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 145-day observation period, transponder maximum and minimum temperatures show significant improvement over those of GEOS-I.

Performance of the GEOS-II

The heat pipe, a device of extremely high effective thermal conductivity, was invented by Gaugler.[1] Later, Wyatt[2] and Grover[3] patented applications of the generic device, and Cotter[4] gave a theoretical explanation of its operation. Recently, Deverall and his associates designed an experimental heat pipe module that 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.[5]

A program to develop a heat pipe for spacecraft temperature control has been in progress for several years at the Applied Physics Laboratory. When it became apparent during the early design stages of GEOS-II 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. The GEOS-II spacecraft, which was launched on January 11, 1968, is the first satellite to have a heat pipe incorporated as an integral part of the thermal design. This report describes the design of the heat pipe system and its performance during test and in orbit.

System Description

Heat Pipes—Two heat pipes, identical in function and differing only in length, were fabricated and installed. As shown in Fig. 1, the heat pipe consists of a section of aluminum alloy 6061 T-6 tubing (1 inch OD and 0.065 inch wall) that is sealed at the ends by welded caps. A wick structure consisting of an annulus of six layers of 120-mesh aluminum wire cloth is in contact with the inside diameter of the tubing. The heat pipe is evacuated 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 nonflammable 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 by a double seal welded closure 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.

During 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,

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[1] R. S. Gaugler, "Heat Transfer Device," U.S. Patent No. 2,350,348, issued June 6, 1944.

[2] T. Wyatt, "Satellite Temperature Stabilization System," U.S. Patent No. 3,152,774, issued October 13, 1964.

[3] G. M. Grover, "Pancake Reactor," U.S. Patent No. 3,243,613, issued March 29, 1966.

[4] T. P. Cotter, *Theory of Heat Pipes,* Los Alamos Scientific Laboratory Report LA-3246-MS, March 1965.

[5] J. E. Deverall, E. W. Salmi, and R. J. Knapp, "Heat Pipe Performance in a Zero Gravity Field," *J. Spacecraft and Rockets* 4, November 1967, 1556-1557.

R. E. Harkness

Heat Pipe System

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 heat pipe.

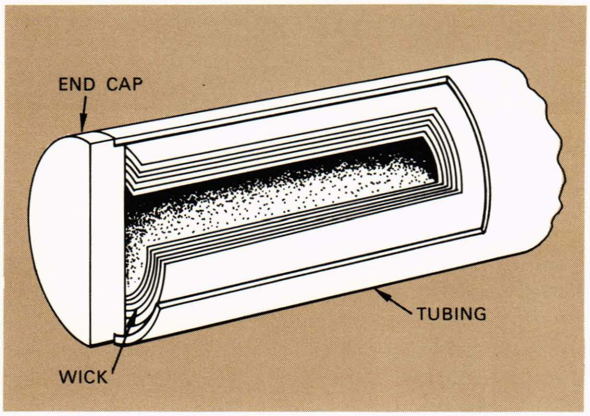

Fig. 1—Schematic of heat pipe.

General Arrangement—Figure 2 shows the arrangement of the components of the system. The satellite electronics are packaged in rectangular parallelopipeds called "books." The collection of books is known as the library and is supported by a floor and surrounded by a reinforced wall of sheet aluminum. The heat pipes, shown by dashed 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 1g environment.) The short heat pipe connects the SECOR (sequential collation of range) unit with the C-band transponders, and the long heat pipe connects the C-band transponders with the range and range rate (R/RR) transponder.

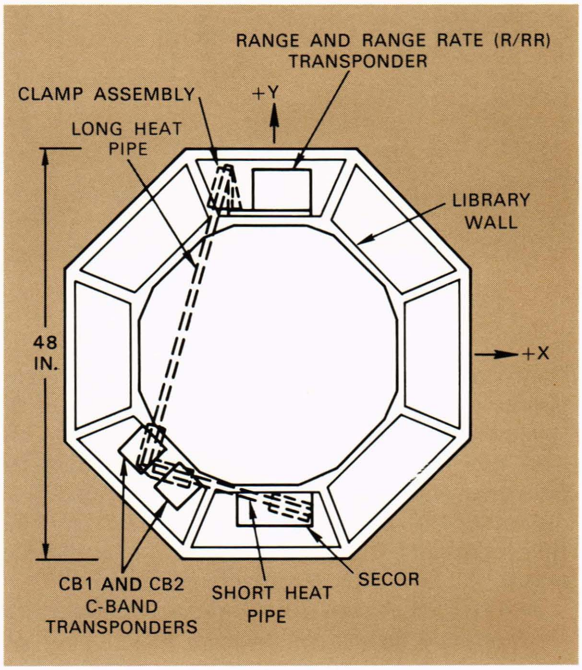

Fig. 2—General arrangement of heat pipe system.

Conduction Heat Transfer Paths—Because of a design requirement to keep GEOS-II as similar to GEOS-I as possible, it was necessary to use long conduction heat transfer paths 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 Fig. 3. A 0.5-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 insulating film between the transponder and the heat sink plate provides electrical insulation, which slightly increases the thermal resistance. A clamp assembly, bolted near the bottom of the heat sink plate, holds the heat pipe for a distance of 5 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 covered with a multilayer, reflective-type insulation. As

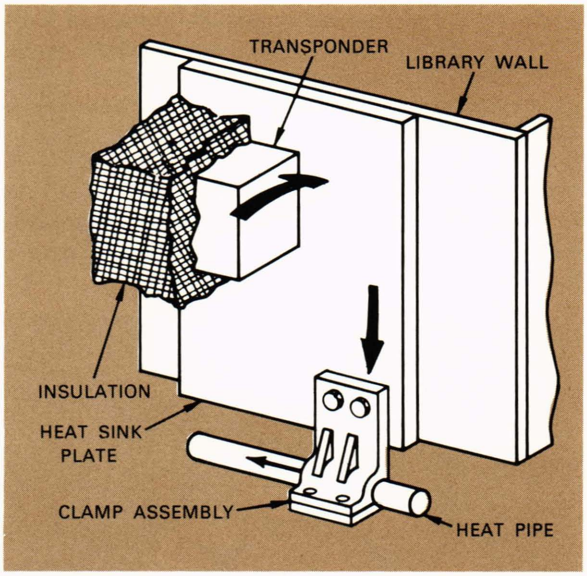

Fig. 3—Conduction heat transfer paths.

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

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 in this case was a thermopile manufactured by Hy-Cal Engineering Co. that had a rated output of 100 mV at 500 Btu/hr ft^2 thermal input. The sensor is rectangular, approximately 2.25 in. x 0.5 in. x 0.080 in. thick. The output of the thermopile was connected to a specially designed amplifier to ensure that the telemetry signal would be adequate in amplitude. The flux sensor/amplifier system was bench-calibrated as a unit. A known amount of electrical power was supplied to a cylindrical heating element held by the clamp assembly, and the heat was removed through that area of the heat sink plate that was in contact with the transponder. The output of the amplifier was read on a digital voltmeter, and heat flux was plotted versus amplifier output to obtain the calibration.

Performance

Bench Tests—Bench tests were conducted to insure that the heat pipes were operating properly and to obtain performance curves for later analysis. The condenser was cooled by a constant temperature bath, and the evaporator was heated by means of a concentric heating element. The entire heat pipe was insulated, except for the condenser which protruded through a special seal into the cooling tank. Copper-constantan thermocouples were affixed to the exterior of the heat pipe.

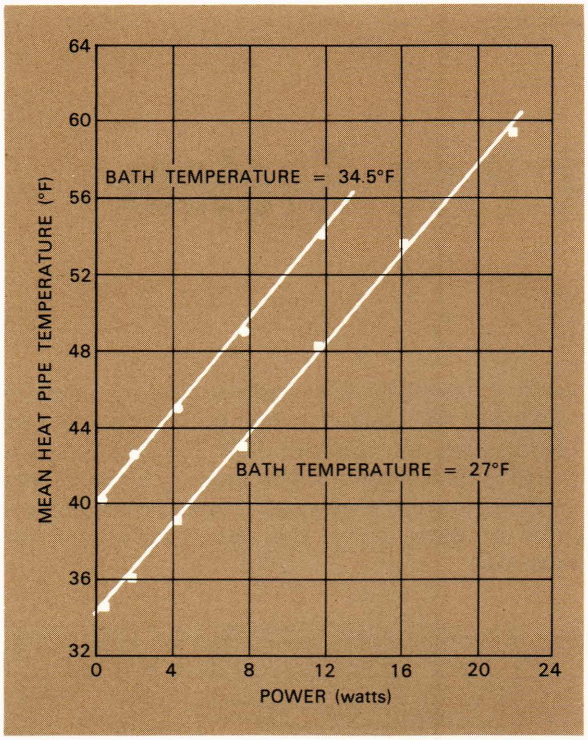

Fig. 4—Mean heat pipe temperature as a function of input power level.

Under steady-state conditions a 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 changing the evaporator or condenser areas. Conditions may also vary if the pipe is not fully evacuated prior to being charged with the fluid or as a result of a leak that allows the fluid to escape or air to flow into the pipe. Figure 4 shows the mean heat pipe temperature as a function of input power level. The mean temperature is observed to increase linearly with power level for a constant bath temperature. Lowering the bath temperature shifts the curve downward.

Thermal Vacuum Tests—The GEOS-II spacecraft was subjected to three basic types of thermal

TABLE I

SUMMARY OF THERMAL VACUUM TESTS

Case	*Maximum Heat Transferred (watts)*	*Mean Heat Pipe Temp. (°F)*		*Transponder Temp. (°F)*			
		Long	*Short*	*R/RR*	*CB1*	*CB2*	*SECOR*
Minimum Sun	14.8	33.3	35.8	34.0	17.5	20.6	53.3
Maximum Q	18.1	61.2	67.9	51.7	67.3	69.0	92.2
Hang-up	64.4	28.1	44.6	9.0	36.3	39.5	66.4

vacuum test: Maximum Q (heat input), 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 ten 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.

Table I summarizes the results of the thermal vacuum testing for the three cases. In the minimum sun case only, the SECOR is energized and heat flows toward the C-band transponders from both the R/RR and the SECOR transponders. The temperatures of the transponders and heat pipes are relatively low as a result of the simulated low exposure to sunlight.

For the maximum Q case, the SECOR was again the only transponder energized. The transponder temperatures are the highest of the three cases. In this test, heat was transferred from the SECOR through the short heat pipe to the C-band transponders and then through the long heat pipe to the range and range rate transponder. A heat transfer rate of 18.1 watts was measured by the flux sensor.

In the hang-up case all transponders were energized, and a maximum of 64.4 watts was transmitted through the long heat pipe. A maximum temperature difference of 57.5°F between the SECOR and the R/RR transponder was recorded for this test.

A series of tests was also conducted to show the effect of heat pipe failure on thermal performance. To accomplish this, the spacecraft was tilted 10° above the X-axis using gravity 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. Therefore, the heat pipe fluid collected in the lower end, and all heat transferred was by conduction through the wick and tubing.

Figure 5 shows the temperature gradient along the long heat pipe while the spacecraft was in the tilted configuration. At time 0521 the temperature difference between the sensors that were farthest apart was about 30°F. At this time, the range and

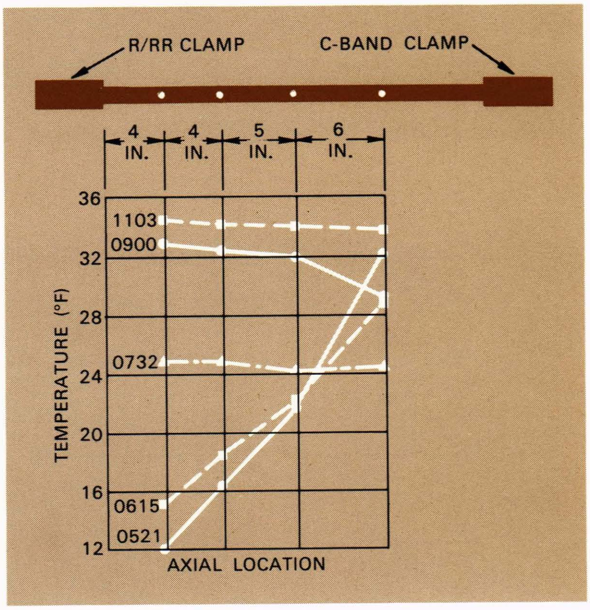

Fig. 5—Temperature gradient reversal during thermal vacuum testing.

TABLE II

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

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 condensed very close to the range and range rate clamp. As the outside of the heat pipe was warmed by this condensation, the vapor traveled farther before condensation occurred. As a result, more of the fluid near the range and range rate end of the pipe, which had flooded this portion of the pipe, vaporized. The evaporator area therefore increased and the heat transfer rate improved until, finally, normal operation was restored.

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

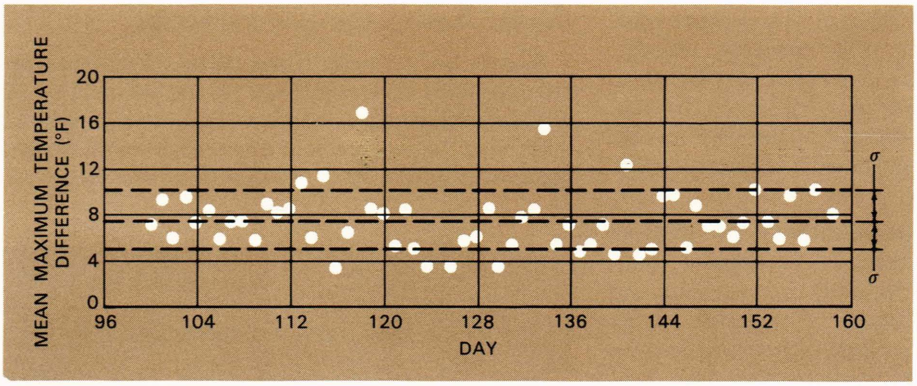

Fig. 6—Mean maximum transponder temperature difference as a function of time for days 100 through 160.

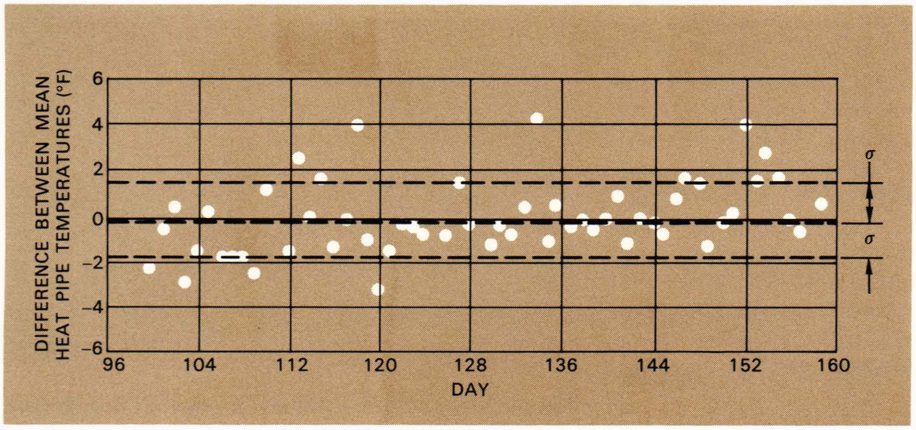

Fig. 7—Daily variation of difference between mean heat pipe temperatures for days 100 through 160.

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 II compares the extreme temperatures and temperature differences between the SECOR and the R/RR transponder covering the latter part of 1965 and all of 1966 for GEOS-I and for the 145 day period between days 16 through 160 of 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.

Of particular note is the large maximum temperature, 138°F, of the GEOS-I range and range rate transponder and the maximum temperature difference of 95°F. These data points were taken during January 1966. Calculations made for GEOS-II predicted a maximum temperature difference of 92°F without the heat pipe system and 32°F with the system.[6] Tests subsequently showed that the thermal resistance of the clamp assemblies was somewhat higher than the value used in the calculations and that, hence, the maximum temperature difference would exceed the predicted value.

The effect of the heat pipe system on reducing the maximum temperature among the transponders may also be seen in Figs. 6 and 7. Figure 6 shows the mean maximum temperature difference, averaged daily, as a function of time for days 100 through 160. During this period satellite operations became rather routine and the mean maximum temperature difference was computed to be 7.4°F with a standard deviation of 2.5°F.

Figure 7 shows the daily differences between the long and short heat pipes for days 100 through 160. These data are indicative of stable thermal performance. The mean and standard deviation of the heat pipe temperature differences for this period were calculated to be −0.1°F and 1.6°F, respectively.

Figure 8 illustrates the performance of the heat pipe system in orbit. These data were selected because they represent the greatest measured heat transfer rates during the period of observation. As shown in the figure, 64.0 watts are flowing through the long heat pipe from the range and range rate transponder to the C-band transponders. There is virtually no heat transfer between CB2 and the SECOR, as evidenced by the measured temperatures of these components. The maximum transponder temperature difference is seen to be 25.3°F. Again, the small temperature difference between the most remote thermistors of the long heat pipe is evidence of proper operation.

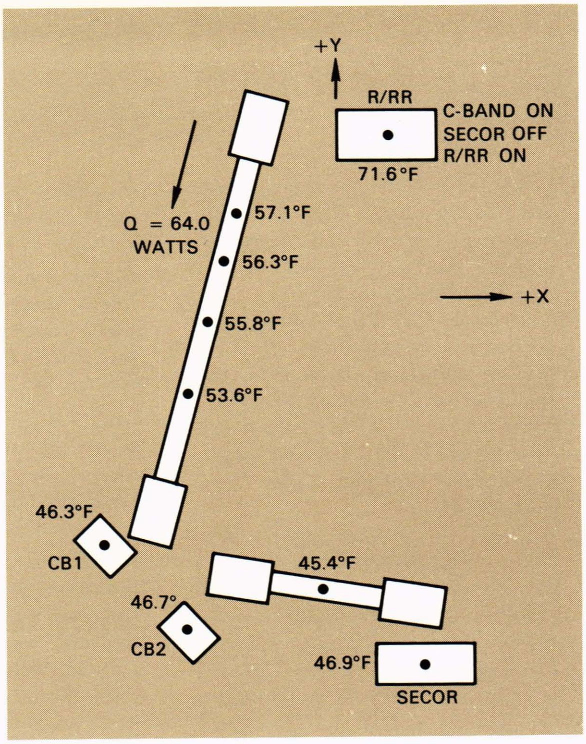

Fig. 8—Performance of heat pipe system in orbit, day 51 at time 0056.

Conclusions

During the period of observation, both heat pipes performed normally. Heat fluxes of as much as 64 watts have been transmitted. The range between the maximum and minimum transponder temperatures for the 145 day period of GEOS-II observations was considerably smaller than the range observed for GEOS-I which, however, has been studied over a much longer period. The mean difference between the heat pipe temperatures was small during the period of observation. As a result, it is concluded that the heat pipe system performance was not biased either by spacecraft attitude or by operation of the transponders.

Acknowledgment

I wish to acknowledge the assistance of Mr. Kenneth E. Miller for the design of the thermopile amplifier and Mr. William C. Denny for fabricating and testing the heat pipes.

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[6] S. E. Willis, *The Effect of the Proposed Heat Pipe on the* $\psi = 90°$, $\beta = 90°$ *Hang-Up Case of GEOS-B*, APL/JHU Memorandum S4S-2-149, February 23, 1967.