

## **Thermal Performance of a Multi-Evaporator Loop Heat Pipe with Thermal Masses and Thermal Electrical Coolers**

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### **ABSTRACT**

This paper describes thermal performance of a loop heat pipe (LHP) with two evaporators and two condensers in ambient testing. Each evaporator has an outer diameter of 15mm and a length of 76mm, and has an integral compensation chamber (CC). An aluminum mass of 500 grams is attached to each evaporator to simulate the instrument mass. A thermal electric cooler (TEC) is installed on each CC to provide heating as well as cooling for CC temperature control. A flow regulator is installed in the condenser section to prevent vapor from going back to the evaporators in the event that one of condenser is fully utilized. Ammonia was used as the working fluid. Tests conducted included start-up, power cycle, heat load sharing, sink temperature cycle, operating temperature control with TECs, and capillary limit tests. Experimental data showed that the loop could start with a heat load of less than 10W even with added thermal masses. The loop operated stably with even and uneven evaporator heat loads, and even and uneven condenser sink temperatures. The operating temperature could be controlled within  $\pm 0.5\text{K}$  of the set point temperature using either or both TECs, and the required TEC control heater power was less than 2W under most test conditions. Heat load sharing between the two evaporators was also successfully demonstrated. The loop had a heat transport capability of 120W to 140W, and could recover from a dry-out when the heat load was reduced. The 500-gram aluminum mass on each evaporator had a negligible effect on the loop operation. Existing LHPs servicing the orbiting spacecraft have a single evaporator with an outer diameter of about 25mm. Important performance characteristics demonstrated by this LHP included: 1) Operation of an LHP with 15mm diameter evaporators; 2) Robustness and reliability of an LHP with multiple evaporators and multiple condensers under various test conditions; 3) Heat load sharing among LHP evaporators; 4) Effectiveness of TECs in controlling the LHP operating temperature; and 5) Effectiveness of the flow regulator in preventing vapor from going back the evaporators.

**KEY WORDS** Two-Phase Heat Transfer, Loop Heat Pipes, Multiple Evaporators, Multiple Condensers

# 1. INTRODUCTION

A loop heat pipe (LHP) utilizes boiling and condensation of the working fluid for heat transfer and surface tension forces developed by the evaporator wick to circulate the fluid for heat transport [1,2]. It can transport large heat loads over long distances with small temperature differences. LHPs have gained increasing acceptance for spacecraft thermal control, and are being used or to be used on several NASA spacecraft and commercial communications satellites [3-5]. All these state-of-the-art LHPs have a single evaporator with an outer diameter (O.D.) of about 25mm.

As the spacecraft become smaller, all spacecraft components, including the thermal subsystem, must be down sized. In addition, an LHP with multiple evaporators is highly desirable to accommodate multiple instruments or an instrument with a large footprint. Several LHPs with a single 15mm or 7mm O.D. evaporator have been built and ground tested [6-10]. Performance of LHPs with multiple 25mm O.D. evaporators have also been demonstrated in ambient tests [11-13].

This paper describes testing of an LHP with two 15mm O.D. evaporators and two condensers. This multi-evaporator LHP (MLHP) has been previously tested and demonstrated excellent performance [14-17]. Modifications to the LHP for this test program included installation of a 500-gram aluminum mass on each evaporator and a thermal electric cooler (TEC) on each compensation chamber (CC). In addition, provisions were made to cool the thermal masses to demonstrate heat load sharing between the two evaporators.

The modified test article, test set-up, tests conducted, and experimental results are presented in the following sections.

# 2. TEST PROGRAM

## 2.1 Test Article and Test Set-Up

The test article, shown in Figures 1 and 2,

consists of two evaporators, two condensers, a common vapor transport line and a common liquid return line. Each evaporator has an integral CC. Both evaporators are made of aluminum tubing with 15mm O.D. and 76.2mm length. One evaporator has a titanium wick with a pore radius of about 3  $\mu\text{m}$ , while the other has a nickel wick with a pore radius of about 0.5  $\mu\text{m}$ . Each CC is made of stainless steel tube of 14.8mm O.D. x 81.8mm L. The vapor line and liquid line, each 1168mm long, are made of stainless steel tube with an O.D. of 3.3mm and 2.2mm, respectively. Each condenser is made of stainless steel tube of 2.2mm O.D. x 762mm L. A flow regulator consisting of capillary wicks is installed at the downstream of the condensers. The

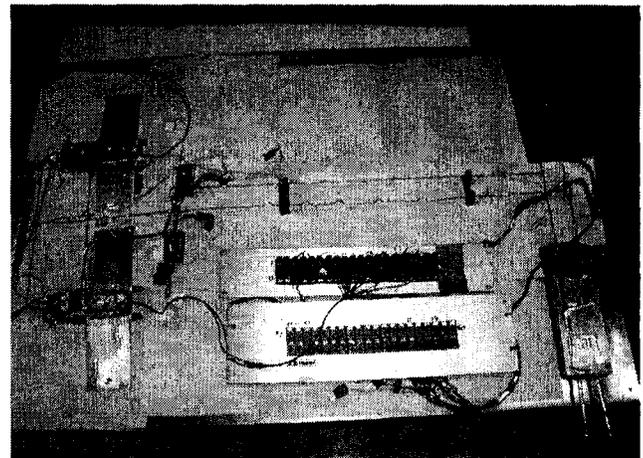


Figure 1. Picture of MLHP

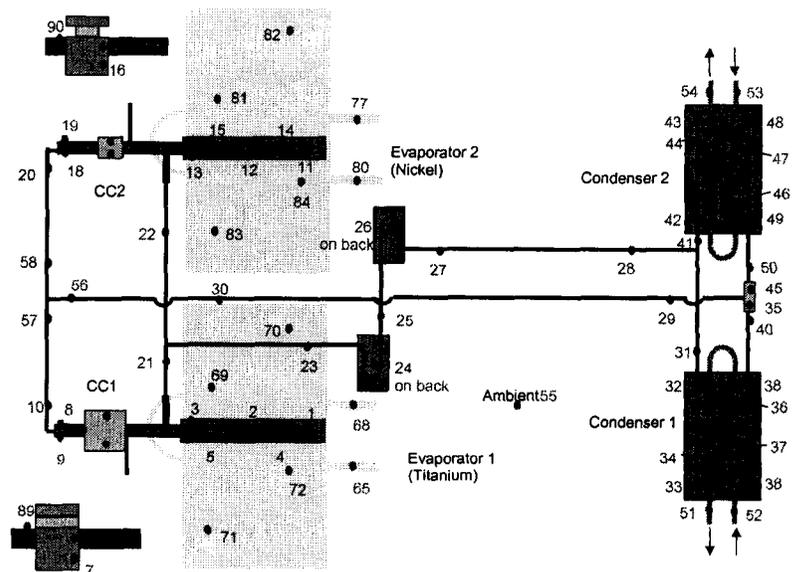


Figure 2. Schematic of MLHP with Thermocouple Locations

loop is charged with 15.5 grams of ammonia.

Each condenser was attached to a cold plate, and each cold plate was cooled by a separate chiller. A 500-gram aluminum mass was attached to each evaporator to simulate the instrument mass. Two cartridge heaters were attached to each thermal mass to provide heat loads between 1W and 200W per evaporator. To demonstrate heat load sharing, each thermal mass had two holes to accommodate a coolant flow. Since only one thermal mass needed to be cooled at a time, a third chiller was used and the coolant flow was directed to the designated thermal mass using control valves.

A TEC was installed on each CC through a copper saddle. The hot side of the TEC was connected to the evaporator through a copper strap. Each TEC was controlled by a bi-polar power supply. Changing the polarity on the power supply changed the TEC operation between heating and cooling modes.

Ninety type T thermocouples were used to monitor the temperatures. A data acquisition system consisting of a personal computer, a CRT monitor, and two data loggers was used to display and store test data every two seconds.

## 2.2 Test Objectives

One of the major operating features of a multi-evaporator LHP is inherent heat load sharing among all evaporators. Evaporators attached to 'off' instruments can receive heat from evaporators attached to "on" instruments, thus eliminating the need for supplemental heaters. The coolant flow to each thermal mass in this test program provides flexibility to demonstrate such a function under various operating conditions. These added thermal masses allowed for a better simulation of the LHP operation in real applications where the evaporators are attached to instruments.

The TEC is used to control the CC saturation temperature by provides heating as well as cooling. One side of the TEC is attached to the

CC, and the other side is connected to the evaporator via a copper strap. This approach has several advantages over the traditional approach using electrical heaters: 1) It is possible to control the CC saturation temperature at the low power region where cooling is needed; 2) The TEC can enhance the start-up success by maintaining the CC saturation temperature at fixed value through cooling; and 3) The TEC control heater power is less than that for the electrical heaters because the TEC, operating in the reverse mode, can draw heat from the evaporator.

Main objectives of this test program were to: 1) Demonstrate robust and stable operation of the MLHP with added thermal masses to evaporators; 2) Demonstrate the heat sharing function between the two evaporators under various test conditions; and 3) Verify the effectiveness of TECs in controlling the loop operating temperature.

## 3. TEST RESULTS

The following abbreviations are used in presenting the test data (also refer to Figure 2):

E1 – Evaporator 1; E2 – Evaporator 2; CC1 – Compensation Chamber 1; CC2 – Compensation Chamber 2; C1 – Condenser 1; C2 – Condenser 2; TEC1 – Thermal Electric Cooler 1; TEC2 – Thermal Electric Cooler 2.

### 3.1 Overview of Test Results

To establish a baseline, the MLHP was first tested without thermal masses and without TECs. Over 100 hours of test data were collected. In addition, extensive tests (more than 600 hours) had been conducted in 2000 on the original MLHP [14-17]. Test results obtained under this test program were very similar to those obtained in 2000.

More than 200 hours of test data were collected with the modified MLHP which incorporated two thermal masses and two TECs. The loop demonstrated stable operation under all test conditions. Successful start-ups were demonstrated with E1/E2 heat loads

of 10W/0W, 0W/10W, 5W/5W, 100W/0W, 0W/100W and 50W/50W. Low power operation included 5 W/0W, 0 W/5W, and 5 W/5W, while high power operation included 70W/70W, 130W/0W, and 0W/140W. The TECs were able to maintain the desired loop operating temperature within  $\pm 0.5K$  under all heat loads and sink temperatures. Either one or both of the TECs could be used to control the loop operating temperature and the required TEC control heater power was less than 2W in most cases. The two evaporators were able to share heat loads automatically. Moreover, the evaporator switched between the evaporator mode and condenser mode of operation depending on the surrounding thermal environment. The loop automatically shut down when neither evaporator received a heat load. One of the sinks could be at a temperature higher than the saturation temperature. The flow regulator was able to stop the vapor flow when a condenser was fully utilized. The heat transport capability of the loop was between 120W and 140W, depending on the evaporator heat load distribution and the operating temperature.

### 3.2 Effect of Thermal Mass

In theory, the thermal mass attached to the evaporator, if well insulated, should not affect the LHP steady state operation. During the transient, the thermal mass will modulate the net heat load to the evaporator. The most profound effect will be during the start-up transient where the net evaporator power will be less than the power that is applied to the thermal mass. This will make the loop more difficult to start.

The MLHP showed no or a very small superheat (less than 2K) during start-up, with or without added aluminum masses. Because of such a small superheat, the thermal mass on each evaporator appeared to have very little effect on the loop start-up.

During the transient, the net heat load into the evaporator is greater than the power applied to the thermal mass when the CC temperature is decreasing, and is less than the power applied to the thermal mass when the CC temperature is increasing. This will happen when the applied power or the

condenser sink temperature varies, and the CC temperature is not actively control and. For MLHP, the transient period was prolonged or shortened slightly with added thermal masses if the CC saturation temperature was not controlled. When the CC saturation temperature was actively controlled by TECs, the thermal masses showed no noticeable effect.

Similar effects of a thermal mass on LHP start-up and other transient behaviors were observed in the ground test of a miniature LHP with a single 7mm O.D. evaporator [7]. In that test, various thermal masses were added to the evaporator.

In the following sections, only results of those tests which had a 500-gram aluminum mass attached to each evaporator are presented.

### 3.3 Start-up

Twenty-two (22) start-up tests were conducted with combinations of the following conditions:

- E1/E2 power: 100W/0W, 0W/100W, 50W/50W, 25W/25W, 20W/0W, 0W/20W, 10W/10W, 10W/0W, 0W/10W, 5W/5W.
- C1/C2 sink temperature: 273K/273K, 273K/293K, 293K/273K, 273K/no coolant flow.
- CC1/CC2 temperature: Neither CC had active temperature control, one or both CCs were controlled at 303K.

All start-up were successful except for one of the 5W/5W start-ups. In the previous test program, one unsuccessful start-up with 5W/5W was also observed when no thermal masses were attached to the evaporators [14]. There were several indications that the loop might be undercharged and the heat leak from the evaporator to the CC was significant at low powers.

Figure 3 shows the loop temperature during start-up with E1/E2 heat load of 100W/0W. The C1 sink was at 273K and no coolant was provided to C2 sink. CC1 was initially controlled at 298K, and then control was deactivated prior to applying 100W to E1 at 10:32. The loop started almost immediately with a superheat of less than 2K. Successful start-up

was indicated by an increase of the vapor line temperature and a decrease of the liquid line temperature.

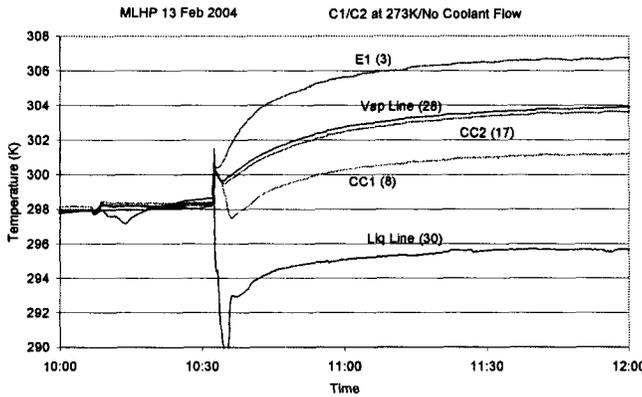


Figure 3. Start-up E1/E2 = 100W/0W

### 3.4 Heat Load and Sink Variations

The MLHP could adapt to rapid changes in evaporator heat loads and/or condense sink temperatures. Figure 4 shows the loop temperatures with varying heat loads when CC1 was controlled at 303K and both condenser sinks were kept at 273K. The loop operating temperature was governed by the CC1 temperature and was stable at 303K under all heat loads. CC2 was liquid-filled and became

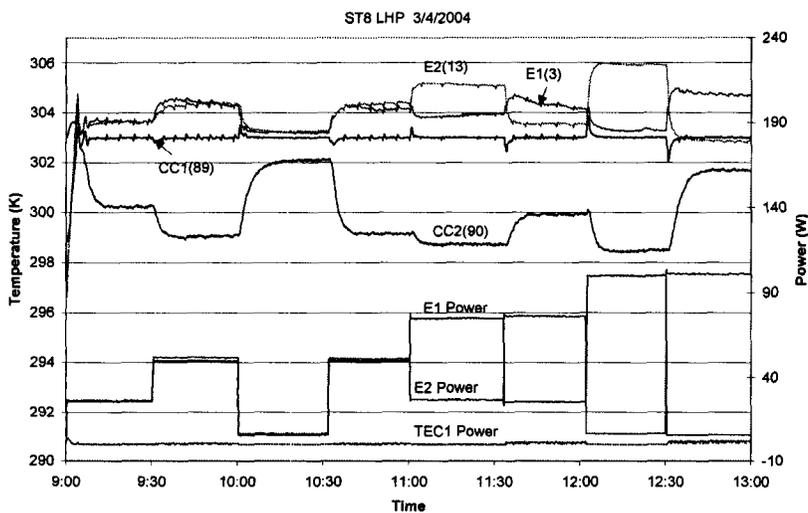


Figure 4 MLHP Breadboard Test with Varying Heat Loads

subcooled. The difference between the evaporator temperature and the CC saturation temperature was driven by the heat transfer requirement and was a function of the evaporator heat load.

Figure 5 shows that the loop operating temperature could be maintained at 303K using either or both of the TECs. The C1 sink temperature was varied between 253K and 293K while the C 2 sink was kept at 273K. Superimposed upon this condition was a power change between two highly uneven heat loads of 100W/5W and 5W/100W. The TEC control heater power was less than 2W under all conditions. A similar test was also performed with the same sink temperature profile and CC saturation temperature control scheme except for a heat load of 50W/50W to the evaporators. The loop demonstrated stable operation and the operating temperature was within  $\pm 0.5K$  of the desired set point temperature.

### 3.5 Heat Load Sharing

In heat sharing operation, the evaporator receiving heat from the other evaporator works as a condenser, dissipating a portion of the total heat load. The amount of heat each condenser receives is dictated by conservation laws of mass, momentum and energy among all three “condensers”. Any change in the total heat load, operating temperature, and/or thermal environment surrounding each “condenser” will change the heat load distribution among all condensers.

Figure 6 shows loop temperatures in a heat load sharing test. CC1 was controlled at 303K by TEC1. The heat load applied to the E2 thermal mass was kept constant at 100W and no heat was applied to the E1 thermal mass. At 11:00, coolant was circulated to the E1 thermal mass, and E1 immediately shared heat from E2. As the coolant temperature decreased, more heat was shared by E1 and dissipated to the circulating coolant. E1 was maintained near the saturation temperature of 303K except at very low E1 sink temperature where insufficient heat was flowing to E1. The heat shared

by E1 as shown on Figure 6 was calculated using the difference of the liquid temperatures as the liquid entered and exited the E1 thermal mass. Near the end of the test, the coolant temperature was set above the CC1 saturation temperature. Consequently, E1 was receiving heat from the coolant, and changed its operation to the evaporator mode. The negative heat shared by E1 indicates that the coolant was losing heat as it flowed through the E1 thermal mass. The control heater power for TEC1 was less than 2W throughout the test.

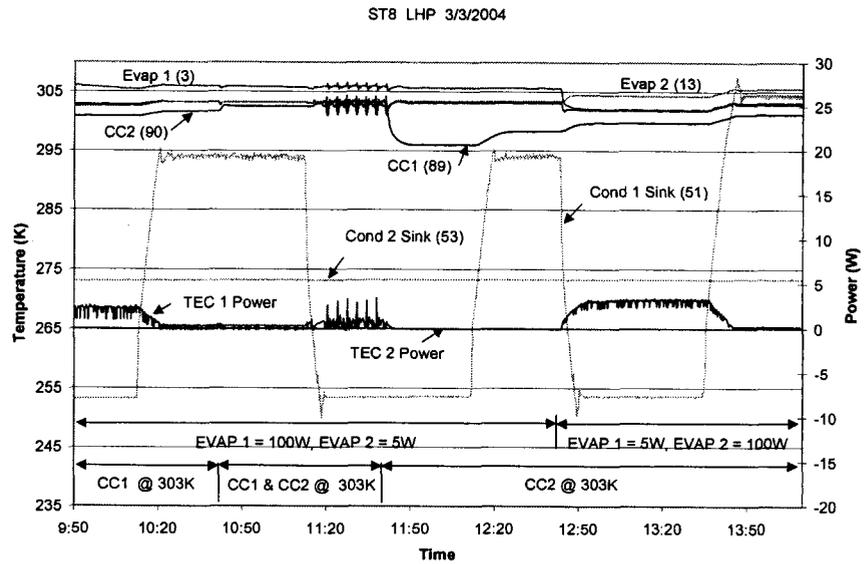


Figure 5. MLHP Test with Varying Heat Loads and Sink Temperatures

Figure 7 shows another heat load sharing test. The heat load to E1 was kept at 100W, and the temperature and flow rate of the coolant flowing through the E2 thermal mass was maintained at 283K and 18.9cm<sup>3</sup>/sec, respectively. The CC1 set point temperature decreased from 303K to 288K with 5K increments. As the saturation temperature decreased, the amount of heat dissipated by the coolant flow also decreased due to a small temperature difference between the saturated vapor and the coolant. Note that the E2 temperature followed closely that of the CC1 saturation temperature. Near the end of the test, the coolant flow to the E2 thermal mass was stopped, and a heat load of 50W/50W was applied to E1/E2. E2 changed to the evaporator mode immediately. The control heater power for TEC1 was less than 2W throughout the test.

E1/E2 heat loads gradually increased from 10W/10W to 80W/80W. The CC2 saturation temperature was maintained at 303K by TEC2, and the C1/C2 sinks were kept at 273K/273K. As predicted, E1 always dried out first due to its coarser

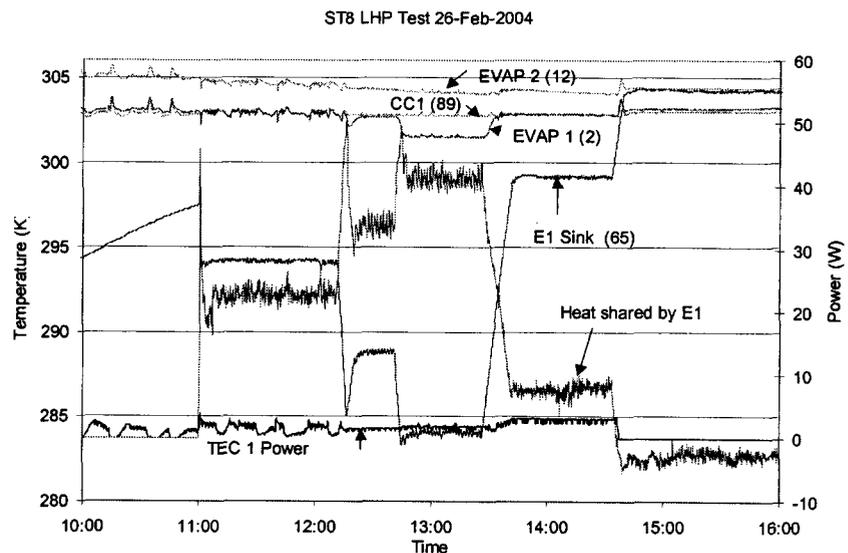


Figure 6. MLHP Heat Load Sharing Test

### 3.6 Capillary Limit

When the total pressure drop exceeds the capillary limit of the wick, vapor will penetrate through the wick and the loop will dry out. Figure 8 shows the loop temperatures during a capillary limit test where

3μm titanium wick. Between 10W/10W and 70W/70W, CC1 was liquid-filled and was at a subcooled state. At 80W/80W, vapor blew through the wick. As a result, CC1 temperature rose sharply and began to control the loop operating temperature. However, the loop could operate steadily at a higher

saturation temperature with 80W/80W. When the heat load was reduced to 50W/50W, the loop recovered from a dry-out, and the operating temperature was the same as it was at 50W/50W prior to dry-out.

### 3. CONCLUSIONS

An LHP having two 15-mm O.D. evaporators and two condensers has been tested in ambient. A 500-gram aluminum mass was added to each evaporator, and a TEC was installed on each CC to control the loop saturation temperature. The loop demonstrated robust and reliable operation under various test conditions. TECs were able to control the loop operating temperature within  $\pm 0.5K$ . The 500-gram aluminum mass is more than 20 times bigger than the evaporator mass itself, and yet it showed no noticeable effect on the LHP transient behavior. A larger mass may be required in future tests to illustrate its effect.

The multi-evaporator LHP retains all of the operating characteristics and advantages of the state-of-the-art LHP with a single evaporator, including high heat transport capability, passive and self-regulating operation, no external pumping power, and flexibility in spacecraft design, integration and ground tests. It also offers many additional advantages: 1) The mass, volume and control heater power are reduced; 2) Multiple evaporators in a single LHP provide a single interface temperature to all instruments, and allow the "off" instruments to receive heat from the "on" instruments, eliminating the need for supplemental heaters; 3) Multiple condensers allow the radiators

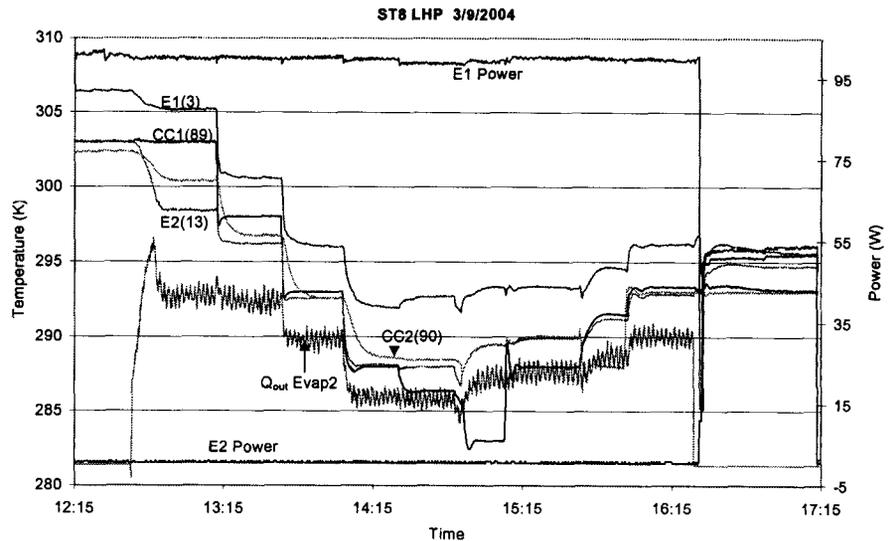


Figure 7. MLHP Heat Load Sharing Test

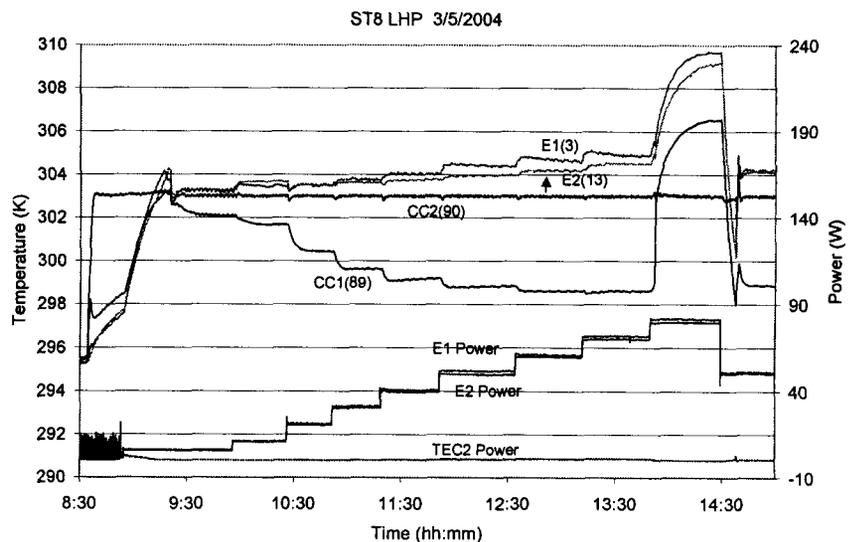


Figure 8. MLHP Capillary Limit Test

to be placed at different locations and can be exposed to different heat sinks; 4) The flow regulator prevents heat from being transmitted back to the instruments; 5) A single TEC can be used to heat and cool the CC and provide tight operating temperature control.

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