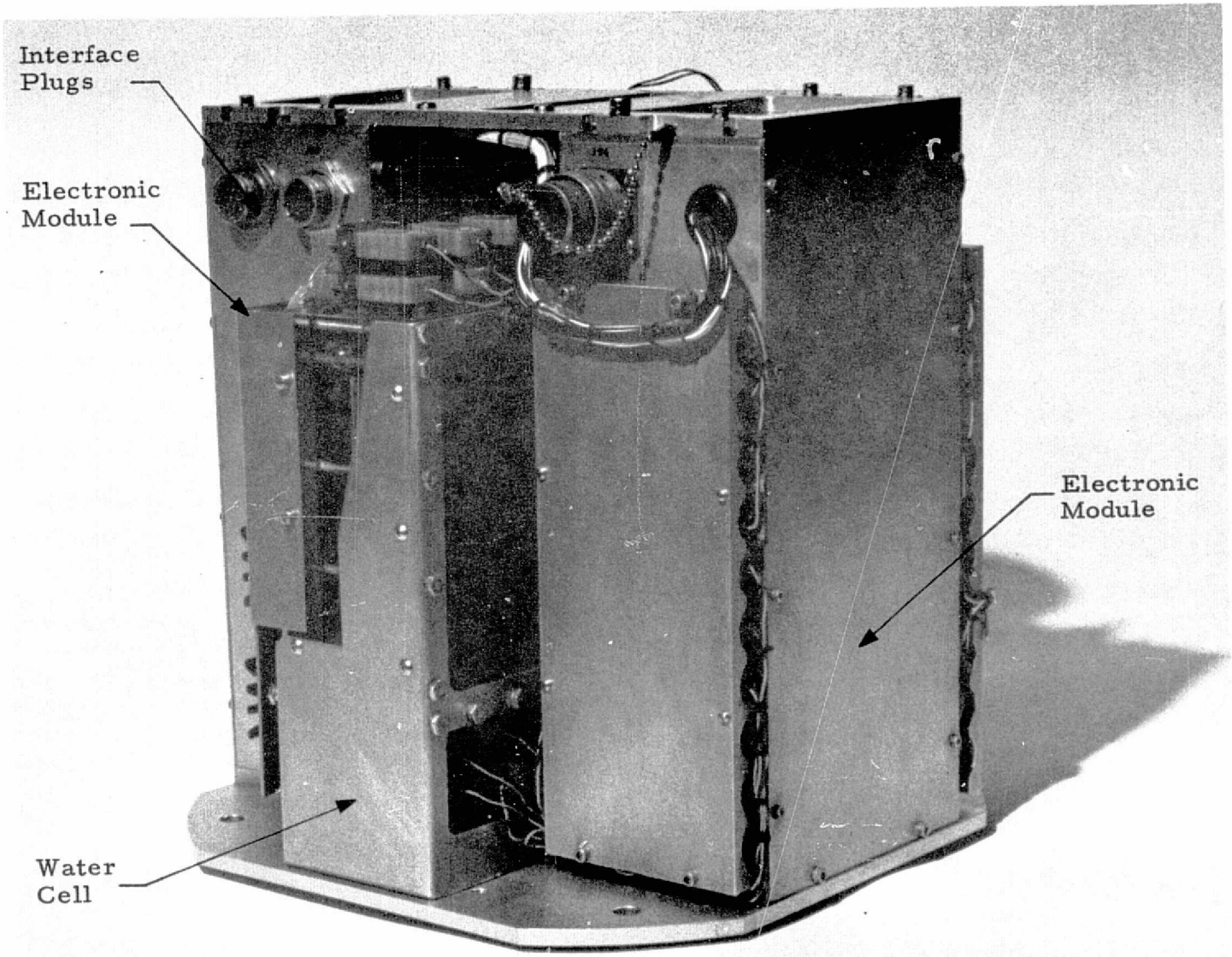


Fig. 11b - Photograph of Convection Measurement Apparatus

calibration system is provided to keep the amplifiers within tolerance after reference points have been established. Low calibration level is 500 mV while the upper level is set at 4.8 V. This range was provided for better calibration resolution. Utilizing the electrical calibrations, the measuring system accuracy can be maintained to ± 50 mV or $\pm 1.2^{\circ}$C.

The electronics accept a supply voltage from +28 to +40 V from an external source. Total power required from the vehicle (external source) is 140 W at 28 Vdc. The varying input voltage is internally regulated to +28 V for heater control and electronics power. A dc-to-dc converter is included to provide a regulated ± 15 V to the necessary electronics.

Triggered at liftoff by an external G switch, a 108 second timer delays the regulated +28 V that is applied to the cell heater. At the end of the 108 seconds, a second timer is initiated to provide a cell heating time of 360 seconds. At the end of this 360 seconds the 28 V power is removed from the heater and stays disconnected until the timers are reset. The heaters are electronically temperature-controlled by a thermocouple feedback mounted on the heater base. This feedback is applied to a transistor controller which regulates the current for a heater temperature of 90°C $\pm 3^{\circ}$ to the water cell and 200°C $\pm 5^{\circ}$ for the mercury cell. Electrical checkout is provided through the umbilical cable and the telemetry system. The approach of using a constant wall temperature rather than a constant heat flux was chosen because (1) a large ΔT between the heated wall and the fluid can be achieved in a shorter time, and (2) the analytical modeling of this boundary condition provides a direct correlation with dimensionless parameters such as Rayleigh number.

The photograph of Fig. 11a shows the fluid cells mounted to the full package in a "vertical position." The capability has also been provided to mount these cells in a "horizontal" position. This provides the option of repeating the experiment with the heating direction changed with respect to gravity direction, i.e., heating from the side or heating from below, etc.

3.4 PAYLOAD INTERFACE

The experimental procedure aboard the rocket will follow an automated sequence of events. At launch time, power is supplied to a series of timers. At a specified later time (i.e., 108 seconds) when the vehicle is beginning the low-g portion of the flight, the timers turn on power to the heater. The measurements are taken during the low-g portion of the flight and the power is turned off by another sequence of timers after the 360 seconds (or other) of available low-g time. The entire experiment package remains intact during the flight and no special procedure is necessary to secure the fluid cells after the test period. All data are obtained via the telemetry system.

The convection measurement system requires a minimum of interface with the rocket payload area itself. The equipment can be mounted to a plate which can be bolted and attached directly to the rocket payload area. The system has a 28 V, 140 W power requirement from the rocket batteries. An appropriate plug is provided for direct connection with this supply. The data will be transmitted via the telemetry system. Ten channels are required for the thermocouple measurements. The amplifier in the system will output a 0 to 5 V signal for interface with the telemetry. Again suitable plugs compatible with the Black Brant vehicle are provided.

The convection measurement system provides its own supporting equipment. The dimensions of the full hardware package are 35 cm in diameter and approximately 33 cm in height. The total package weight is estimated to be 16.1 kg. A breakdown of the package weight is given in Table 3. The experiment will require approximately this amount of weight and payload area to carry out the measurements aboard the sounding rockets. No facilities, other than the above, are required.

Table 3

CONVECTION MEASURING SYSTEM
WEIGHT SUMMARY

Equipment	Weight (kg)
Amplifier Housing Unit	4.85
Power and Control Unit	3.90
Water Cell Module	1.91
Mercury Cell Module	4.08
Mounting Plate and Brackets	1.36
Total	16.10

3.5 CHECK OUT OF FLUID CELLS

The fluid cell modules were bench tested before delivery to NASA-MSFC for integration with the electronic modules. These bench tests consisted of:

- Operation of the heaters
- Response of the thermocouples
- Operation of expansion mechanisms
- Checking for fluid leaks
- Response of cells to partial vacuum
- Determining repeatibility of all operations, and
- Observation of fluid convection (water cell).

The cell heater leads were connected to 28 Vdc power supplies. The thermocouples in the fluid were connected through appropriate reference junctions to a strip chart recorder. The heater plate thermocouples were connected to a digital voltmeter to allow a quick readout of the heater temperature to avoid overheating.

Figure 12 is a plot of the measured heater temperature versus time for the mercury cell. The figure is for a "heating-from-above" case which minimizes the convection and somewhat simulates the heat-up that would be expected in low-g. The power was turned off at 180 seconds to prevent overheating the cell. The bench test shows that the maximum heater temperature of 200°C is approached in about three minutes. This is within the allowances which were predicted analytically.

Figure 13 is a similar plot for the water cell. These data were taken in a "heating-from-below" orientation, and the plot is made up of data read from the heater plate thermocouple. The plate never reached the maximum temperature of ~93°C due to large convection cells which developed. However, the "heating-from-above" orientation causes the plate to reach the maximum temperature in less than two minutes. The power was turned off at approximately 270 seconds. The heater rise time is well within the limits required for proper operation of the cell.

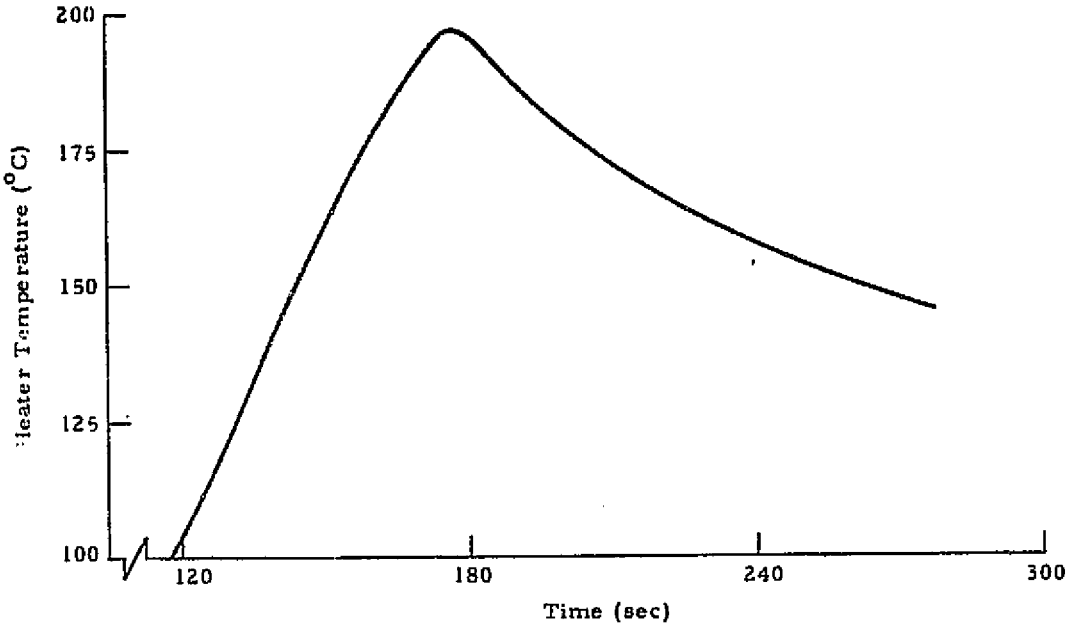


Fig. 12 - Measured Heater Temperature History for Mercury Cell (Heated Above 28 Volts)

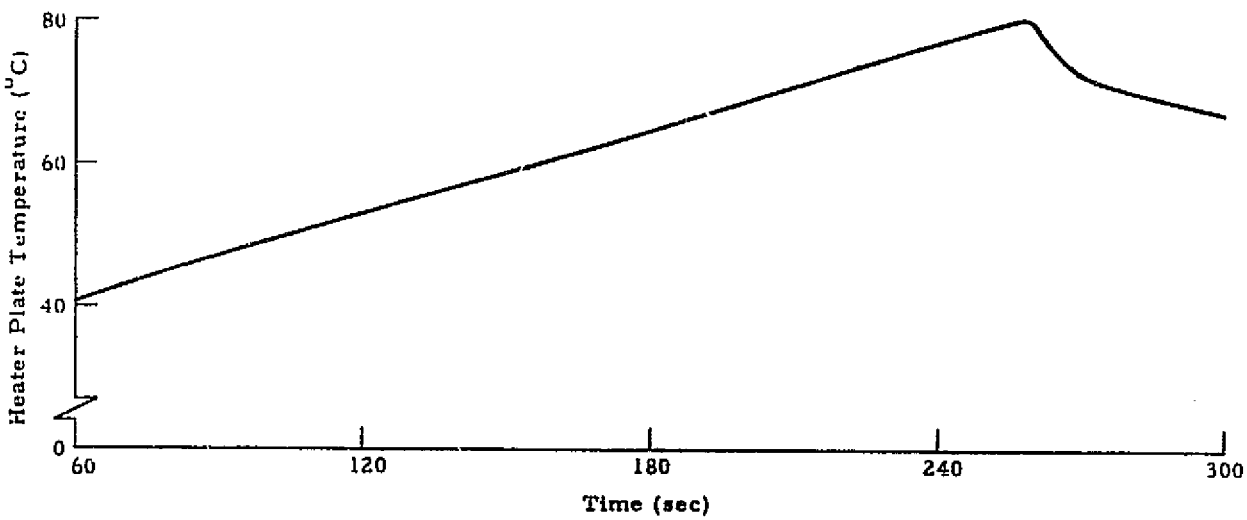


Fig. 13 - Measured Heater Plate Temperature for Water Cell (Heated Below 28 Volts)

The thermocouple data for the remaining probes in the two cells was reduced and proper operation was verified. The thermal expansion mechanisms operated properly through six heat-up/cool-down cycles. The water cell expansion chambers could be viewed through the plexiglass walls which provided visual observation of their operation. The final checkout of the cells consisted of repeating the operations with the cells in a vacuum chamber. The low pressure external environment produced no adverse effects on the heater cycles, expansion process or thermocouple responses.

The water cell plexiglass container allowed visual observation of the fluid convection which results when the water is heated. This was observed in several bench tests of the water cell by using a simple shadowgraph. A light source, collimating lens and viewing screen were used to view the changes in density gradient as the water was heated. This provided an additional bench check out of the water cell and also served to verify the analytical predictions.

Section 4
DATA ANALYSIS PROCEDURE

The procedure for analyzing the data from the convection measurement package will consist of: (1) comparing the reduced flight data with ground laboratory data taken with the exact experimental configuration, and (2) utilizing a digital computer program which computes the entire flowfield and thermal history in the fluid cells. The temperature data will provide a quantitative measure of the convective or diffusion effects in a low-g sounding rocket environment.

4.1 COMPUTER MODELING

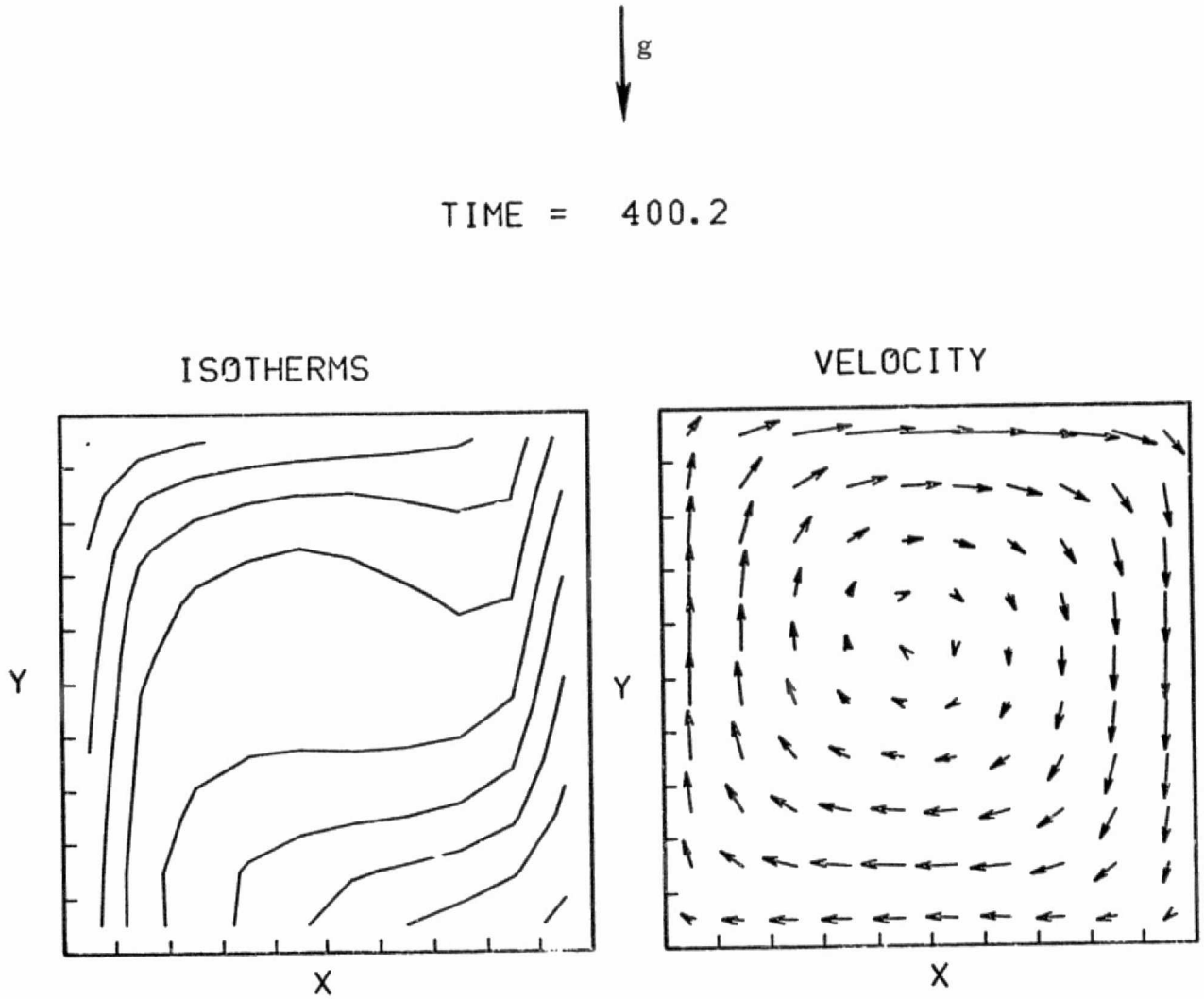
The computer program discussed in Section 2 (Ref. 12) is the primary tool to be used in the data analysis. This program utilizes a finite difference solution of the full Navier-Stokes equations for convection in an enclosure. The magnitude and direction of the gravitational vector can be arbitary and time-dependent. The solution assumes that the flow is laminar and either two-dimensional or axisymmetric. The g data from the rocket accelerometer will be input to provide a g versus time curve for the body force term in the equations. The solution procedure used by the program does not require the usual Boussinesq assumption of a linear density dependence on temperature. This will be especially useful for comparing the calculated temperature gradients with the flight data. This program represents the current state of the art in convection computation.

The numerical technique is designed to handle a variety of thermal boundary conditions. The heater temperature will be known as a function of time from the thermocouple measurements. The thermal boundary conditions for the container walls can be calculated as heat losses by the program using the material properties of plexiglass, RTV rubber and the fluid temperature

histories. The boundary conditions are determined by using a three-dimensional thermal analyzer program which solves the heat conduction equation. The finite heat capacity and the conduction properties of the heater plates, the plexiglass walls, etc., are taken into account. These boundary conditions are then used for the convection calculations and an iteration process converges the solution. The computer program calculates the transient portion of the solution as well as any steady state which may be reached. The program has been used for a number of projects involving convection in enclosures and has been verified by comparing calculated data with experimental data from the literature. Documentation of portions of this work are available in Refs. 2, 3, 12, 13 and 14.

Figure 14 is an example solution map from the program to illustrate the type of data analysis to be performed. The illustrative problem shown consists of a rectangular container of water with an aspect ratio of 1 in a 10^{-3}g environment. The left wall is held at a constant hot temperature, the right wall is cooled and the lower wall is adiabatic. The upper surface is unconfined with a linear temperature profile. The Grashof number is 20,000 and the Marangoni number is 1400. Figure 14b shows the velocity vector maps in the x-y plane at 400 seconds after heating begins. This computer generated map indicates the cellular flow pattern in the container. The length of the vector indicates relative magnitude and the arrow represents direction. Figure 14a shows the isotherms (lines of constant temperature) at the same solution time. The program produces a complete flowfield and thermal definition; any or all of the variables can be printed, plotted or mapped.

Figures 15 and 16 are predicted temperature profiles for the water cell and mercury cell, respectively. These curves represent the thermal histories which are expected if no convection occurs, i.e., g = 0. Figure 15 is a plot of temperature versus distance, x, from the heater plate at the centerline plane of the plexiglass water cell. The position x = 0 is the heater plate and x/w = 1.0 is the inside of the plexiglass wall. The heater plate was allowed to reach 200°F and then maintained at this value (this simulates the electronic control system).



a. Isotherms

b. Velocity

Fig. 14 - Convection Solution Maps for Illustrative Example Problem

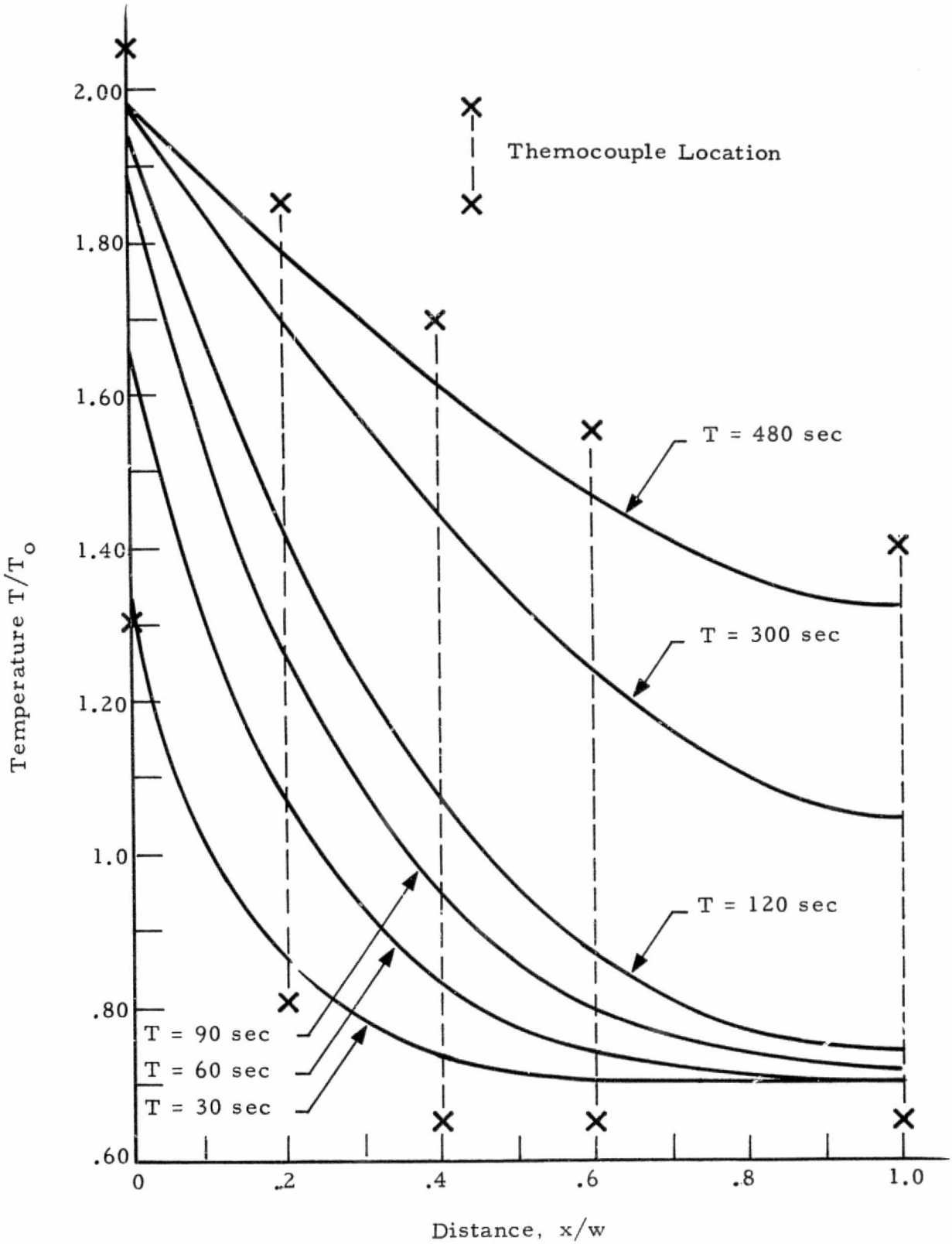


Fig. 15 - Temperature Predictions for Water Cell (g = 0, T_o = 100°F, w = 1.27 cm)

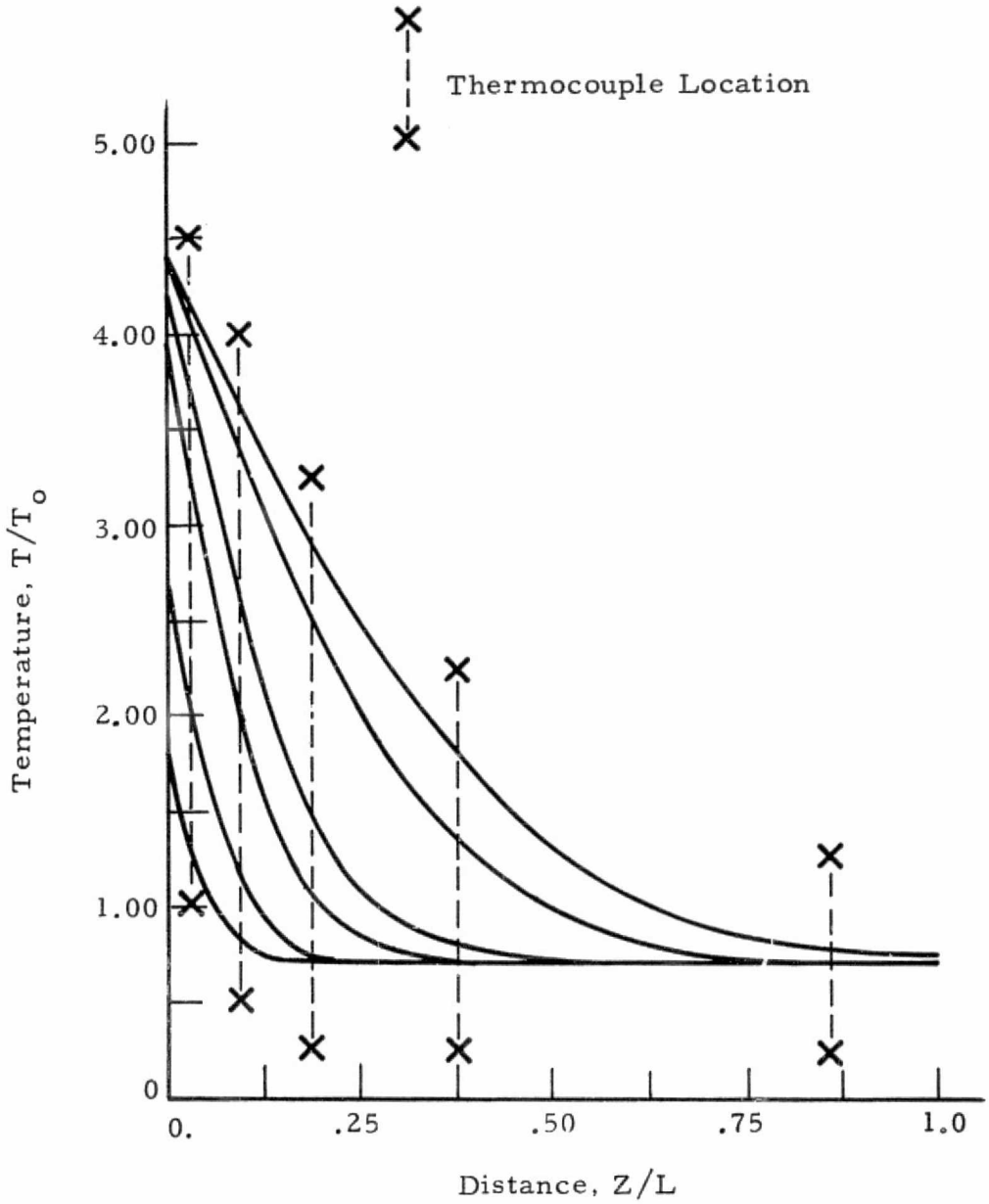


Fig. 16 - Temperature Predictions for Mercury Cell (g = 0, T_o = 100°F, L = 20.32 cm)

The location of the thermocouples in the water cell are shown by the X marks on the plot. Figure 16 is a similar plot for the mercury cell. The temperature versus axial distance Z is plotted at the centerline of the cylinder. The position z = 0 represents the heater plate which is maintained at 450°F. The thermocouple locations in the axial plane of the cylinder are shown.

These fluid thermal histories can be used for comparing the flight data with predictions. If no convection occurs during the flight measurement time, the thermocouple responses should agree, within tolerances, to these predictions. Deviation from these predicted profiles provides the first qualitative measure of the convective environment aboard the rockets. The analytical predictions which will be obtained from the convection computer program using the flight accelerometer g data can then be used to quantify the convective environment.

4.2 EVALUATION

The data evaluation procedure is summarized by the following steps:

- Obtain data using the fluid cells in the 1-g laboratory environment.
- Reduce the flight thermocouple data to obtain temperature versus time at discrete locations in the fluid.
- Obtain the accelerometer g data and reduce these data for use in the convection computer program.
- Run the convection computer program for the enviromental conditions of the experiment.
- Compare flight data, ground-based data and analytical predictions for temperature distributions in the fluids.
- Assess the magnitude and effects of convection on the experimental test cells.
- Extrapolate the results of the analysis to typical promising space processes and state its implications for space processing aboard sounding rockets.
- Document the findings of the investigation for application to assessing the suitability of sounding rockets for space manufacturing.

In summary, the results from this investigation will provide: (1) valuable information to the space processing community on convection and diffusion effects in a low-g environment; (2) data on the environment of sounding rockets for application to various space processing experiments; (3) a flight proven apparatus and technique for further experimentation aboard rockets. The measurements obtained will provide data needed immediately to plan and design for further flights. The temperature measurements in a heated fluid will yield data never before obtained in a low-g situation and which are impossible to obtain on earth. Extrapolation of these findings may prove useful in understanding the unexplained phenomena which have been observed previously in space-produced material. The baseline definition of the convective environment aboard the rockets is expected to be a major result from the convection measurement package. This information will be extremely valuable to the entire space processing community for future ventures.

Section 5
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Appendix
CONVECTION MEASUREMENT PACKAGE TEST PROCEDURES

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Appendix

1.0 Introduction

Four operating procedures shall be used to test, check out or calibrate the convection measurement package. These procedures are Acceptance Test, Functional Test, Horizontal Preflight Calibration and Vertical Preflight Calibration, as given in the following paragraphs. For the operation of any of these tests, certain precautions must be taken:

CAUTIONS

1.1 Before each test insert the thermocouple reference junction shorting plugs (p53, p54) and the heater plugs (p55, p56). Remove them after each test except the preflight calibration tests. Record active time in Table A-1.

1.2 Allow 24-hour cooldown time after each heater operation before recycling the operation.

1.3 The heater in the cylindrical cell is "limited life," and its operation should be kept to a minimum.

1.4 Notify NASA-MSFC ES34 (telephone 453-0944) at least 24 hours before the planned operation of the Convection Measurement Package.

1.5 Allow one hour warm-up time before performing any operation.

2.0 Acceptance Test Procedure

Before setting up or operating with this test procedure observe all cautions listed in paragraphs 1.1 through 1.5. The Acceptance Test Procedure is to be used as a final test after all development has been completed or when the unit has been modified.

2.1 Equipment Required

- Convection Measurement Package (CMP)
- Ground Support Equipment (GSE) Test Panel
- Digital Voltmeter
- Variable (28 to 40 Vdc) Power Supply Rated at 6 A.
- Sweep Second Hand Watch
- Ammeter (0 to 6 A).

2.2 Test Set-Up

This is a bench type set-up where none of the other payload units are available for interfacing. Connect the GSE Test Panel to the CMP. Connect the dc Power Supply to the GSE Test Panel. Use the digital voltmeter to measure the output of each channel. Monitor the supply current with the ammeter.

2.3 Operation

2.3.1 Set the power supply to 28 $\pm$0.5 Vdc. Allow one hour for warm-up.

2.3.2 Record the voltage on position 23. It should be 3.5 to 3.9 V.

2.3.3 Select the "Low Calibrate" mode of operation.

2.3.4 Measure each active channel output and record the digital voltmeter readings 1 through 20 on the attached data sheets (Table A-2). These shall be within 200 mV of the previously recorded calibration values. Also, observe that the panel meters are reading approximate values. Vc and Vr will be read 0 until heater regulation occurs, then Vc and Vr will indicate

.25 to 2 V as a function of regulation. Meters labeled T2 and T13 will indicate 0 to 5 V as a function of temperature. Figure A-1 is a plot of temperature versus voltage.

2.3.5 Select the "High Calibrate" mode of operation.

2.3.6 Repeat 2.3.4 above.

2.3.7 Select the "Operate" mode of operation.

2.3.8 Actuate the launch simulate switch and note the time on a sweep second hand.

2.3.9 Record the time interval that it takes for the heaters to come on as noted by an increase in supply current. This time shall be 108 $\pm$10 seconds. Record the supply current.

2.3.10 Monitor the heater temperatures from both cells (T1 and T13), during this period. The rate of rise will vary depending upon orientation but shall not exceed 450°F(5 V) for the cylindrical cell and 205°F (4.1) for the rectangular cell.

2.3.11 Record the time that the heaters turn off. This time shall be 400 $\pm$30 seconds after the heaters come on.

2.3.12 Adjust power supply to 40 $\pm$5 Vdc and record the voltage on position 23. It should be 3.5 to 3.9 V.

2.3.13 Disconnect all shorting plugs.

3.0 Functional Test Procedure

Before setting up or operating with this test procedure observe all cautions listed in paragraphs 1.1 through 1.5. The Functional Test Procedure is to be used on all payload integration tests and after environmental tests have been performed to check that the unit is operating. This test does not include heater operation. The heater test should be added after the last environmental test.

3.1 Equipment Required

Same as Paragraph 2.1.

3.2 Test Set-Up

This can be a bench type set-up where none of the other payload units are available for interfacing or it may be used integrated with the payload and receiving power from the service module. Connect the GSE Test Panel to the CMP. If required connect the dc power supply to the GSE Test Panel. Use the digital voltmeter to measure the output of each channel.

3.3 Operation

3.3.1 Assure that power is within operating range. Position 23 on the rotary switch should indicate 3.5 to 3.9 V. Allow one hour warm-up.

3.3.2 Select the "Low Calibrate" mode of operation.

3.3.3 Select each active channel output and record the digital voltmeter readings. These shall be within 200 mV of the previously recorded calibration values. Also, observe that the panel meters are reading approximate values.

3.3.4 Select the "High Calibration" mode of operation.

3.3.5 Repeat 3.3.3 above.

3.3.6 Disconnect all shorting plugs.

4.0 Horizontal Preflight Calibration Procedure

Before setting up or operating with this test procedure observe all cautions listed in paragraphs 1.1 through 1.5. The Horizontal Preflight Calibration procedure is used when the payload is horizontal and accessible at the launch site. This procedure shall also be used at any time the amplifier settings are required to bring the calibrate values to the original settings.

4.1 Equipment Required

Same as Paragraph 2.1.

4.2 Test Set-Up

This procedure will normally be performed when the CMP is mechanically attached to the payload but accessible for electrically disconnecting. Connect the GSE Test Panel to the CMP. Connect the Power Supply to the GSE Test Panel and use the digital voltmeter to measure the output of each channel.

4.3 Operation

4.3.1 Set the power supply to 28 ±0.5 Vdc. Allow one hour for warm-up.

4.3.2 Select the "Low Calibrate" mode of operation.

4.3.3 Adjust the amplifier zero control of amplifier number one until the digital voltmeter reads the original calibration setting ±10 mV.

4.3.4 Select the "High Calibrate" mode of operation.

4.3.5 Adjust the amplifier range control of amplifier number one until the digital voltmeter reads the original calibration setting ±10 mV.

4.3.6 Repeat paragraph 4.3.2 through 4.3.5 until amplifier number one is within tolerance without further adjustment.

4.3.7 Repeat paragraphs 4.3.2 through 4.3.6 until all active channels are adjusted.

4.3.8 Disconnect all shorting plugs.

5.0 Vertical Preflight Calibration Procedure

Before setting up or operating with this test procedure observe all cautions listed in paragraphs 1.1 through 1.5. The Vertical Preflight Calibration Procedure is to be used when the payload is mounted vertically atop the launch vehicle and ready for launch. Its purpose is primarily to record the calibration signals through the telemetry system and therefore shall be performed shortly before launch. This procedure can also be followed at times when payload integration tests require the check out through the telemetry system.

5.1 Equipment Required

- Integrated Payload
- GSE Test Panel
- Telemetry Ground Station

5.2 Test Set-Up

This procedure will normally be performed when the CMP is installed on the payload and electrically accessible through the umbilical connection only. Connect the GSE Test Panel to the umbilical connector. Activate the on-board and ground telemetry system.

5.3 Operation

5.3.1 Select the "Low Calibration" mode.

5.3.2 Record these data on the telemetry ground station.

5.3.3 Select the "High Calibration" mode.

5.3.4 Record these data on the telemetry ground station.

5.3.5 Select the operate mode.

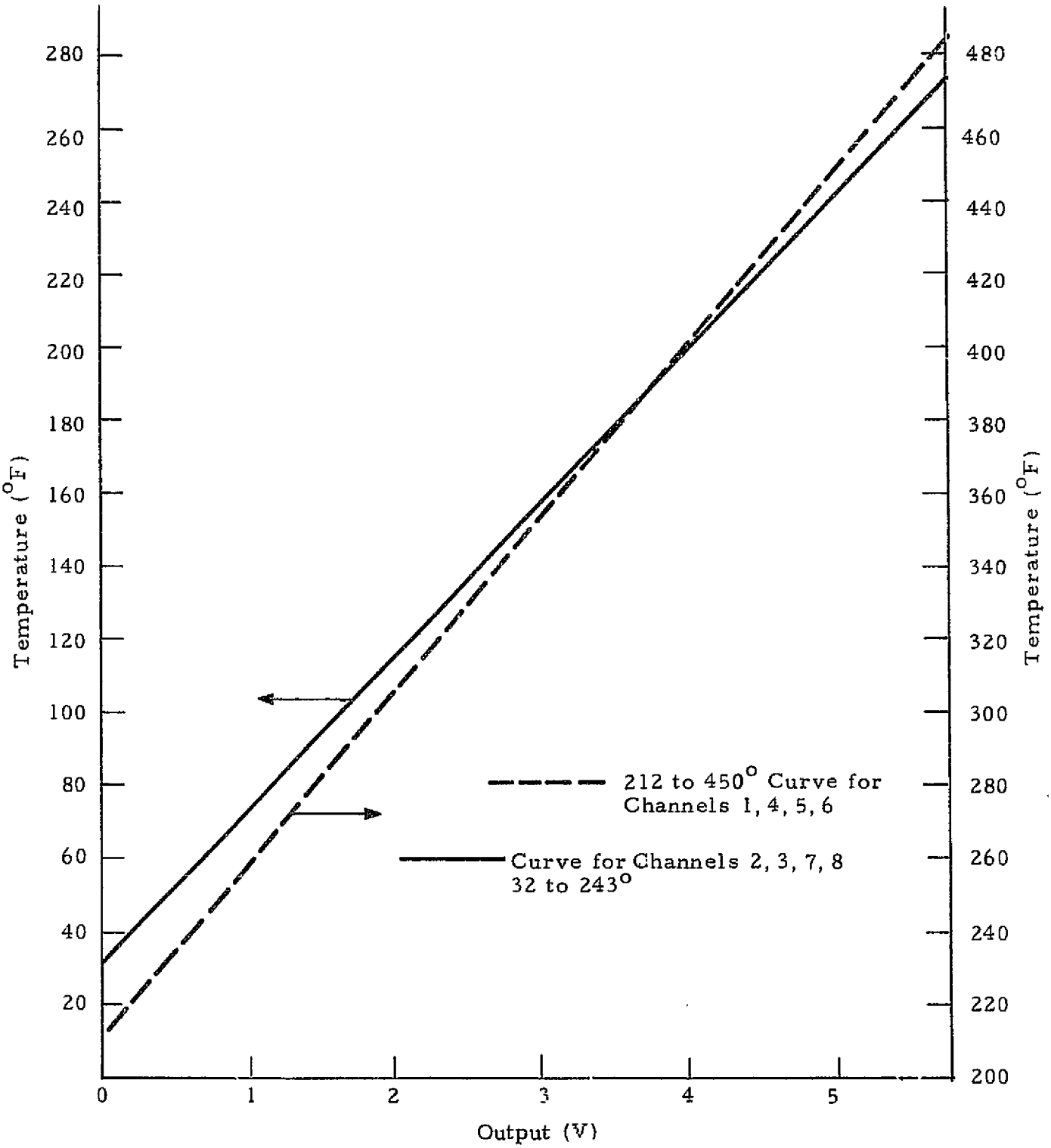

Fig. A-1 - CMP Conversion Chart

Table A-1

ACCUMULATIVE TEST TIME THERMOCOUPLE REFERENCE JUNCTIONS

Test Personnel	Time On	Date	Time Off	Date	Active Time	Total Time

Table A-2

CONVECTION MEASUREMENT PACKAGE

	Date_____ by:_____		Date_____ by:_____		Date_____ by:_____		Date_____ by:_____	
Ch. No.	Cal. Low	Cal. High	Cal. Low	Cal. High	Cal. Low	Cal. High	Cal. Low	Cal. High
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14								
15								
16								
17								
18								
19								
20								
Monitor								
21								
22								
23								