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THE GEOS-II HEAT PIPE SYSTEM AND ITS PERFORMANCE IN TEST AND IN ORBIT

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ACKNOWLEDGEMENT

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ABSTRACT

The GEOS-II spacecraft is the first satellite to be equipped with a heat pipe as an integral part of the thermal design. The heat pipe, a device of extremely high effective thermal conductivity, is employed to minimize the temperature differences between transponders located in opposite quadrants of the spacecraft. Measured heat transfer rates through the pipe of as much as 64 watts, together with small temperature gradients on the outside of the heat pipe, are evidence of proper operation. Based on a period of observation of 60 days, transponder maximum and minimum temperatures show improvement over GEOS-I performance.

1.0 INTRODUCTION

The GEOS-II spacecraft is the first satellite to have a heat pipe incorporated as an integral part of the thermal design. The heat pipe, a device of extremely high effective thermal conductivity, was invented by Gaugler.[7] Later, Grover applied the device to special power-generating systems,[1] and Cotter gave a theoretical explanation of its operation.[2] Recently, Deverall and his associates designed an experimental heat pipe module which was orbited on the Atlas-Agena vehicle used for the ATS-A satellite. The results of this experiment indicated that the absence of gravitational forces does not affect the performance of a heat pipe.[3]

At the Applied Physics Laboratory, a program to develop a heat pipe for spacecraft temperature control has been in progress for several years. When it became apparent, during the early design stages of the GEOS-II effort, that large temperature differences could exist among the various transponders, it was decided to connect the transponders by two heat pipes to minimize these temperature differences. This report describes the design of the GEOS-II heat pipe system and its performance during test and in orbit.

2.0 SYSTEM DESCRIPTION

2.1 Heat Pipes

Two heat pipes, identical in function and differing only in length, were fabricated and installed. As shown in Figure 1, the heat pipe consists of a section of 1 inch O.D. x .065 inch wall 6061 T-6 aluminum tubing which is sealed at the ends by welded caps. A wick structure consisting of an annulus of 6 layers of 120 mesh aluminum wire cloth is in contact with the inside diameter of the tubing. The heat pipe is evacuated by a vacuum pump and charged with slightly more than enough freon-11 to wet the wick. Freon-11 was chosen for the working fluid because of its low freezing point and because its non-flammable characteristic made it safe to use in a welded structure. A further advantage was its low pressure at the expected operating temperature range. After charging, the pipe is hermetically sealed. A double seal welded closure is used to insure the integrity of the pipe. This operation is the most critical of all during the fabrication process. Any leakage path, however small, will ultimately result in leakage of all the working fluid from the heat pipe in the hard vacuum conditions to which it is subjected.

In operation, heat enters one end of the heat pipe and vaporizes some of the fluid. The freon vapor travels to the cooler end of the pipe where it condenses. The condensed fluid is returned to the hot or evaporator end of the heat pipe by the capillary action of the wick. The result of this closed cycle operation is that large amounts of heat can be transmitted with a very small axial temperature gradient along the outer surface of the isothermal section of the heat pipe.

2.2 General Arrangement

Figure 2 shows the arrangement of the components of the system. The heat pipes, shown in dotted lines, are arranged in a horizontal plane parallel to the XY plane and below the library floor. (The arrangement of the heat pipes in a horizontal plane allows the system to be tested in a 1-g environment.) The short heat pipe connects the SECOR with the C-Band transponders, while the long heat pipe connects the C-Band with the Range and Range Rate transponders.

2.3 Conduction Heat Transfer Paths

Because of a design requirement of keeping GEOS-II as nearly similar to GEOS-I as possible, it was necessary to use long conduction heat transfer paths to transfer heat to and from the heat pipes. These conduction paths represent the greatest portion of the overall thermal resistance of the system. The design approach is illustrated schematically in Figure 3. A one-half inch thick heat sink plate of aluminum alloy 2024 is mounted to the library wall. The transponder is in turn mounted to the heat sink plate. A thin film of insulation was used between the transponder and heat sink plate to provide electrical insulation for the transponder. This insulation increased the thermal resistance slightly. Bolted to the heat sink plate near the bottom is a clamp assembly which holds the heat pipe for a distance of five inches. Indium foil is used to insure good thermal contact between the heat pipe and the clamp and between the clamp and the heat sink plate. The transponder, clamp assembly and heat pipe are then covered with a multi-layer reflective type insulation.

As shown by the figure, heat generated in the transponder must either be radiated to other parts of the spacecraft or may be transferred by conduction to the heat sink plate. A part of the energy reaching the heat sink plate is transmitted to the library wall by conduction, a part is radiated to other parts of the spacecraft and the rest is transferred by conduction to the heat pipe via the clamp assembly.

2.4 Instrumentation

Six telemetry channels were allocated specifically for the heat pipes. Four of these channels were used for temperature measurements along the length of the long heat pipe, and one was used for a temperature measurement midway between the extremities of the short heat pipe. Calibrated thermistors were used as the temperature sensors.

The remaining telemetry channel was used for a heat flux measurement. The sensor used for this purpose was a thermopile manufactured by Hy/Cal Engineering and having a rated output of 100 mv at 500 Btu/hr ft^2 thermal input. The sensor is rectangular in shape, being approximately $2\frac{1}{4}$" x $\frac{1}{2}$" x .080" thick. A slot was milled into the flange of the

Range and Range Rate clamp assembly to receive the component. Again, Indium foil was used to obtain good thermal contact. The output of the thermopile was connected to a specially-designed amplifier[4] to insure that the telemetered data would not be lost in the noise. The flux sensor/amplifier system was bench-calibrated as a unit by supplying a known amount of electrical power to a cylindrical heating element held by the clamp assembly. The heat was removed through that area of the heat sink plate which is in contact with the Range and Range Rate transponder. The output of the amplifier was read on a digital voltmeter and a plot of heat flux versus amplifier output was made to obtain the calibration.

3.0 PERFORMANCE

3.1 Bench Tests

Bench tests were conducted using the equipment illustrated schematically in Figure 4. The major units of test equipment are the refrigeration unit, cooling tank and a 24 point temperature recorder. An absolute pressure transducer, together with a wheatstone bridge and voltmeter is used to measure vapor pressure. Copper-constantan thermocouples, affixed to the exterior of the heat pipe, were used to sense temperature. The condenser end of the heat pipe protrudes through a seal in the cooling tank wall while the evaporator end of the heat pipe is heated by means of a concentric heating element. The heat pipe is completely insulated with the exception of the condenser.

The refrigerator unit is equipped with a compressor which circulates a constant flow of refrigerant through two evaporators. The main evaporator is located in the cooling tank, and the auxiliary evaporator is located in the cabinet. A sensing bulb and bellows assembly are used to control the temperature of the coolant in the tank. When the temperature reaches the control setting a solenoid valve is energized, diverting the refrigerant from the main to the auxiliary evaporator. The cooling tank is filled with mixture of water and antifreeze.

After the start-up transients are over, the heat pipe exhibits a steady-state behavior wherein the section of the pipe between the condenser and evaporator is nearly isothermal. This temperature can be varied by changing the power level, changing the cooling bath temperature or by changing the evaporator or condenser areas. Conditions may also be changed by not fully evacuating the pipe prior to charging with the heat pipe fluid or as a result of a leak which allows the fluid to escape or air to flow into the heat pipe. Figure 5 shows the mean heat pipe temperature as a function of input power level. The mean temperature is seen to increase linearly with power level. The effect of bath temperature is also shown. For the conditions of the experiment, a change of bath temperature of $6\frac{1}{2}$°F resulted in a mean heat pipe temperature difference of about 6°F.

Figure 8 shows the hang-up case with all transponders on. It is noted that the maximum amount of heat was transmitted in this case and that a maximum temperature difference of 57.4°F between the SECOR and the Range and Range Rate transponders occurred.

A series of tests was also conducted to show the effect of heat pipe failure on the thermal performance. To accomplish this, the spacecraft was tilted 10° about the X axis to defeat the action of the heat pipe. The tests were conducted in such a manner that the C-Band transponders were always hotter than the Range and Range Rate transponder. The C-Band transponders were at a higher elevation than the Range and Range Rate transponder, and the capillary pumping action was insufficient to overcome the gravity head. The heat pipe fluid therefore collected in the lower end, and all heat transferred by the pipe was by conduction through the wick and tubing.

Figure 9 shows the temperature gradient along the long heat pipe while in the tilted configuration. At 0521 the temperature difference between the sensors farthest apart was about 30°F. At this time the Range and Range Rate transponder was interrogated causing heat to flow in the opposite direction. In this case, gravity aided the return of the condensed fluid. The temperature profiles taken at 0615, 0732, 0900 and 1103 show the rate at which the initial large temperature gradient was reversed as the heat pipe attained steady state. It is interesting to note that the measured heat flux increased from an initial value of 14.8 watts to 75.5 watts at 1103. This resulted from the fact that, initially the freon vapor condenses very close to the Range and Range Rate clamp. As the outside of the heat pipe is warmed by this condensation, the vapor travels farther and farther before the slight vapor superheat is removed and condensation occurs. As a result, more of the fluid near the Range and Range Rate end of the pipe, which had flooded this (evaporator) portion of the pipe, vaporizes. The evaporator area is therefore increased and the heat transfer rate is improved until, finally, normal operation is restored.

3.2 Thermal Vacuum Tests

The GEOS-II spacecraft was subjected to three basic types of thermal vacuum tests: maximum Q, corresponding to the hottest expected conditions to which the satellite would be exposed; minimum sun, corresponding to the coldest expected conditions; and hang-up, which simulates the maximum expected thermal gradients across the satellite. The maximum Q case occurs 10 days after transition from less than 100% sunlight exposure to 100% sunlight. The solar constant, albedo and power generated by the solar array were assumed to be maximum for this case. The minimum sun case simulates the resultant solar exposure when the orbit normal is perpendicular to the earth-sun line. The solar constant, albedo and power generated by the solar array were assumed to be minimum for this case. In the hang-up case, the orbit normal is parallel to the earth-sun line, and the same side of the satellite is always facing the sun.

Figures 6, 7 and 8 show heat pipe system performance during thermal vacuum testing of the three cases. It is to be noted that the modes of satellite operation are slightly different: All three transponders were on for the hang-up case, while only the SECOR was on for the minimum sun and maximum Q cases presented in Figures 6 and 7. The small temperature gradients along the outside surface of the long heat pipe are evidence of proper operation.

In Figure 6, heat is seen to flow toward the C-Band transponders from both the Range and Range Rate and SECOR transponders. The temperatures of the transponders and heat pipes are relatively low as a result of the simulated low exposure to sunlight. The SECOR temperature is largest owing to the fact that this component was energized and was therefore generating heat.

Figure 7 shows the results for the maximum Q case, again with only the SECOR energized. The transponder temperatures are seen to be the maximum of the three cases. In this test, heat was transferred from the SECOR through the short heat pipe to the C-Band transponders and thence through the long heat pipe to the Range and Range Rate transponder. A total of 18.1 watts of heat flux was measured by the flux sensor.

3.3 Performance in Orbit

As mentioned previously, the purpose of the heat pipe system is to minimize the temperature differences among the transponders. Although the temperature difference may be made smaller by energizing the coldest transponder or by not energizing the hottest transponder, such a scheme imposes a constraint on satellite operations. Further, it is even possible that the transponder might get so cold that it could not be operated. For these reasons the heat pipe system was installed on the spacecraft.

Table I provides a comparison of the extreme temperatures and temperature differences between the SECOR and Range and Range Rate transponders covering the latter part of 1965 and all of 1966 for GEOS-I and for the 60 day period between days 16 through 75 1968 for GEOS-II (The C-Band transponders were not included in this comparison since GEOS-I was not equipped with them.) Based upon this limited sample size for GEOS-II, considerable improvement is noted in all respects.

Table I: Comparison of Transponder Temperature Extremes

	SECOR Temp. °F		R/RR Temp. °F		Maximum ΔT, °F	
	Max.	Min.	Max.	Min.	SECOR-R/RR	R/RR-SECOR
GEOS-I	110	6	138	12	65	95
GEOS-II	83	34	79	37	36	38

Of particular note is the large maximum temperature of the GEOS-I Range and Range Rate transponder of 138°F and the maximum temperature difference of 95°F. These data points were taken during January 1966. It is noted that calculations made for GEOS-IIpredicted a maximum temperature difference of 92°F without the heat pipe system and 32°F with the system.[5] Tests subsequently showed that the thermal resistance of the clamp assemblies was somewhat higher than that used in the calculations and that, hence, the maximum temperature difference would exceed the 32°F value, as has already happened.

The effect of the heat pipe system on reducing the maximum temperature among the transponders may also be seen in Figures 10 and 11. Figure 10 shows the mean maximum temperature difference, averaged daily, as a function of time. The trend is shown by the dotted line and is seen to be slowly rising. This trend is believed to be caused by more frequent transponder operation and the environmental conditions. The environmental conditions for most of the time period shown closely approximate the maximum Q case of the thermal vacuum test.[6]

Figure 11 shows the daily difference between the mean temperatures of the long and short heat pipes. The mean was calculated to be +0.4°F with a standard deviation of 3.5°F. Good agreement is shown with Figure 10 since the mean temperature of a heat pipe lies somewhere between the temperatures of the transponders which it connects. Inasmuch as the axial temperature gradient along a heat pipe is small, this figure also shows that the clamps represent the largest thermal resistance in the system.

Figures 12 and 13 show the performance of the heat pipe system in orbit. These sets of data were selected because they represent the greatest measured heat transfer rates during the period of observation. In Figure 12, all three transponders were energized and a total of 43.5 watts was measured at the flux sensor. A temperature gradient of 1.7°F was measured between the two most remote thermistors on the long heat pipe while the maximum transponder temperature difference was 26.9°F.

Figure 13 illustrates a case where the heat flow is in the opposite direction, from the Range and Range Rate transponder toward the C-Band transponders. As shown, a power level of 64.0 watts was measured by the flux sensor with a temperature gradient of 3.5°F being measured between the most remote thermistors on the long heat pipe. The maximum transponder temperature difference is seen to be 25.3°F.

It was shown previously in Section 3.2 that the heat pipe can act to reverse a temperature gradient on the outside of the heat pipe and parallel to its axis which is opposite to the direction of heat flow within the pipe. In orbit, such a condition occurs when the spacecraft orientation with respect to the sun changes radically or whenever a colder transponder is energized. Figure 14 is an example of such a gradient reversal. As a result of the C-Band transponders being hotter than the Range and Range Rate transponder, an initial gradient of 1.9°F existed between the two most remote thermistors. The Range and Range Rate transponder was then energized, causing the external heat pipe temperature gradient to reverse. Approximately 18.8 watts were being transmitted through the pipe when the last data were obtained.

4.0 CONCLUSIONS

1. During the period of observation, both heat pipes exhibited normal performance.
2. Heat fluxes of as much as 64 watts have been transmitted.
3. The range between the maximum and minimum transponder temperatures for the 60 day period of GEOS-B observations has been considerably smaller than the range observed for GEOS-A over a much longer period. Further observation of GEOS-B is required before a firmer conclusion may be drawn.
4. Reversal of the external heat pipe axial temperature gradient has been observed both in thermal vacuum tests and during orbit.
5. The mean difference between the heat pipe temperatures has been shown to be small during the period of observation. As a result, it is concluded that system performance has not been biased either by spacecraft attitude or by operation of the transponders.

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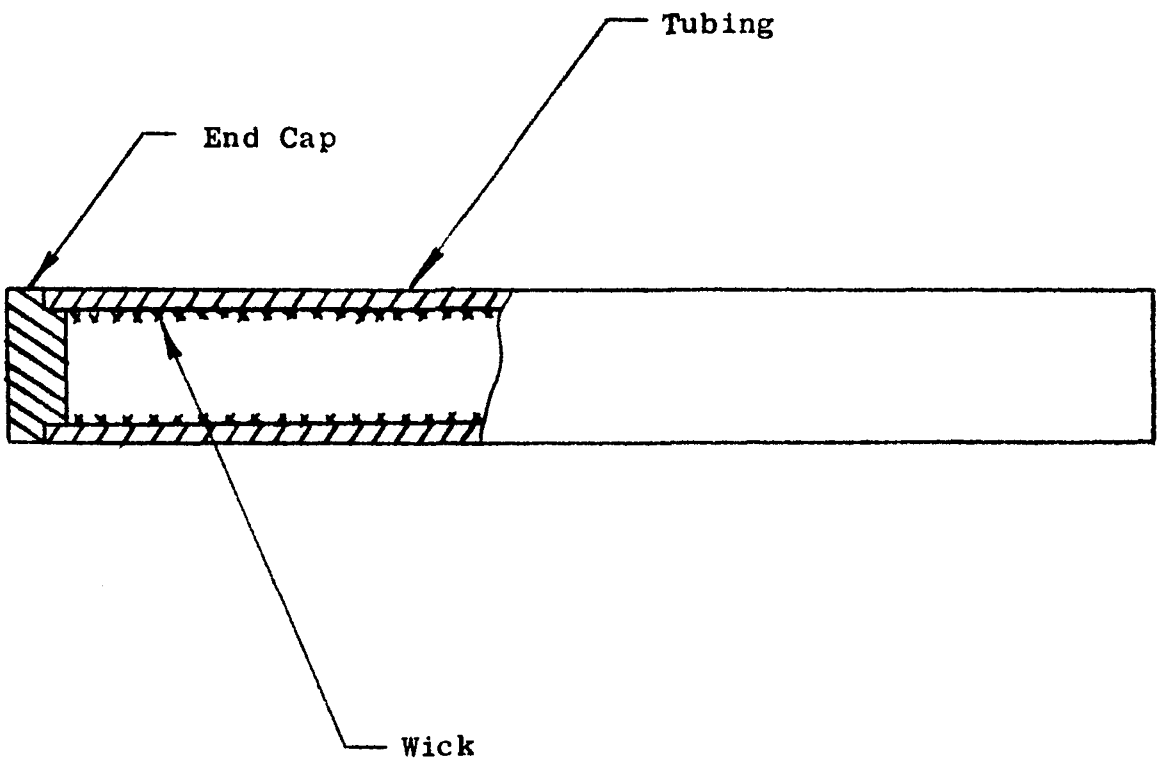


FIGURE 1. Heat Pipe Schematic

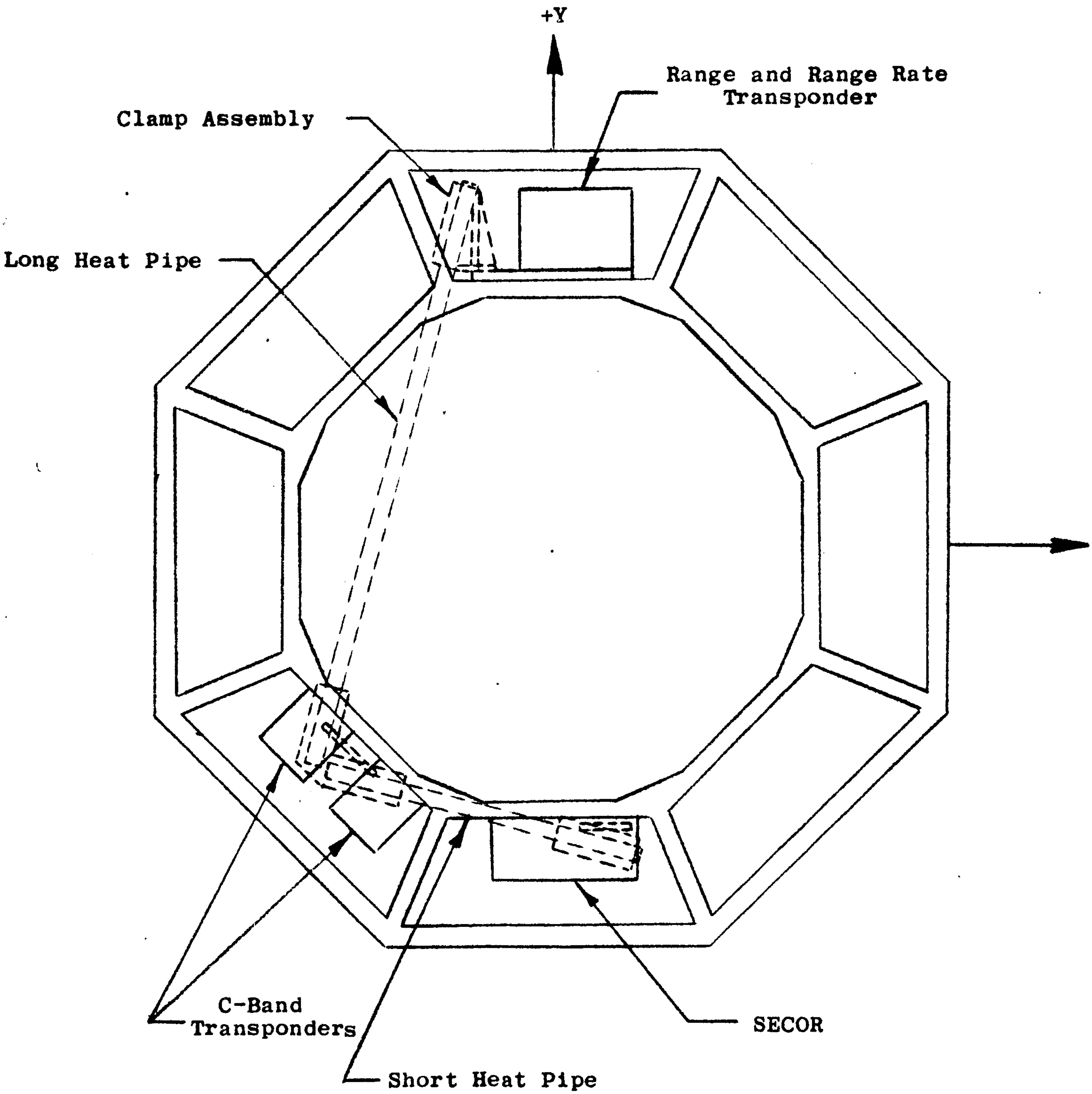


FIGURE 2. General Arrangement of Heat Pipe System

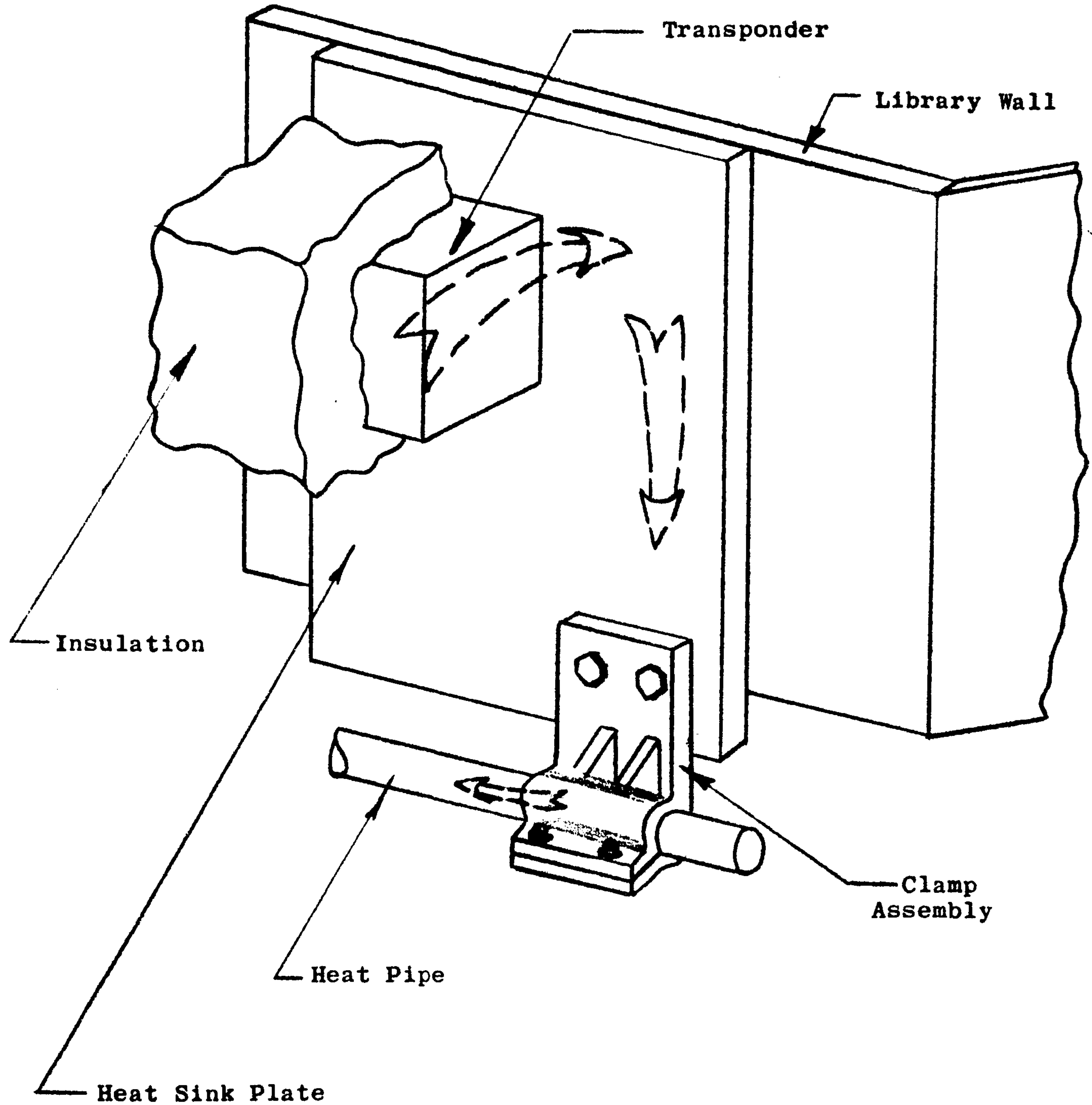


FIGURE 3. Conduction Heat Transfer Paths

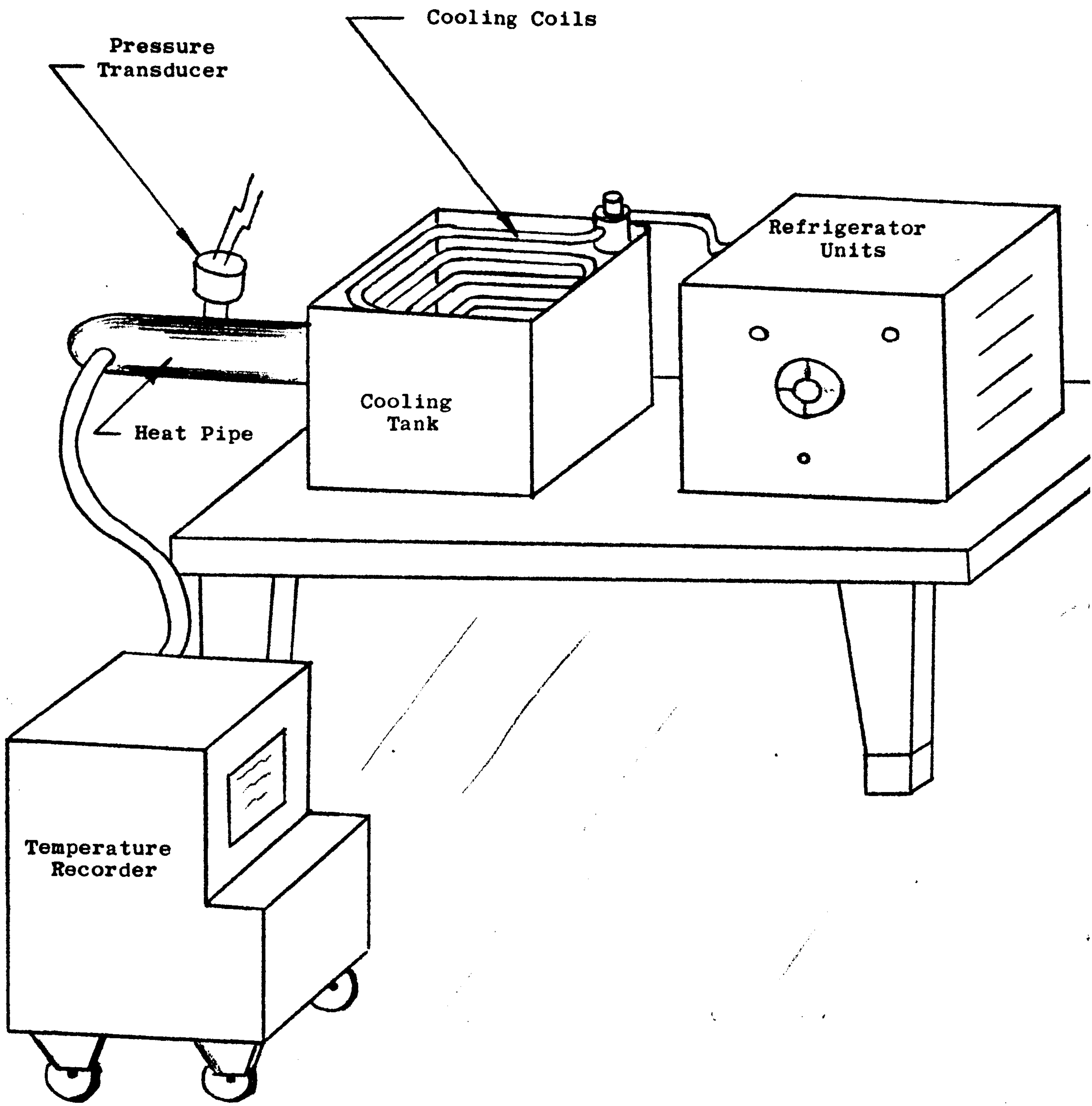
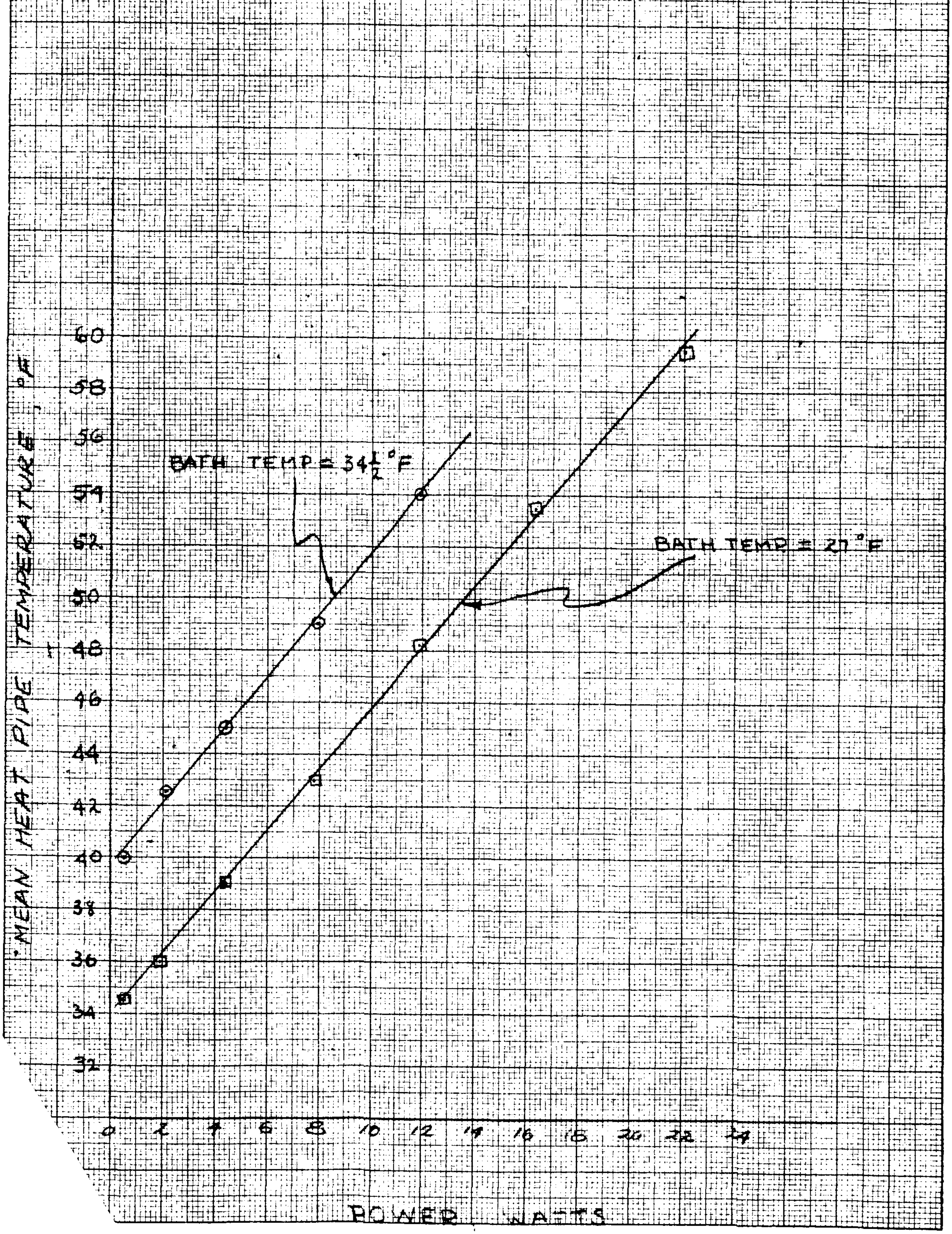


FIGURE 4. Bench Test Arrangement

FIGURE 5. Mean Heat Pipe Temperature as a Function of Input Power Level



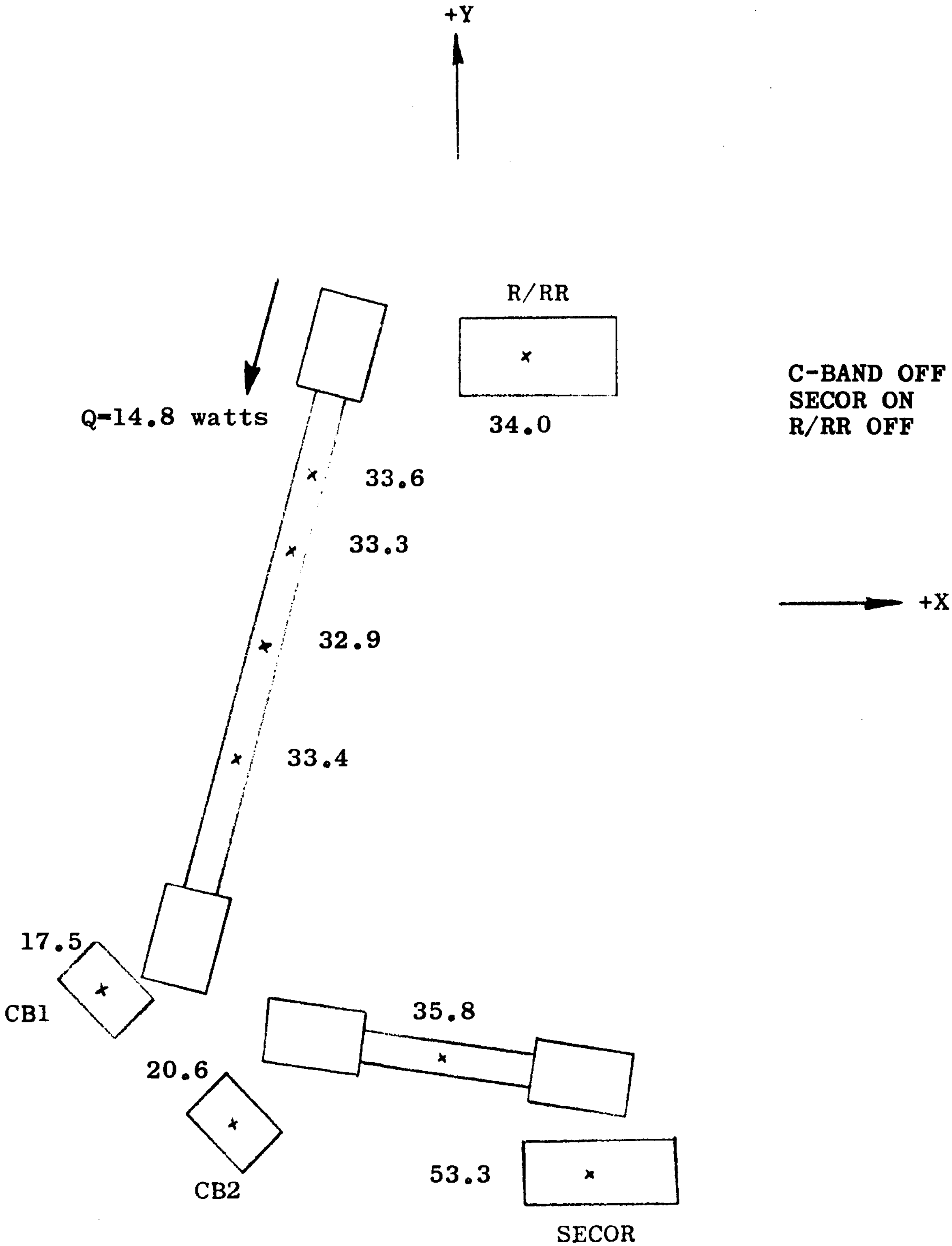


FIGURE 6. Heat Pipe System Performance during Thermal Vacuum Tests--Minimum Sun Case

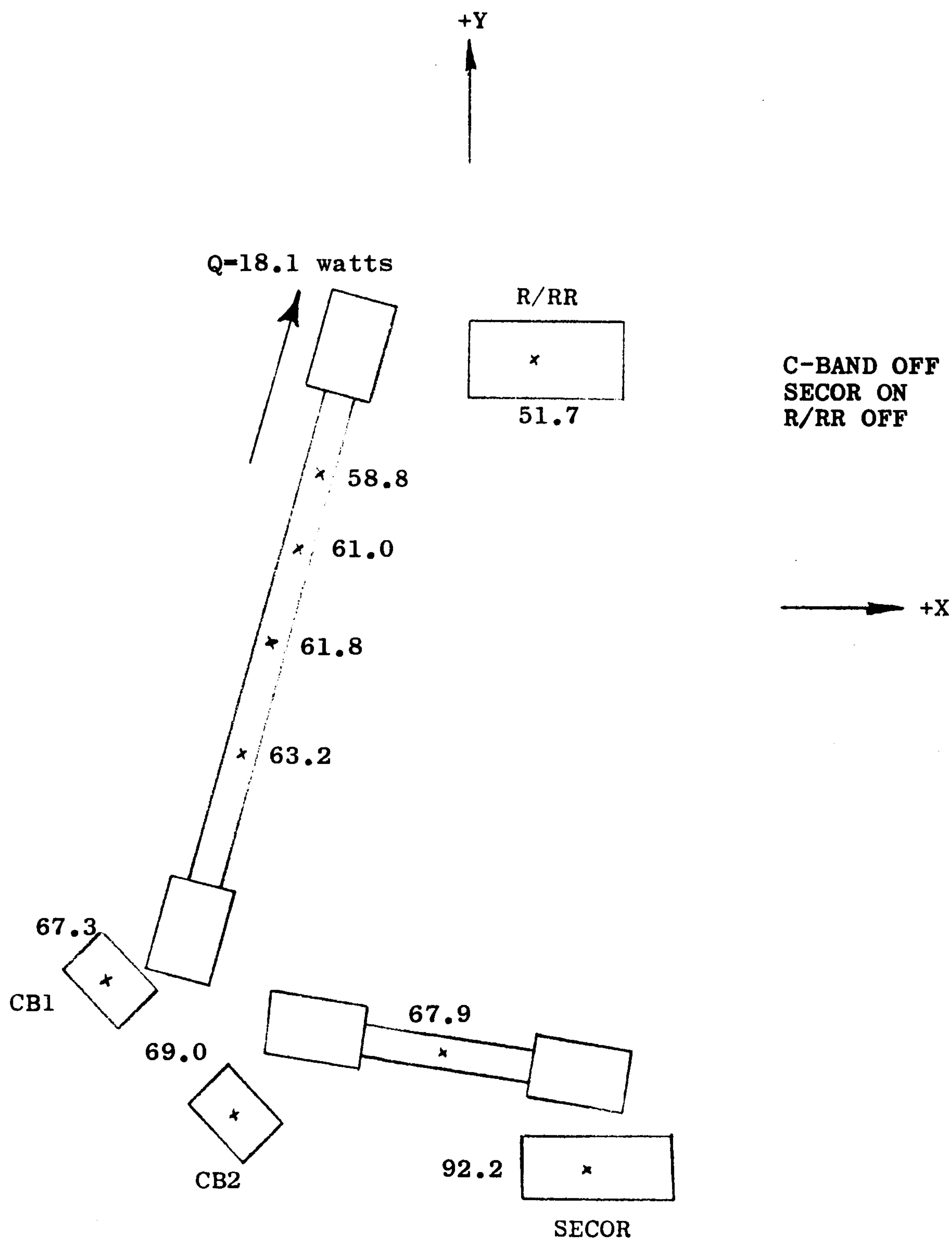


FIGURE 7. Heat Pipe System Performance during Thermal Vacuum Tests--Maximum Q Case

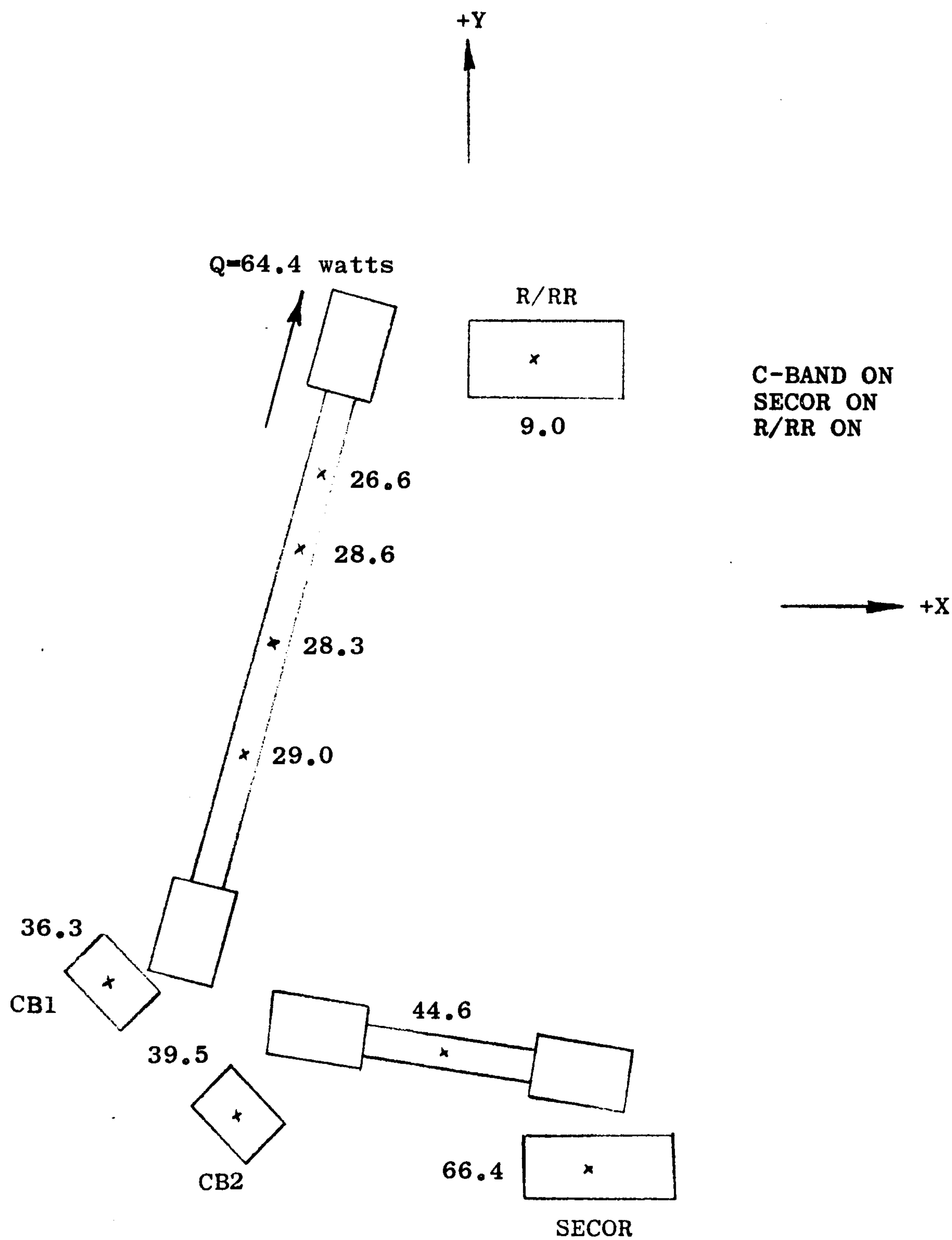


FIGURE 8. Heat Pipe System Performance during Thermal Vacuum Tests--Hang-up Case

FIGURE 9. Temperature Gradient Reversal during Thermal Vacuum Testing

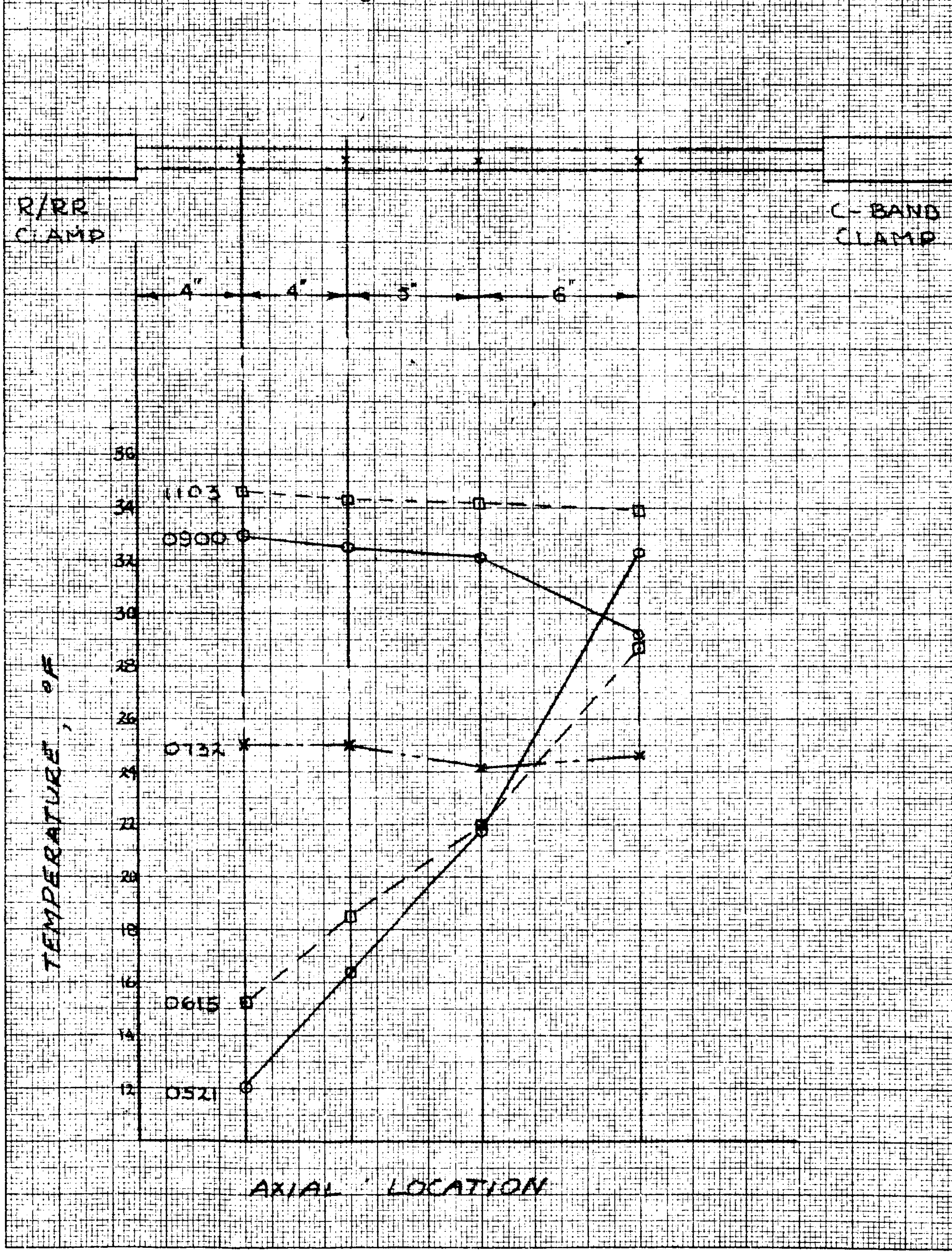
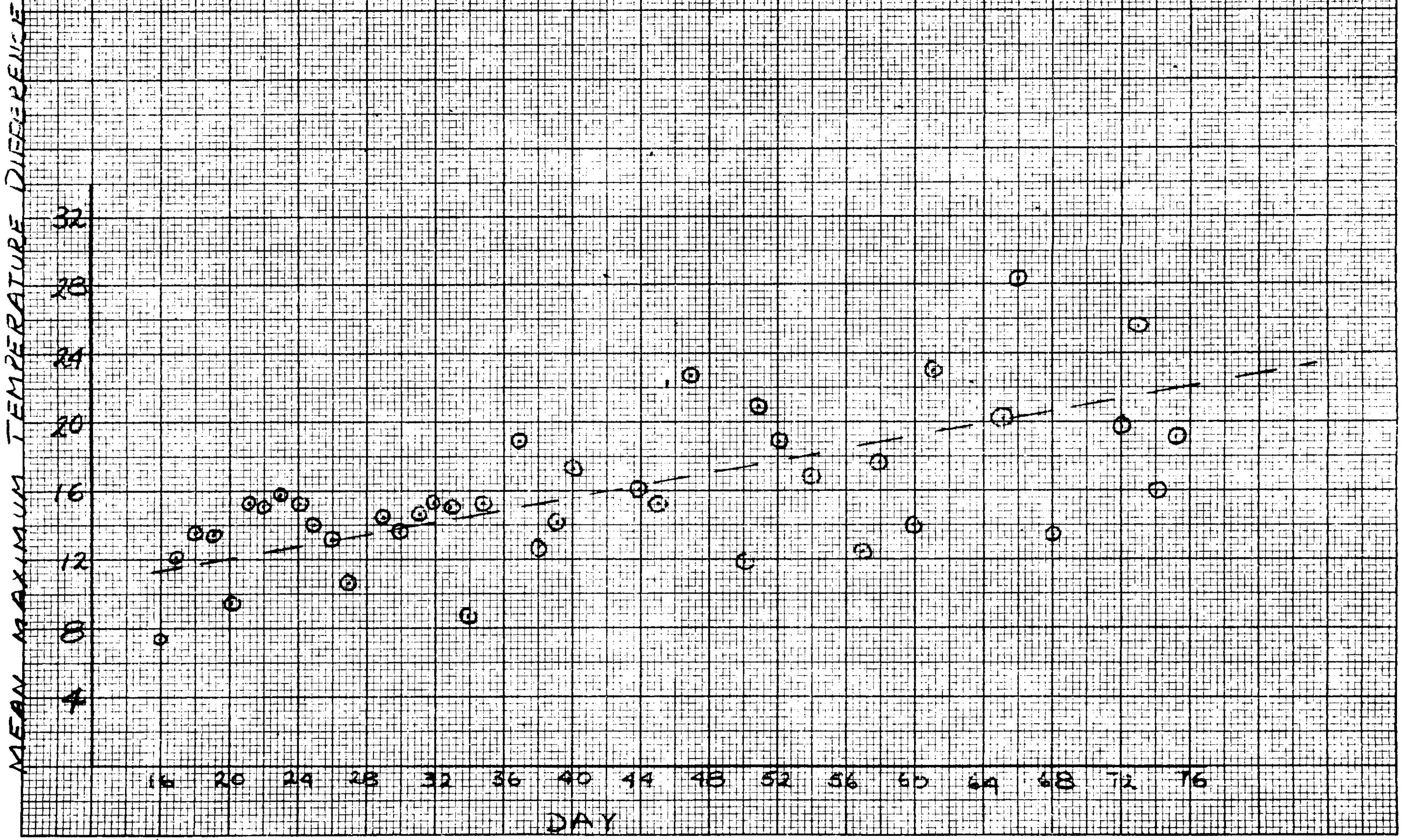


FIGURE 10. Mean Maximum Transponder Temperature Difference as a Function of Time



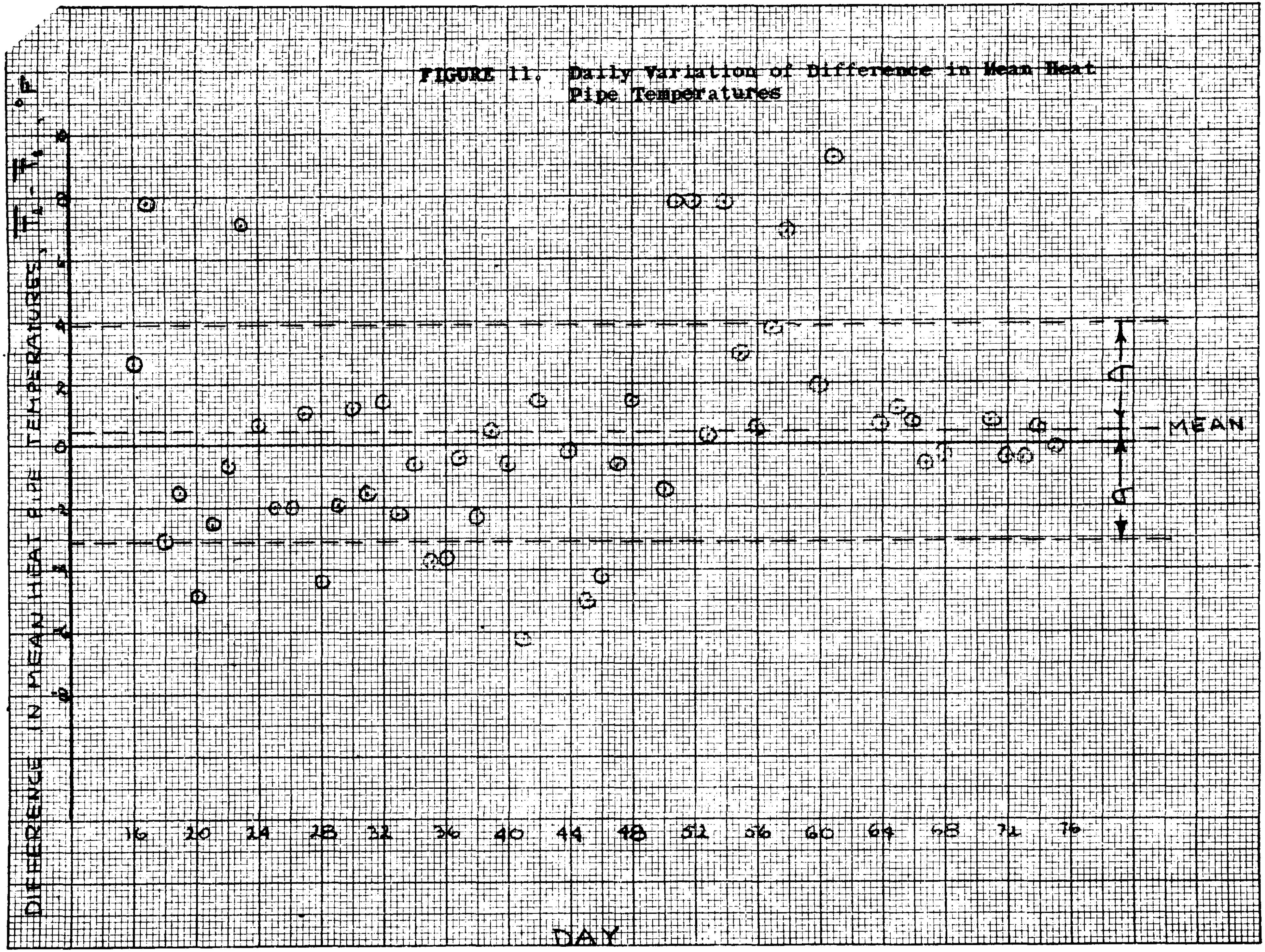


FIGURE 11. Daily Variation of Difference in Mean Heat Pipe Temperatures

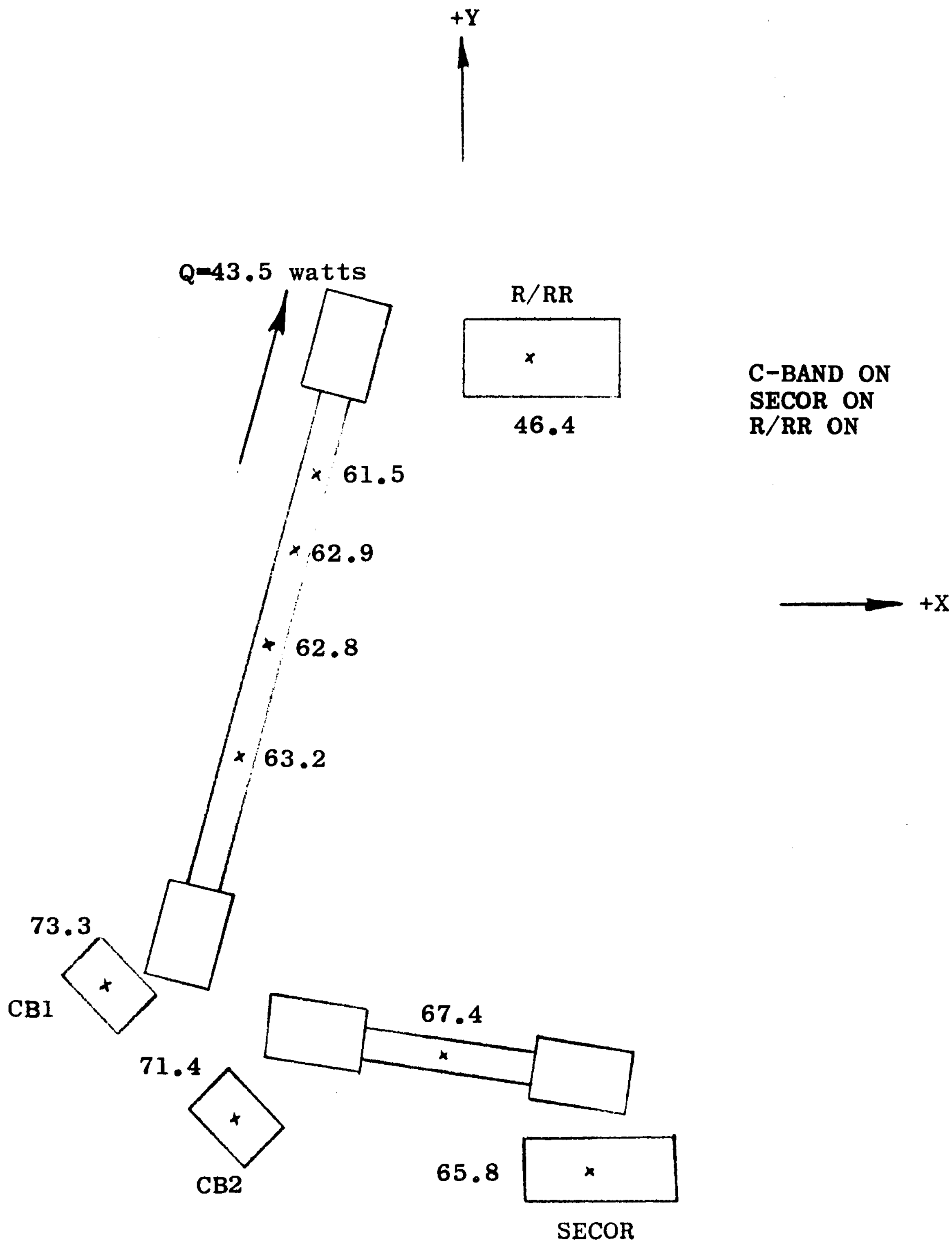


FIGURE 12. Performance of Heat Pipe System in Orbit, Day 40 at 1243

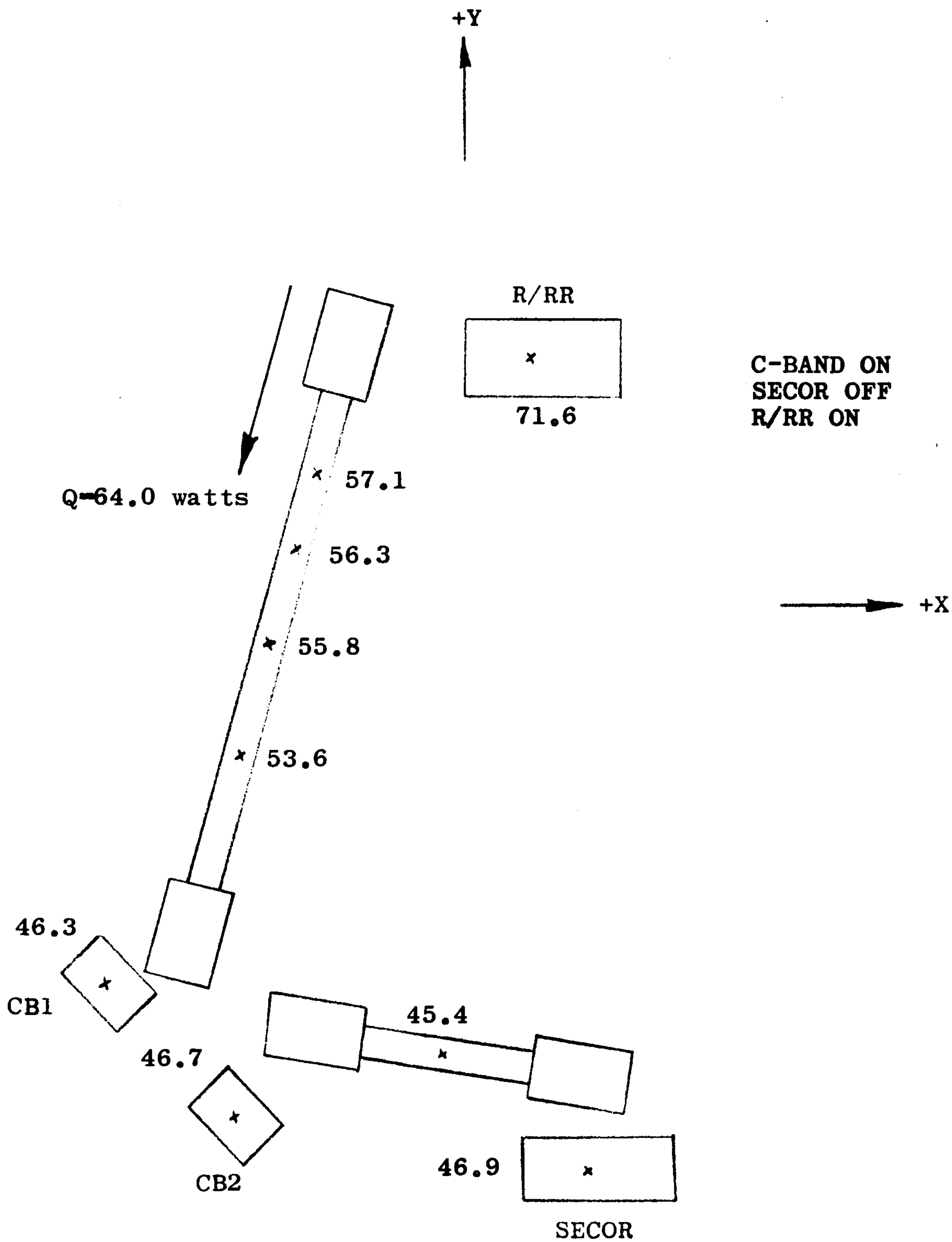


FIGURE 13. Performance of Heat Pipe System in Orbit, Day 51 at 0056

FIGURE 14. Temperature Gradient Reversal in Orbit