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A Variable-Conductance Heat Pipe Radiator for MAROTS-Type Communication Spacecraft

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A variable conductance heat pipe (VCHP) radiator has been designed, built and tested, and has undergone life testing for twelve months at ESTEC. The design constraints were based on the anticipated thermal control requirements for the microwave transistor power amplifiers intended for the MAROTS satellite. Thus the radiator was required to maintain all operating amplifiers within 5°C of one another and within the temperature range 30-40°C. The radiator performance was also evaluated for extended powered-down periods and during eclipse. Experimental results show little change in performance after twelve months of life testing.

Introduction

IT was anticipated some years ago that the clear evolutionary trend in communications spacecraft toward higher power consumption, resulting in even greater waste heat generation, would create thermal problems which could not readily be solved by conventional thermal control techniques. In particular, use of conventional solid radiators to cool the output amplifiers of high-power communications payloads would result in unacceptably high unit temperatures and/or large mass penalties. The solution lay in the use of heat pipes to improve the effective thermal conductivity in the radiator. During the early stages of development of the MAROTS spacecraft, it became apparent that a potentially difficult thermal situation existed on the radiator for the communications system transistor power amplifiers (TPA's), and the decision was made in 1974 to develop a heat pipe radiator which would meet the requirements of the MAROTS spacecraft.

The most important requirements for this radiator are summarized as follows[1]:

1) Eight TPA modules should be accommodated, any five of which might operate at a given time.

2) The temperature of operating TPA's must remain in the range 30-40°C and within 5°C of one another.

3) When operating, each module dissipates 37 W.

4) With only one module operating (eclipse survival condition), the temperature of that module should remain above 0°C.

5) The radiator should be positioned on the north face.

6) Its lifetime in geosynchronous orbit should be seven years.

It was clear from a brief inspection of these requirements that, due to varying solar and other conditions during the satellite's life, a simple heat pipe radiator would not provide the necessary degree of temperature control. The radiator therefore makes use of variable conductance heat pipes (VCHP's) to adjust the effective radiator area automatically in response to changes in equipment temperature.

The control function is performed by a noncondensing gas, contained in reservoirs at the cold end of each heat pipe, which expands to partially block the condenser section as the working fluid vapor pressure falls in response to falling equipment temperatures. The system is entirely passive in operation, although readily adaptable for active control for still tighter equipment temperature control.

Radiator Design

As shown in Fig. 1, the radiator consists of a central mounting platform and four radiator panels. The mounting platform carries the eight TPA's, and consists of a solid aluminum plate with conventional, constant conductance heat pipes to improve the heat distribution in the platform. The four radiator panels, together with the mounting platform, must dissipate a total of 185 W at temperatures between 30 and 40°C. In addition, the height of the panels (in the satellite z-direction) was constrained to not more than 30 cm to minimize the risk of integration problems with an OTS-type service module. The result, as is shown in Fig. 1, is that the radiator panels must bend around onto the northeast and northwest faces of the satellite. Six VCHP's are incorporated in the radiator panels to distribute the heat from the mounting platform, and the radiator panels are slotted in a direction perpendicular to the VCHP's to improve the temperature control accuracy (by reducing the amount of "uncontrolled" heat flowing parallel to the VCHP's). Each VCHP is equipped with a control gas reservoir at the end farthest from the mounting platform.

Aluminum extruded-groove heat pipes (similar to those on the ATS-6 spacecraft) with anhydrous ammonia as the working fluid, are employed. The outside diameter is 12 mm and the extrusion includes an integral flange to facilitate attachment to the radiator panels. Stainless steel wire mesh wicks are incorporated in the gas reservoirs. The control accuracy achievable at the central mounting platform is greatly affected by variations in reservoir temperature. The reservoirs are therefore connected to their respective heat pipes by thin-walled small diameter connecting tubes to isolate them as far as possible from the effects of temperature

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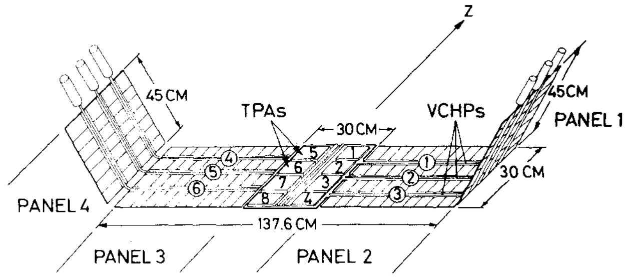

Fig. 1 Radiator layout.

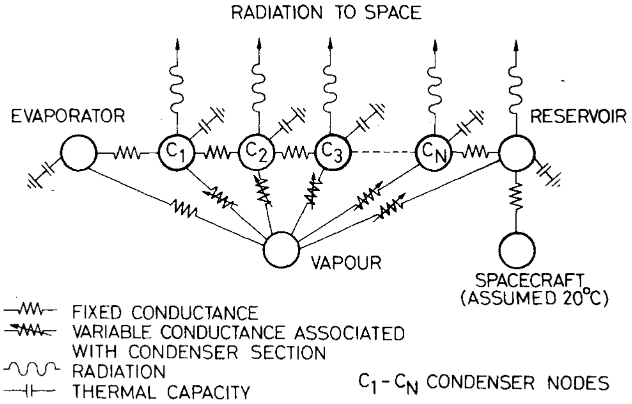

Fig. 2 Schematic nodal model of VCHP.

changes on the radiator panels. A stainless steel wire mesh wick is incorporated in each connecting tube to provide a capillary connection between the heat pipe and reservoir. The reservoir/condenser volume ratio employed was 5:1. Further details of the design may be obtained from Ref. 1.

Radiator Analysis

The design was supported by a simplified analysis using the thermal analyzer and VCHP analysis programs then available at Dornier System. Since the radiator panels occupy three different planes, so that the effect of the sun varies not only with time but also from panel to panel, a detailed transient analysis would have been extremely expensive, and was outside the scope of the investigation. Instead, a number of steady-state worst cases were defined which exceeded the environmental envelope that such a radiator would see in practice. Thus:

1) The worst-case hot condition was defined as the steady-state condition occurring with sun incident at 66.5 deg on the central mounting platform and adjacent inboard radiator panels, and at 6.5 deg on one of the outboard radiator panels. The remaining panel was assumed shadowed. This condition represents the worst condition that could occur during summer solstice.

2) The worst-case cold condition was defined as the steady-state condition with all the radiator in shadow and thus represents the worst condition that could occur at winter solstice.

3) The eclipse survival condition was covered by a steady-state analysis using the above worst-case cold conditions with only one TPA active.

The radiator was regarded, for the purposes of analysis, as a central mounting platform cooled by six separate VCHP's each with its own integral set of fins. Thus conduction between VCHP's through the radiator panel fins was neglected. The analysis was then performed in two distinct stages. First, the heat pipe operating characteristics were calculated for three different environmental conditions: fully shadowed (winter solstice and eclipse), partially shadowed at summer solstice (outboard panel shadowed), and fully sunlit at summer solstice. Second, these characteristics were included in the thermal analysis of the central mounting platform.

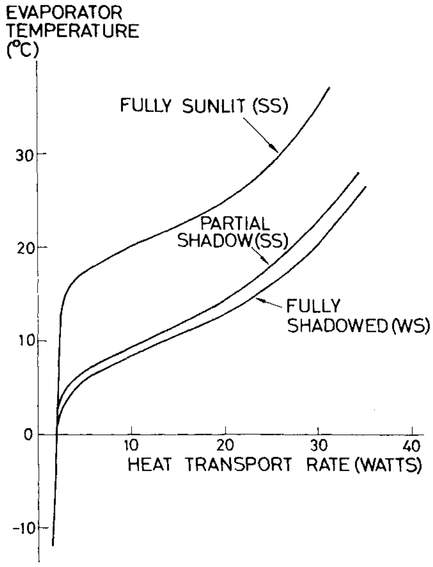

Fig. 3 Calculated VCHP performance characteristics.

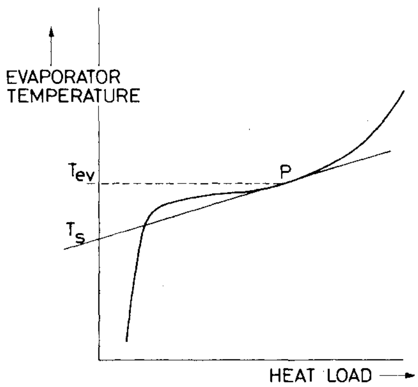

Fig. 4 Typical VCHP performance characteristics.

VCHP Performance Characteristics

A nodal model of the VCHP, including reservoir, was established and is shown schematically in Fig. 2. The fins were lumped in with the adjacent heat pipe wall nodes, and a fin efficiency factor was used to correct for the effect of the fin temperature gradients which would occur in practice. The VCHP analysis program was essentially a "spread front" routine in that the effects of wall conduction were fully taken into account but diffusion was ignored. The output showed the evaporator temperature as a function of heat transfer rate for the specified boundary conditions (sun incidence angle, etc.). The characteristics obtained are shown in Fig. 3.

Central Mounting Platform Analysis

Figure 4 shows a typical VCHP characteristic. If, for a given evaporator temperature T_{ev}, the tangent to the characteristic curve is drawn (line T_SP in Fig. 4), then the evaporator will, for small changes in heat load, behave as if it were connected to a heat sink at temperature T_S by a simple thermal resistance given by the slope of the line T_SP. The analysis technique consisted of initially guessing the evaporator temperatures and then, by using the relevant curve in Fig. 3, obtaining the effective heat sink temperatures and connecting resistors. This information was incorporated in the central mounting platform thermal model and the resulting temperature distribution was computed. The

calculated evaporator temperatures were then compared with the initial guessed temperatures, and, if a significant difference existed, a new set of heat sink temperatures and connecting resistors was obtained and the computation repeated. This type of manual iteration would be quite unsuitable for analyzing a complex radiator in a complex environment (e.g. where shadowing from solar arrays, antennas, etc., are involved), but proved adequate for this radiator model.

Manufacture and Test

The radiator was manufactured and prepared for testing at Dornier System before being transported to ESTEC for testing in the HBF2 thermal vacuum chamber. Since it was not planned to test with a solar simulator, the radiating surfaces of the radiator and reservoirs were coated with black paint, and not with the second surface mirrors which would be required on a flight version. Film heaters were attached to the back of the radiator panels and to the reservoirs to simulate the effect of the sun, and eight TPA simulation heaters were attached to the mounting platform. About 130 thermocouples were provided to monitor radiator performance.

Due to the sensitivity of heat pipe operation to gravity effects, the radiator was mounted in the vacuum chamber with its z-axis vertical. Thus all the VCHP's were horizontal except for the two constant conductance heat pipes on the central mounting platform which were vertical. Testing was conducted, therefore, with always the lowest TPA heaters operating, to ensure that the vertical heat pipes could operate in the reflux mode. A horizontal attitude for the VCHP's was ensured by the specially constructed test fixture which allowed levelling to be performed from outside the chamber after pump-down and cool-down of the shrouds.

The VCHP's were charged with ammonia during manufacture, but because of the difficulties anticipated in metering in exactly the calculated quantity of control gas, filling with control gas and fine adjustment of gas inventory were performed experimentally at ESTEC with the radiator operating in the simulated space environment in the vacuum chamber. After this the system was removed from the vacuum chamber, the six VCHP's were sealed by crimping and overwelding, and the radiator was returned to the chamber for performance testing.

The radiator was subjected to an extensive program of testing to evaluate its performance as a function of total heat load (by varying the number of operating TPA's) and for different combinations of operating TPA's. The major part of the testing was performed with the radiator operating in the passive mode. However, after the testing in passive mode had been completed, a number of additional tests were performed to explore the performance in active mode. This was achieved by using the output from temperature sensors on the central mounting platform to control the reservoir temperatures via suitable controllers and the reservoir solar simulation heaters.

Results

Passive Mode

Figures 5, 6, and 7 show the results in the passive mode for simulated summer solstice and winter solstice conditions. Each figure shows the temperature and operational status of the TPA heaters, and the resulting temperature distribution along each of the VCHP's. Operating TPA's are indicated by

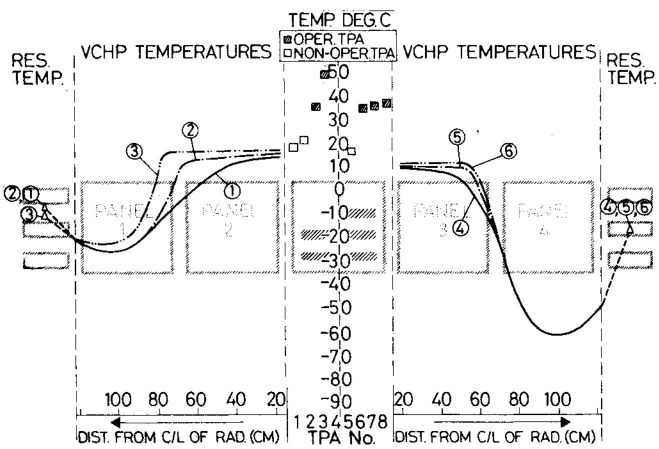

Fig. 5 Summer solstice—passive mode.

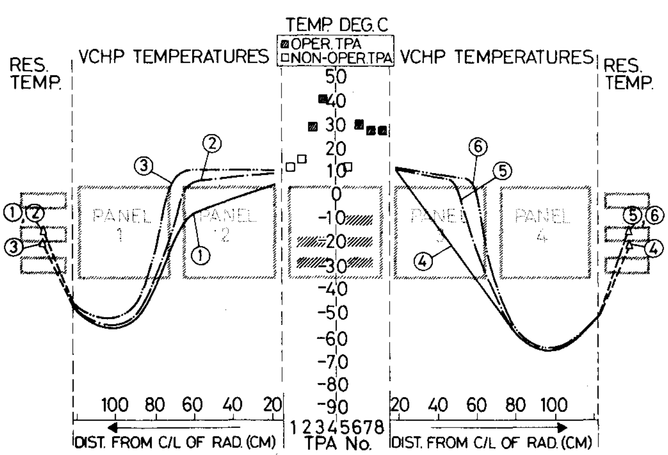

Fig. 6 Winter solstice—passive mode.

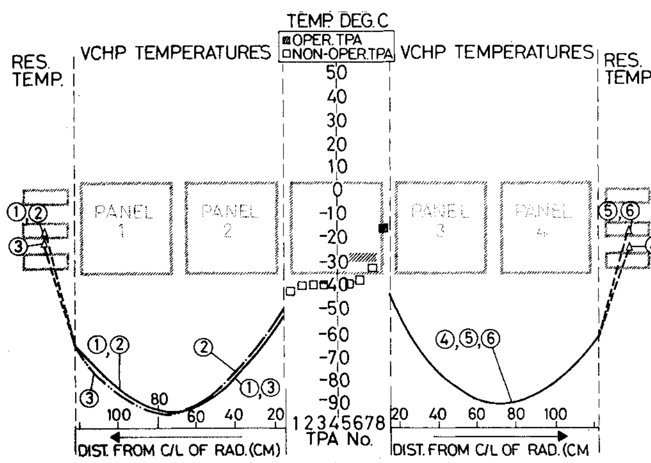

Fig. 7 Eclipse survival condition—passive mode.

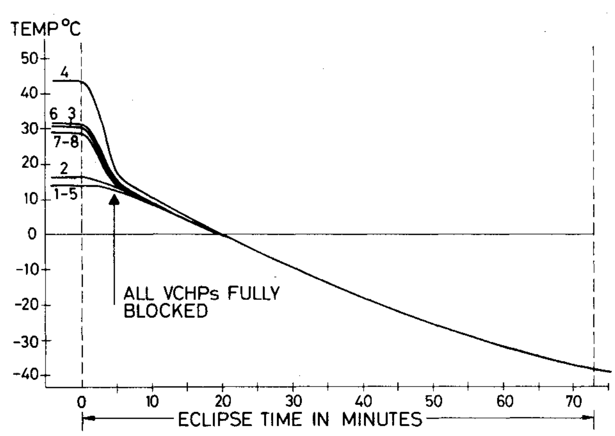

Fig. 8 Eclipse transient simulation—passive mode.

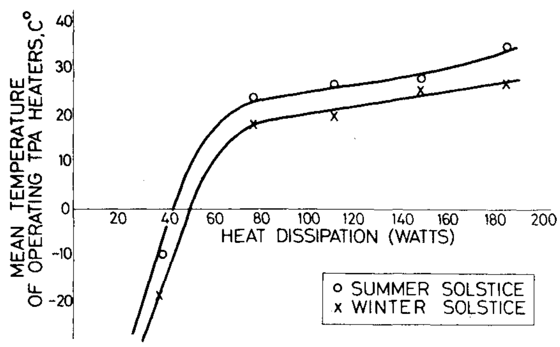

Fig. 9 Radiator temperature control characteristics—passive mode.

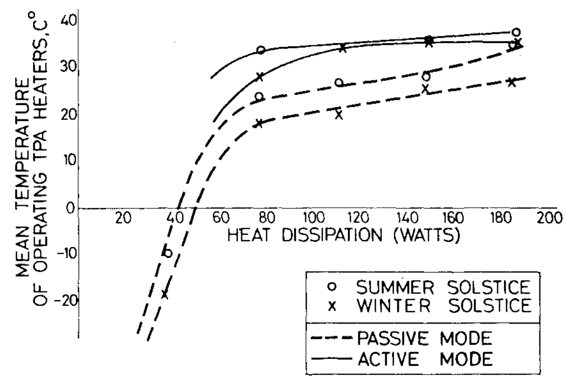

Fig. 11 Radiator temperature control characteristics—active mode.

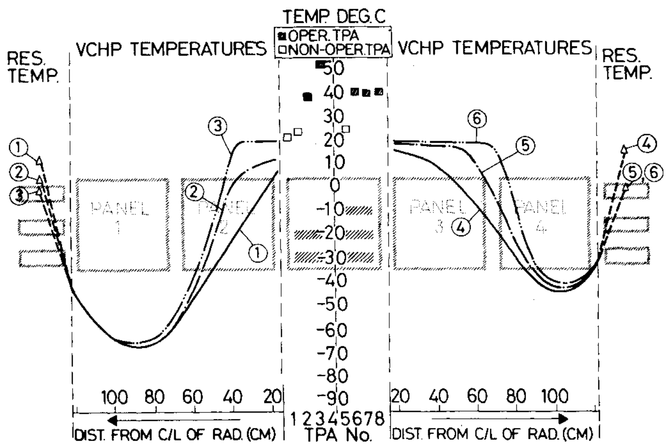

Fig. 10 Winter solstice—active mode.

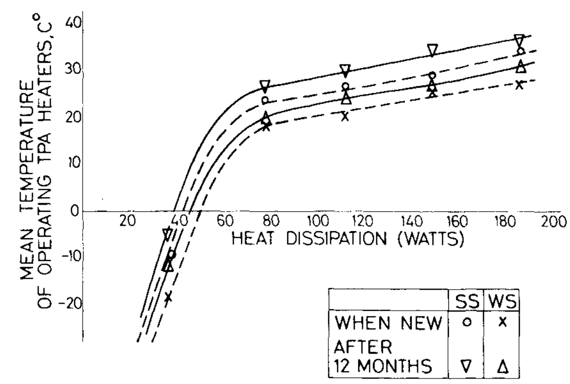

Fig. 12 Radiator temperature control characteristics—passive mode. Results of twelve months life testing.

shading. The VCHP's and TPA heaters are numbered as indicated in Fig. 1. It should be noted that no attempt was made to follow a 24-hour transient simulation: the summer solstice case, for example (Fig. 5), shows the worst-case hot condition with maximum solar input, and the winter solstice case (Fig. 6) shows the situation with no sun on the radiator. Figure 7 shows the steady-state temperature distribution with only one TPA heater operating in a sunless environment. Figure 8 shows a simulated eclipse transient where in fact all heaters are switched off at the start of eclipse. Immediately prior to this test the radiator was in the winter solstice condition shown in Fig. 6. The rate of cooling indicated is somewhat pessimistic, since the TPA simulation heaters have a far smaller thermal capacity than the real TPA's.

From the figures it can be seen that the thermocouple on TPA No. 4 is, when operating, always about 15°C hotter than its operating colleagues. It would be expected that such an anomaly would be reflected in the temperature distribution of the associated VCHP's, which is not the case, and it was concluded that this thermocouple had been incorrectly located. The thermocouple was therefore ignored in the preparation of the remaining figures (Figs. 9, 11 and 12).

The temperature control achieved is indicated in Fig. 9, where the mean temperature of the operating TPA heaters is shown as a function of heat dissipation. When operating at full power, the mounting platform ran about 2.5°C colder than expected, which indicated a slight initial undercharge of control gas. The seasonal variation in temperature, 7.5°C (27.5°C to 35°C), was well within the specified maximum of 10°C. With the exception of a faulty thermocouple, all operating TPA heaters were within the specified maximum 5°C of one another.

Reference to Fig. 5 shows that a significant portion of the radiator was unused even in the maximum sun case. This was due to the use of black paint instead of the second surface mirrors which were assumed in the design. The same cause accounts in large part for the low temperature of the operating TPA heater in Fig. 7 (winter solstice, one TPA active).

Active Mode

The results of the tests in active mode are illustrated in Figs. 10 and 11. Figure 10 shows the temperature distribution at winter solstice, and Fig. 11 illustrates the improved temperature control obtained. The power consumption of the reservoir heaters in this mode was only of the order of a few watts.

Cold Start-Up

In addition to the above performance tests, a cold start-up test was performed. The TPA heaters were switched off and the system allowed to cool until the radiator panels and central mounting platform were below −100°C. At this temperature the ammonia would have been frozen. The reservoirs were not frozen, however, due to heat leaking (by design!) from the "satellite" through the reservoir supports. Five TPA heaters were then switched on, and the radiator warmed up and recovered normally. The radiator was operating in the passive mode during this test.

Life Test

After performance testing the radiator was operated at full power for one month in the vacuum chamber. At the end of that time there was no indication of a change in performance, and the radiator was transferred to a laboratory environment and the life testing continued in air. Due to the changed environmental conditions the heater power had to be reduced from 185 to about 100 W to keep within the TPA temperature limits. After a total of twelve months life testing the radiator was again moved to the vacuum chamber and the performance remeasured.

The results, indicated in Fig. 12, show that the radiator "set point" has apparently increased by about 3°C. There are a number of possible explanations for this. Inspection of the reservoir temperatures shows that the mean reservoir temperature was about 1.5°C warmer than in tests twelve months previously. However, this would only have accounted for about 0.5°C increase in TPA temperature. Another possible explanation is that noncondensible gas has been produced, perhaps due to the use of stainless steel mesh in the aluminum reservoirs. However, a 3°C rise in temperature implies a 9% increase in gas load, which is a lot of gas; in addition there was no evidence of an increase in the mean evaporator temperature. The most likely explanation appears to be that small movements or aging effects in the central mounting platform assembly, which was only bolted together using a thermal grease, have changed slightly the effective conductances between the TPA heaters and heat pipes. The life testing is continuing.

Conclusions

A VCHP radiator has been developed and tested, and has undergone twelve months of life testing. The radiator performance in passive mode was very close to that specified, and is entirely adequate for many spacecraft applications. Requirements for very tight temperature control can be readily accommodated by operating the radiator in active mode provided a few watts of electrical power are available.

The radiator was retested after the first twelve months of life testing. The small increase in radiator "set point" temperature has been tentatively attributed to changes in interface conductances within the TPA mounting platform assembly.

References

[1] Koch, H. and Kreeb, H., "Development of Variable Conductance Heat Pipe Radiators," *Proceedings of the Second International Heat Pipe Conference,* ESA SP-112, Vol. 1, 1976, pp. 661-671.