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ABSTRACT

This paper describes the testing of the prototype loop heat pipe (LHP) for the Geoscience Laser Altimeter System (GLAS). The primary objective of the test program was to verify the loop's heat transport and temperature control capabilities under conditions pertinent to GLAS applications. Specifically, the LHP had to demonstrate a heat transport capability of 100 W, with the operating temperature maintained within ±2K while the condenser sink was subjected to a temperature change between 273K and 283K. Test results showed that this loop heat pipe was more than capable of transporting the required heat load and that the operating temperature could be maintained within ±2K. However, this particular integrated evaporator-compensation chamber design resulted in an exchange of energy between the two that affected the overall operation of the system. One effect was the high temperature the LHP was required to reach before nucleation would begin due to inability to control liquid distribution during ground testing. Another effect was that the loop had a low power start-up limitation of approximately 25 W. These issues may be a concern for other applications, although it is not expected that they will cause problems for GLAS under micro-gravity conditions.

INTRODUCTION

As part of the Earth Science Enterprise, the science objectives of the Geoscience Laser Altimeter System (GLAS) are to obtain ice sheet and ocean topography, and global profiles of land and vegetative canopy. In order to accomplish this, GLAS utilizes three lasers that dissipate approximately 120 W each when operating, but only one laser is needed at a time. The lasers must be maintained at a temperature of 293±2K. In order to transfer the heat and meet the temperature requirements, a heat pipe/loop heat pipe (LHP) system was proposed for thermal control.

Since GLAS was still in the conceptual design stage, it was desirable to build and test a thermal control system reflective of that proposed for the mission. In the actual application, a heat pipe will be mounted to each of the lasers through a thermal interface. The condenser section of the heat pipe will be connected to the evaporator section of the LHP. The condenser region of the LHP will be mounted to a radiator panel. The front of the panel will then radiate to space. NASA/Goddard Space Flight Center purchased a prototype LHP from Dynatherm Corporation in 1997. The Thermal Engineering Branch at Goddard subsequently completed testing of this prototype.

Testing for the GLAS LHP was divided into three parts. The first set of tests, which was designed to determine the temperature drop through the system and the thermal conductances at various interfaces, was performed strictly using a heat pipe assembly. In these tests, a chill block was used to simulate
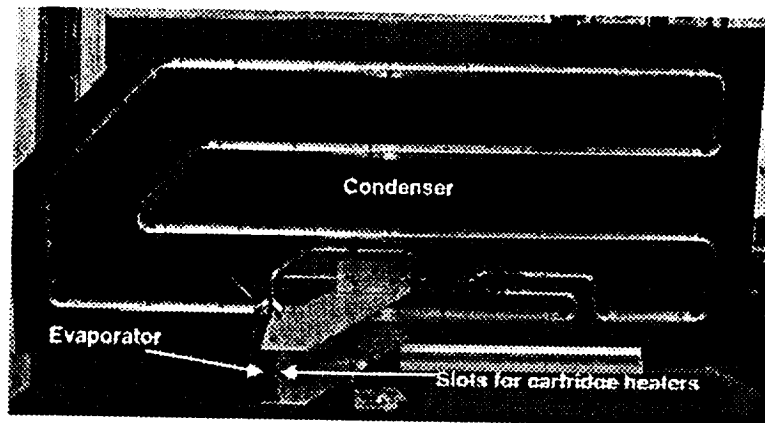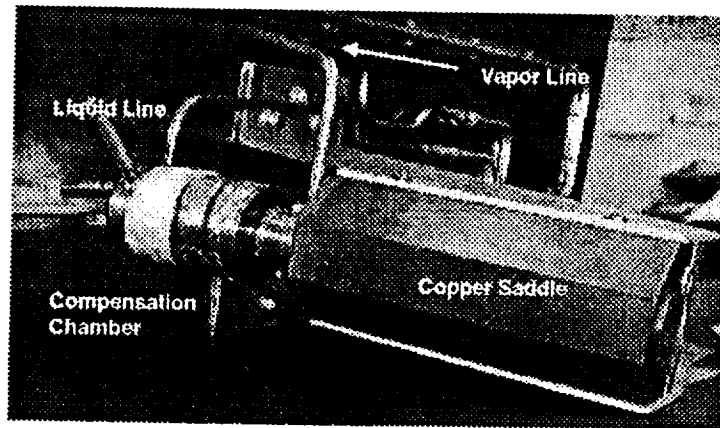
Figure 1 GLAS LHP

Figure 2 GLAS LHP Evaporator and
Compensation Chamber

the LHP evaporator and a heater block was used to simulate the laser box. The second set of tests was conducted utilizing the GLAS prototype LHP. In these tests, heaters were used to simulate the heat pipe condenser. The purpose of these tests was to evaluate the thermal performance characteristics of the LHP. In order to characterize the performance of the system as a whole, the last set of tests was performed with the complete assembly of the heat pipe and LHP. This paper solely concentrates on the results of the second and third series of tests.

BACKGROUND

The loop heat pipe was developed in the former Soviet Union in the early 1970's.[1] Similar to two-phase capillary pump loops, it is comprised of three main parts: an evaporator section, a transport section, and a condenser

section.[2] The primary difference between capillary pumped loops (CPLs) and LHPs is the location of the two-phase accumulator. In CPLs, the accumulator is called a reservoir and, depending on the evaporator design, is removed from the evaporator by either a reservoir feed line or liquid line. Due to this physical separation, in CPLs, the accumulator is not directly thermally coupled to the evaporator. In LHPs, the accumulator is called a compensation chamber (CC) and it forms an integral part of the evaporator. The CC is joined to the evaporator by a capillary connection, which is facilitated by a wick structure. The secondary wick structure ensures that the evaporator wick remains wetted at all times.

Figures 1 and 2 show actual photographs of the GLAS LHP. As heat is applied to the evaporator, liquid is vaporized. The vaporized

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fluid flows through the vapor transport section and into the condenser where heat is removed from the fluid. If the maximum heat rejection capacity of the condenser is not reached, the vapor is condensed and the fluid exits as a subcooled liquid. The liquid then enters the liquid transport section, flows through the bayonet tube in the CC and into the evaporator. This constant supply of liquid to the evaporator is what makes the LHP so robust.

Since the evaporator and CC are connected to each other, when power is applied to either of the two an exchange of energy occurs. This exchange of energy, which is referred to as a heat leak, has two sources. The one of least importance is the energy conducted through the metal envelope. Although of secondary importance, this transfer of heat does contribute to the overall heat leak between the evaporator and CC.

However, more important is the energy conducted from the evaporator to the CC across the wick. If the liquid in the cavity between the evaporator and CC is two-phase, a heat pipe effect occurs; i.e. the evaporator behaves as a heat pipe evaporator while the CC behaves as a heat pipe condenser. So when heat is applied to the evaporator some of that energy is transferred to the compensation chamber and vice versa. Once the loop begins operating, the subcooled liquid exiting the condenser becomes instrumental in maintaining stability in the CC because of the heat leak. In addition to verifying the heat transport capability, this paper will also describe how the heat leak and the distribution of liquid between the evaporator and CC impact the loop's operation.

TEST PREPARATION AND SETUP

The prototype LHP consists of an evaporator with an integral CC, a condenser, a vapor transport line, and a liquid transport line. The evaporator is cylindrical with a diameter of 25.4 mm and a length of approximately 150 mm. Its envelope is constructed of low carbon steel and it contains a sintered nickel wick structure with an effective pore radius of less than 1.2 μm. A copper saddle, to hold three 100 W cartridge heaters, is attached to the evaporator's envelope. A 30 W heater was also mounted to the CC for temperature control purposes. The CC, which is used to hold excess liquid, is 76.2

mm long and has an outer diameter of 46 mm. The liquid and vapor transport lines are each 460-mm long. They are made from smooth wall tubing that is 5.54 mm in diameter and has a wall thickness of 0.51 mm. The condenser is a single pass, direct condensation heat exchanger. It is made from an extruded small diameter (outside diameter of 5.54 mm) aluminum tubing, with an integral fin. The heat exchanger, which is 4.06 m in length, is mounted to a radiator panel similar to that proposed for GLAS. The condenser tubing is bent into a serpentine shape, which makes passes across the panel. The integral fin or stiffening rib is removed in the bend zones to facilitate bending. The aluminum condenser tubing is attached to the stainless steel transport sections using bi-metallic joints.

In the second set of tests, cartridge heaters were used to simulate the heat pipe. However, in the third set of tests an aluminum heat pipe, which was fabricated in house, was used instead. The heat pipe was charged with 15.3 g of ammonia. To simulate the laser a heater block, with a 46 Ω resistance heater epoxied to the bottom, was attached to the evaporator section of the heat pipe. Due to the manufacturing of the heat pipe, it was necessary to test it in boiler mode, meaning that the condenser section of the heat pipe had to be elevated higher than the evaporator. As a result for all tests conducted with the heat pipe, the heat pipe was tilted 6.25 mm. For tests with the LHP, the CC was tilted such that it was angled beneath the evaporator.

Relays and variacs were used to control the heaters. A FTS chiller was used to cool the radiator panel. Copper/constantan (Type T) thermocouples were used to monitor temperatures at various locations throughout the system. Nomex was used to insulate the whole system. Data was recorded using a NEFF data acquisition system and LabVIEW.

TEST PROGRAM

The LHP was tested to 1) characterize the effects of several parameters on the system's start-up capabilities, 2) determine the response of the system to power/sink temperature cycling, and 3) investigate the ability of the CC to maintain the loop's operating temperature at a pre-determined set point. Based on those objectives, start-up, power cycle, sink
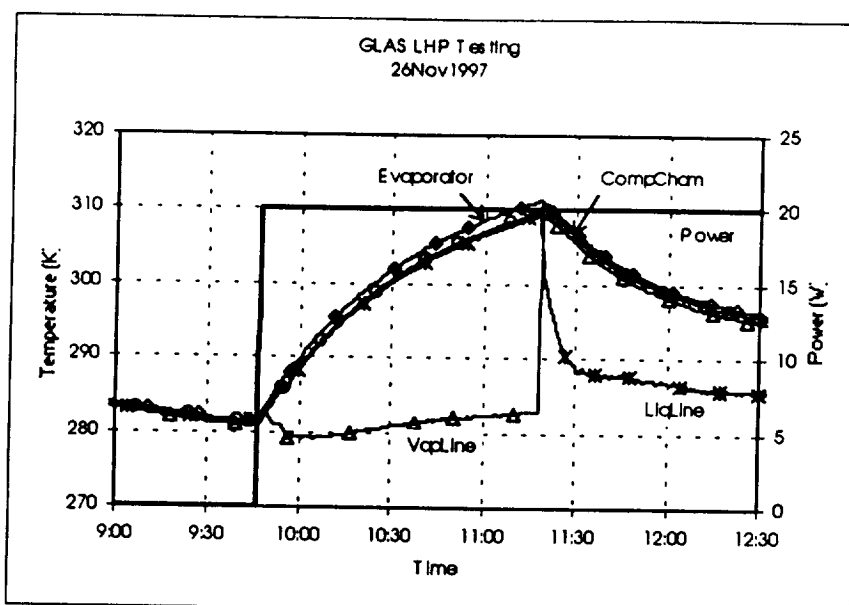
Figure 3 Non-controlled Start-Up With the LHP Condenser Vertical/Evaporator Level

temperature cycle, and steady state operations tests were performed with the LHP oriented in three positions. The first orientation was with the radiator panel vertical. These tests were completed with the centerline of the CC and evaporator leveled within 2.5 mm. Additional tests were completed with the evaporator tilted 6.25 mm below the CC. Later, the radiator was rotated 90° so that it was horizontal. In these tests, the CC was situated directly above the evaporator.

The prototype LHP had three cartridge heaters, two 100 W and one 150 W. The heat input for start-up was varied between 10 to 150 W, and the sink temperature ranged from 253K to 288K. After start up, the system was taken through either a series of power steps, sink temperature changes, or CC set point changes. Once testing was completed using the cartridge heaters, one of the heaters was replaced with the heat pipe.

TEST RESULTS

A total of 46 start-ups of the system were completed. These include tests with and without the heat pipe attached. Within those tests, numerous power cycle, sink temperature cycle, and steady state tests were performed. The CC temperature was either held constant or allowed to change with the system parameters. For tests with control, a thermostatically controlled heater

was used to maintain the CC temperature. The operation of the controller was very smooth, and no significant fluctuation was observed due to the controller.

The maximum power applied to the LHP was 350 W, more than three times higher than the nominal power of the GLAS laser diodes. No attempt was made to find the maximum heat load capacity of the LHP after the limit of electrical heaters was reached. In all the tests, the LHP did not show any sign of deprime.

Although the chiller was able to maintain the sink temperature within 4K of the chosen set point, some high frequency oscillations of the sink temperature were observed. Nonetheless, the effect of these fluctuations on the system performance was negligible since the induced fluctuations in the working fluid temperatures were less than 0.25K.

As previously mentioned, the LHP was tested with the condenser either horizontal or vertical and with either heaters or a heat pipe as the source of power. As a result, test observations are presented in four sections: condenser vertical and LHP evaporator level; condenser vertical and LHP evaporator tilted; condenser horizontal with LHP evaporator beneath the CC; condenser vertical, LHP evaporator tilted with heat pipe.

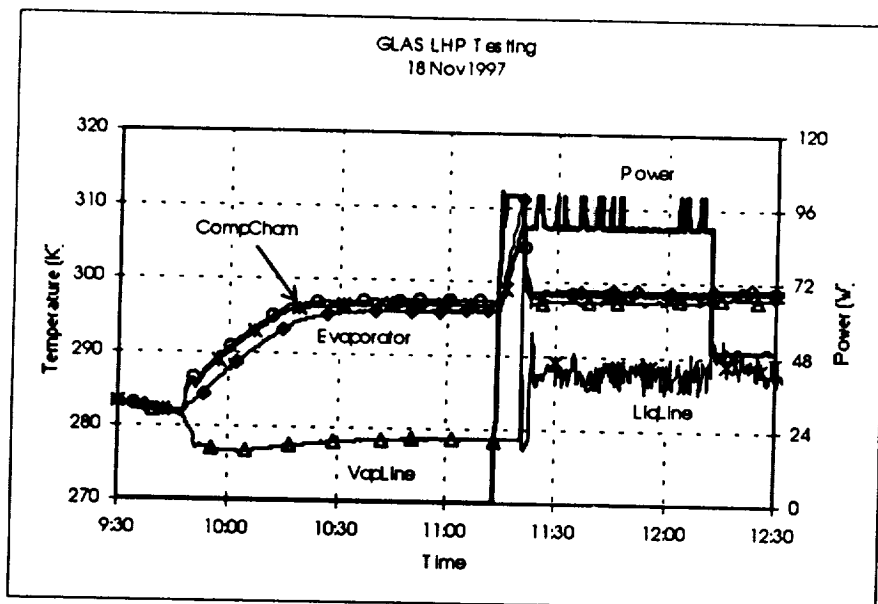**Condenser Vertical/LHP Evaporator Level**

Figure 4 Controlled Start-Up With the LHP Condenser Vertical/Evaporator Level

Start-up Tests—Loop start-ups were a significant part of the investigation. Table 1 presents a summary of the start-ups performed with the condenser/radiator vertical and level. A start-up was considered unsuccessful if after several hours, normally three to four, the system showed no indication of starting. In these tests the loop temperatures would level out without any evidence of nucleation or vaporization in the evaporator. Figures 3 and 4 show two successful start-ups.

Table 1 Results of Start-Ups With Condenser Vertical and the LHP Evaporator Level

Power	# of Attempts	# of Successful Start-Ups
25 W	4	1
50 W	2	2
90 W	1	1
100 W	13	13
150 W	1	1

For the test illustrated in Figure 3 the CC was not controlled, while for the test in Figure 4 the CC was set to 293K. For both tests, a heat load of 100 W was applied to the evaporator and the sink was kept at 273K. For test in this orientation, a couple of important phenomena were observed. The first could be directly attributed to the heat leak that was previously mentioned.

When power was applied to either the evaporator or CC, heat was conducted through the metal envelope to the secondary wick. Since the fluid in the channel between the evaporator and CC was probably two-phase, the evaporator and CC temperatures increased simultaneously when power was put into the system. The loop did not start until the temperature difference between the evaporator and CC facilitated nucleate boiling. More specifically, there needed to be enough power put into the evaporator so that it could surpass the CC temperature by at least a couple of degrees. Once this happened, incipient boiling would begin. If the evaporator was unable to overtake the CC, the two would continue to increase in temperature and eventually level off when the parasitic heat losses were equal to the input. Nonetheless, the loop would not start.

For powers between 50 and 150 W, the LHP started regardless of the sink temperature. The low power limitation of the system was found to be around 25 W. In the four 25 W start-up attempts only one was successful and it took 1.5 hours for nucleation to occur. In the other three tests, after 3.5 hours the evaporator and CC temperatures had slowly increased until they stabilized at 328K. At this point, the parasitic heat losses were equal to the heat input and the temperatures reached steady state without the
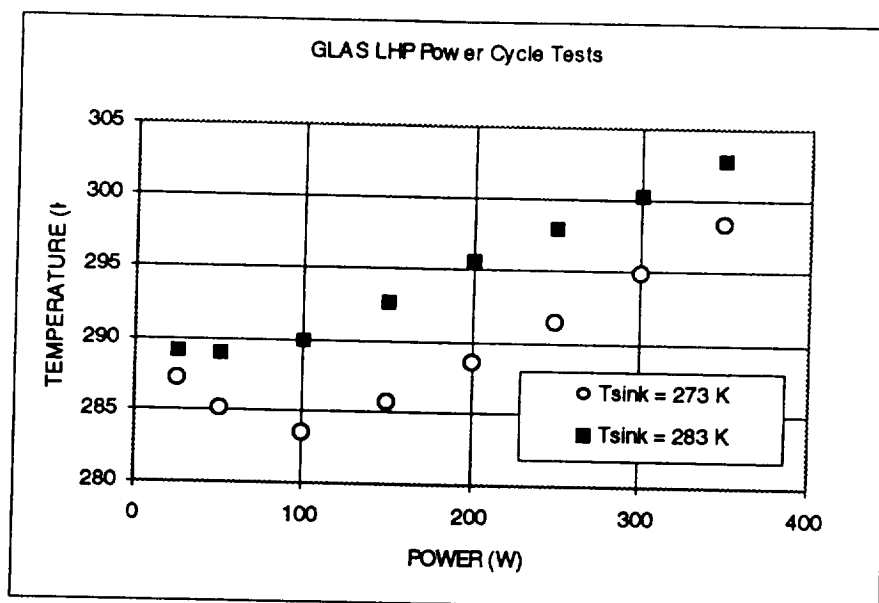
Figure 5 Effect of Power on Operating Temperature

loop starting. To better understand the low-power start-up characteristics, additional low power tests were conducted. Those results are discussed in the LHP/HP section.

The second phenomenon observed during start-up was the apparent reversal of flow through the CC and evaporator. When power was applied to the system, the liquid line temperature increased while the vapor line temperature decreased. This occurrence seemed to indicate that liquid was being drawn into the evaporator from the vapor line and vapor was flowing out of the CC into the liquid line. The flow reversal continued until the capillary pressure developed by the secondary wick in the CC and evaporator could no longer sustain the pressure drop developed in the system. At this point the vapor line temperature leveled somewhat. However, the liquid line remained vapor-filled and its temperature followed the evaporator temperature. As soon as nucleate boiling began and the primary wick began the pumping action, the liquid inlet temperature dropped to below saturation and the vapor line temperature increased to saturation. The vapor in the liquid line was either pushed into the CC or condensed by the influx of cold liquid from the condenser. The observations were seen over and over again in each of the start-ups with the radiator in this orientation.

Power Cycle Tests—In the real application, the laser power dissipation will remain relatively constant, but in the prototype testing it was desirable to see how the system would react to increases and decreases in power. For these tests, once the system started and the operation stabilized, the sink temperature was held constant and the loop was taken through a series of power steps depending on the power input at start-up.

In the tests where the CC was not controlled, there was a point on the power versus temperature curve where the lowest operating temperature was attainable (Figure 5). This temperature was a function of the sink temperature. Therefore, for tests performed with the same power input and different sink temperatures, the loop would stabilize at a lower temperature for the colder sink. Once the loop reached this point, any increase or decrease in power resulted in an increase in the LHP operating temperature. In the controlled test, as long as the CC set point was higher than the system steady state operating temperature for the non-controlled conditions, the CC was able to maintain the temperature within ±1K. When this no longer held true, the CC lost its control over the loop operating temperature and the loop functioned as it would have had the CC not been controlled. As observed throughout testing, for a

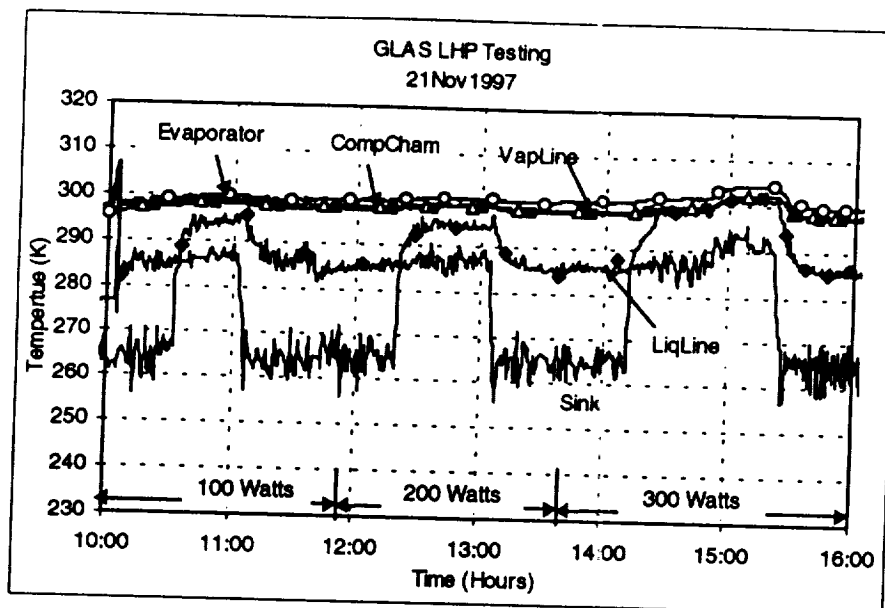American Institute of Aeronautics and Astronautics

Figure 6 Sink Cycle Test

given evaporator power, the system reached a steady state temperature that was a function of the heat leak between the evaporator and the CC, parasitic heat losses/gains, the sink temperature, and the ability of the condenser to reject heat. Throughout loop operating, depending on the conditions in the loop, one or several of these factors became dominant.

In the non-controlled tests, the steady state temperature was always the lowest temperature achievable under those conditions. If power was increased, the CC temperature increased because of the heat leak and the increase in the condenser temperature. When power was decreased, the CC temperature increased because of the heat leak, the slower fluid flow rate, and the parasitic heat gains.

For the controlled tests, when the power was increased to the point where the condenser became fully utilized the ability of the condenser to reject heat was the dominant factor in determining the LHP's operating temperature. Prior to the condenser becoming completely fully opened, the loop operated in variable conductance mode. In this mode of operation, as power was increased or decreased, the vapor front in the condenser shifted back and forth utilizing only the area necessary to reject the heat. Once the condenser became completely opened, the liquid returning to the CC was no

longer subcooled. The combination of the heat being leaked from the evaporator to the CC and the warmer liquid from the condenser resulted in a rise in the CC temperature. The compensation temperature increased until it reached a new set point such that the condenser could not only dissipate all the heat input in the system, but also provide subcooling to the liquid returning back to the evaporator. As a result, the subcooled liquid counterbalanced the heat leak and enabled the CC to maintain the new saturation temperature. The new operating temperature was the steady state temperature the system would have achieved, under the same conditions, had the CC not been set.

When the evaporator power was lowered below the optimal power, the effects of the heat leak became the governing factor. At higher powers, the cold liquid returning to the CC kept it at an equilibrium temperature. However, as the heat load to the evaporator was decreased, the mass flow rate of the fluid slowed as well. This resulted in a higher CC temperature. When the heat leak from the evaporator to the CC was minimized, a decrease in power resulted in a decrease in the operating temperature.

Sink Temperature Cycle Tests—Varying the sink temperature and holding the power constant had similar effects as varying the power and holding the sink temperature constant. In

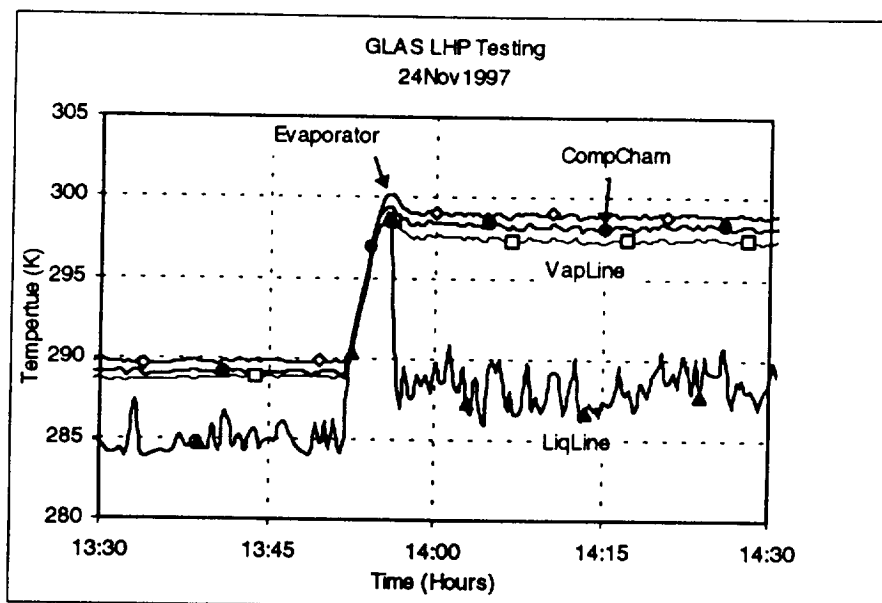American Institute of Aeronautics and Astronautics

Figure 7 Compensation Chamber Setpoint Change

the non-controlled tests, when the sink temperature was cycled, the LHP operating temperature increased or decreased depending on the temperature of the fluid leaving the condenser. For tests where the sink was lowered in temperature, the colder liquid from the condenser resulted in a decrease in the operating temperature. When the sink temperature was increased back to the original setting, the operating temperature increased to the previous value. As the sink temperature was increased, the loop operating temperature increased due to the influx of warmer liquid into the CC. The primary difference between the controlled and non-controlled test was that in the controlled test, the CC was able to maintain the loop operating temperature until the condenser heat dissipation capacity was exceeded.

Figure 6 shows a controlled test where the CC was set to 298K. For this test, in order to fully utilize the condenser, the power was increased from 100 to 300 Watts and sink temperature was cycled between 263 and 283K. The operating temperature was fairly constant up to 300W as the sink temperature was cycled between 263K and 283K. However, when the sink temperature was increased to 288K, the condenser was no longer able to reject all the heat and have the loop operate at 298K. At this time, the CC lost its control over the loop

operating temperature. At the higher operating temperature, the condenser was able to dissipate the heat load and still provide enough subcooling to keep the CC at the equilibrium set point. The loop eventually reached steady state at a higher operating temperature. Again, when the sink temperature was lowered back to 263K, the CC resumed control of the loop and maintained its temperature at the set point.

Steady State Operation Tests—Six steady state operating tests were performed. For all of these tests, the LHP was very stable with no noticeable degradation in system performance.

Table 2 Steady State Operation Tests With the Condenser Vertical and the LHP Evaporator Level

Power	Sink Temp	LHP Evap Temp	CC Temp	Duration of Test
25 W	263K			12 Hrs
25 W	273K	287K	286K	12 Hrs
50 W	273K	285K	284K	12 Hrs
50 W	283K	289K	288K	12 Hrs
100 W	273K	281K	280K	3.5 Hrs
100 W	283K	295K	294K	3.5 Hrs

CC Temperature Cycling Tests—Most tests were performed with the CC temperature set to 298K. To study the effect of varying the control temperature on the loop performance, several tests were performed by cycling the CC set point between 288K and 298K and holding

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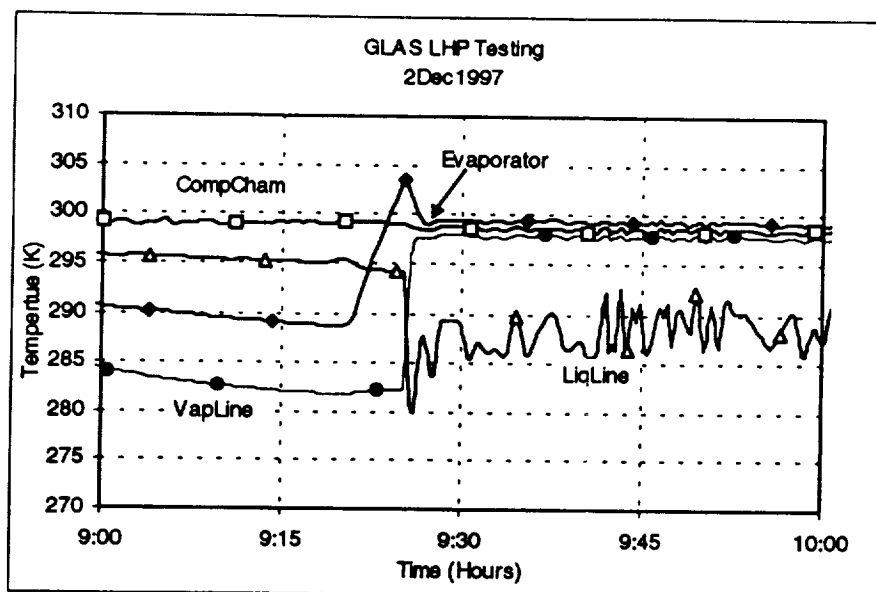American Institute of Aeronautics and Astronautics

Figure 8 Start-Up Test With the LHP Condenser
Horizontal/Evaporator Beneath the Compensation Chamber

the sink temperature and evaporator power constant.

In test where the CC set point was decreased from 298K to 288K, the evaporator and the vapor line temperatures dropped accordingly. Since a portion of the condenser remained flooded, the liquid line temperatures were not affected. However, when the CC control temperature was raised back to 298K, a quick reverse flow was observed as shown in Fig. 7.

The CC heater power was approximately 20 watts. When the controller turned the power on, the sudden expansion in the CC resulted in an expulsion of two-phase liquid into the liquid line. At the same time the evaporator continued to generate vapor. During the temperature increase, the liquid line, vapor line, and evaporator climb along with the CC. At some point in the loop, near the end of the vapor line, a stagnation point occurred because the flow is pushing in both directions. Once the CC reached the new set point, the liquid inlet temperature dropped as the fluid starting flowing in one direction—through the vapor line, condenser, liquid line, and into the CC. Eventually, the loop temperatures reached

steady state with the operating temperature controlled by the CC temperature of 298K.

Condenser Vertical/LHP Evaporator Tilted 6.35mm

Since the heat pipe had to be tested in boiler mode, it was desirable to test the LHP with the same tilt to determine the effect of the heat pipe on the overall performance of the LHP. Therefore, the evaporator was tilted 6.35 mm below the CC. The tests results with and without the heat pipe were the same, but the total pressure drop in the loop, the overall thermal conductivity of the core wick, and the heat leak were all affected by the tilt.

When the condenser was in the vertical position all the start-ups were preceded by a reverse flow regardless of whether or not the CC temperature was controlled or what the CC set point or sink temperatures were. When the condenser was in the horizontal position, no reverse flow was observed, prior to nucleate boiling—again irrespective of controlling the CC or sink or CC set point temperatures. However, for tests performed with a tilt, reverse flow was random. In three of the seven controlled start-ups performed no reversed flow was observed. However, in the two non-controlled start-ups, reverse flow was observed. At this time there is
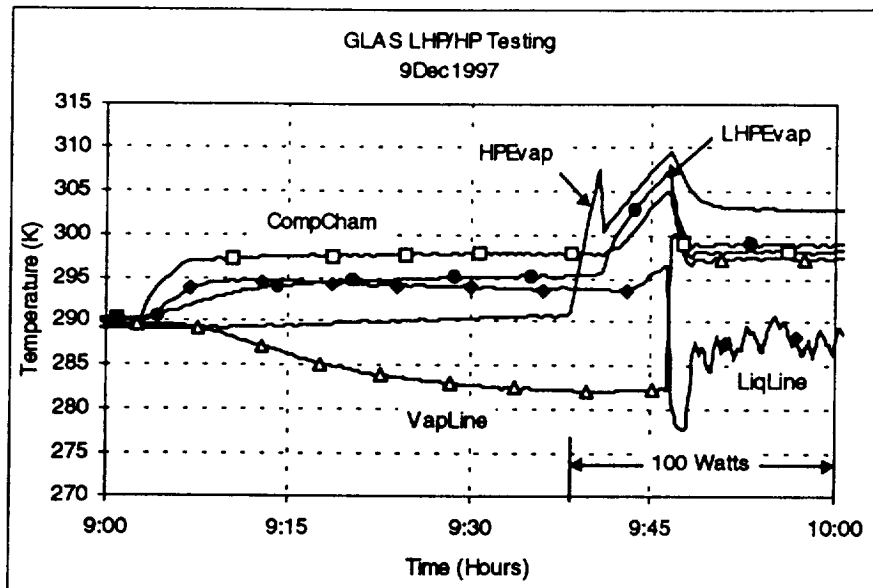
Figure 9 Start-Up Test With the Heat Pipe/LHP Assembly

no logical explanation for why the reverse flow was random.

Condenser Horizontal/LHP Evaporator Beneath the CC

By rotating the condenser 90°, the vapor connection between the CC and evaporator was substantially reduced because the heat leak is transmitted only by conduction. This impacted mainly the start-ups. The other test results were similar to those described in the previous sections. As a result, only the start-ups will be discussed in this section.

With the condenser above the evaporator, the secondary wick between the evaporator and CC was totally flooded prior to start-up. Consequently, unlike the start-ups with the condenser in the vertical position, no reverse flow was observed prior to the onset of nucleate boiling (Figure 8). Furthermore, when power was applied to the evaporator, the CC temperature was unaffected and the evaporator temperature increased until boiling incipience. Once the system started, the evaporator temperature reached steady state at a temperature slightly higher than that set by the CC temperature.

Heat Pipe/LHP Assembly Testing

Start-up Tests—Table 3 shows the results of the start-up attempts. Heat was directly applied to the heat pipe evaporator though a heater block. Then, the applied heat was transferred to the LHP evaporator through the heat pipe condenser. The LHP response was expected to be similar to the previous case where the heat was directly applied to the LHP by the cartridge heaters.

Table 3 Results of Start-Up Tests With the Heat Pipe/LHP Assembly

Power (W)	# of Start-Up Attempts	# of Successful Start-Ups
10	1	0
25	4	1
35	2	1
50	1	1
100	4	4

Figure 9 shows the LHP temperature profiles as well as the heat pipe evaporator temperature for a 100 W, 273K sink, controlled start-up test. As depicted in Figure 9, nucleate boiling occurred in the heat pipe before the LHP. Once this occurred, the heat pipe temperatures immediately dropped. The heat pipe then started transferring heat to the LHP causing its temperatures to increase. Since the heat pipe was not able to reject the 100 W until the LHP started, its temperatures started increasing with the LHP evaporator. As a result, the temperatures on the heater block and heat pipe often got up to 308K before the system started.

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Once the LHP started, the heat pipe temperatures dropped and reached a steady state value that was several degrees higher than the LHP evaporator temperatures. The resulting temperature drop from the heater block to the LHP evaporator was approximately 10K. Therefore in order to run the heater block (laser) at 293K, the LHP had to run at 283K. Of course, the temperature drop is a function of the interface conductances.

To better understand the low-power start-up characteristic of the system, several start-ups at 10 W and 25 W were attempted. Only one start-up at 25 W was successful (refer to Table 3). The sink temperature was set to 273K, and the CC was not controlled. It took approximately 3 hours for the system to start. The evaporator temperature went up to 315K. Two more attempts to reproduce this start-up at the same conditions were unsuccessful.

25 Watts is probably very close to the minimum power required to start this LHP. This would suggest that the start-up is dependent upon the heat leak between the evaporator and the CC. If the heat leak from the evaporator to the CC is high relative to the net heat to the evaporator, the evaporator will not be able to generate the necessary superheat to initiate nucleate boiling, and the loop will not start.

Power and Sink Temperature Cycling Tests—The LHP responded to the power cycle and to the sink temperature cycle tests in the same manner as the previous tests performed without the heat pipe attachment. It is important to note that as the power was increased, the temperature drop between the heat pipe evaporator and LHP evaporator increased significantly. This indicates the need to improve the thermal conductance between the heat pipe and the LHP evaporator. Nonetheless, for a power input of 100W and a sink temperature of 273K, the LHP was able to maintain heat pipe heater block at 293 ±2K. When the sink temperature was cycled, the heat pipe evaporator temperature remained constant until vapor blew through the LHP condenser and it fully opened. Once this occurred, the LHP's temperature increased, resulting in an increase in the heat pipe operating temperature and subsequently the heater block temperature.

CONCLUDING REMARKS

The LHP tested in this program utilized a wick structure between the evaporator and CC. Due to the internal design, a vapor connection existed between the two. As seen in the test data, this was very significant. This resulted in prolonged start-ups and higher temperatures before nucleation occurred. When the vapor connection was substantially reduced the system started like a CPL.

When the HP/LHP assembly was tested, the heat pipe started before the LHP but its temperature did not stabilize until the LHP started. Again, depending on the distribution of fluid through the system and the power input, start-up sometimes took hours. Once steady state was reached, the system was able to meet GLAS' requirements of maintaining the heater block at 293K ±2K for a sink of 273K. For all of the tests, the response of the system to power steps, sink temperature changes, and CC set point changes was explainable and reproducible.

The test program described in this paper was designed to verify the capabilities of this prototype LHP. Some of the test observations may require design changes or additional tests of which the results will be presented in future publications.

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