Propylene Loop Heat Pipe Design and Thermal Performance

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ABSTRACT

A pair of propylene Loop Heat Pipes has been designed, built, tested and delivered for use in cooling the 2 main Ocean Color Instruments for the Plankton, Aerosol, Cloud, ocean Ecosystem satellite, due to be launched by NASA in 2023. The target operating condition was to convey 5W-20W in the -40C to -20C temperature range. All wetted materials were stainless steel, while aluminum Saddles and Radiator Panels were used to enhance heat spreading. The Evaporator Wick was 100mm long and used micron scale sintered powder. The Radiator, at 660mm x 326mm, was machined from an aluminum block rather than being assembled as a composite. Maximum heat transport was measured at 180W. A special round of testing to assess the capacity of the Secondary Wick qualified the design. The units were delivered in a flat configuration to enable thorough ground testing, and then bent into the final configuration for installation into the instrument.

NOMENCLATURE

FPA = Focal Plane Array, the active sensor device that requires cooling
G10 = A phenolic composite material
LHP = Loop Heat Pipe
OCI = Ocean Color Instrument
LRL = Liquid Return Line
PACE = Plankton, Aerosol, Cloud, ocean Ecosystem satellite
Q = Heat Load (Watts)
RGA = Residual Gas Analyzer
TVac = Thermal Vacuum Testing
UVVIS = Ultraviolet to Visible wavelength spectrometer instrument
VISNIR = Visible to Near Infrared wavelength spectrometer instrument
W = Watts, the unit of measure for power and heat
ΔT = Temperature Differential

INTRODUCTION

The Ocean Color Instrument of NASA’s Plankton, Aerosol, Cloud, ocean Ecosystem probe has two spectrometers, a UVVIS and a VISNIR, that are used to survey the color of the earth’s oceans as a means of assessing their health. Each spectrometer dissipates about 20W and operates in the temperature range of -40C to -20C. Two Loop Heat Pipes are used, one for each spectrometer, to remove the heat and reject it to space. The LHPs use propylene as a working fluid and all wetted surfaces are stainless steel. The Evaporator has an aluminum Saddle that interfaces with the Focal Plane Array heat source and conducts the heat to the LHP Wick. The stainless steel Condenser Line is soldered into a serpentine groove in a machined aluminum plate to serve as a Radiator. LHPs share the same Evaporator/Reservoir Pump design, and have similar Radiators. The Transport Lines use the same tubing size but the UVVIS is about 1.8x the length of the VISNIR. The Transport Lines were fabricated in a straight configuration. The LHP's were processed in that straight form, and initial thermal vacuum testing was done with the LHP mounted horizontally, to simulate zero-gravity. After initial testing was complete, and performance confirmed, the Transport Lines were (very carefully) bent into the final shape and the thermal performance confirmed with another round of TVac testing. Three pairs of LHP's were delivered, with one pair to be used for flight hardware.

PERFORMANCE REQUIREMENTS

The specification for the Loop Heat Pipe includes the following:

Parameter	Magnitude
FPA Heat Load	Minimum 5W, Maximum 20W
Transient Heat Transport Requirements (estimated Cold Start condition)	Maximum 90W
Operating Temperature Range	-40C to -20C, at the Evaporator
Sink Temperature Range	-159C to -123C, see Figure 1
Temperature Control	±0.5C over a 90 minute period
Storage Temperature Range	-55C to 45C
Mass	3100g VISNIR
	3200g UVVIS

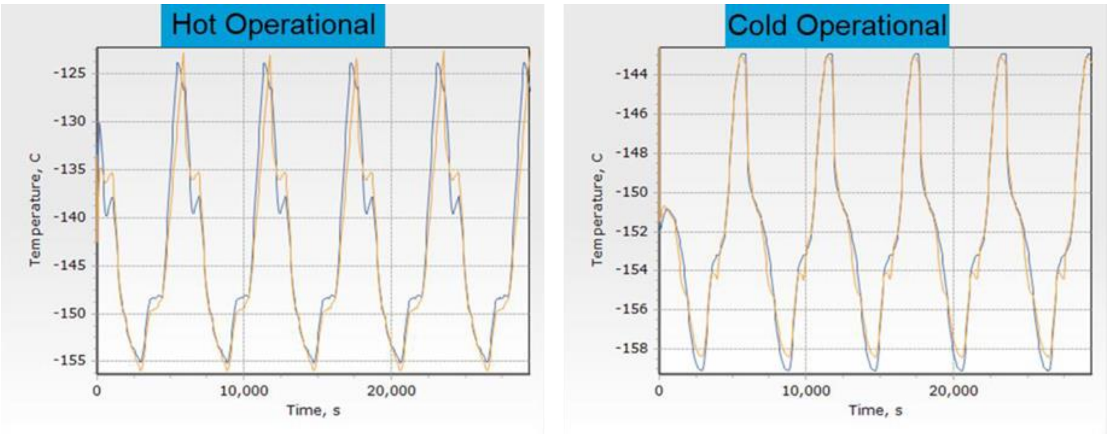

Figure 1. Sink Temperature Ranges for Hot and Cold Operation

PHYSICAL DESCRIPTION

The OCI Loop Heat Pipe designs are a stainless steel loop charged with propylene, with an aluminum Saddle and Radiator panel for improved conductance at the heat inflow and outflow stations. Both LHP designs use the same Evaporator/Reservoir Pump design. The Evaporator Wick uses sintered stainless steel powder, with a pore radius of ~1.5 x 10^{-6} m and permeability of ~1 x

10^{-14} m^2. The Wick outer diameter is 15.6mm, bore diameter 6.5mm, and length 109mm. The outer surface of the Wick is scored with circumferential and longitudinal vapor grooves. The Wick is embedded in a stainless steel Sleeve, which in turn is embedded in the aluminum Saddle. The Reservoir is mounted on-center to the Wick. The Liquid Return Line enters on that center at the back end of the Reservoir and passes through the Reservoir and up into the central bore of the Primary Wick. There it delivers returning liquid to the Primary Wick. There is a screen wick assembly that lines the interior of the Reservoir and wraps tightly around the Liquid Return Line in the central bore of the Primary Wick. This Secondary Wick delivers liquid to the Primary Wick in situations when the massflow of vapor out exceeds the massflow of liquid in through the Liquid Return Line.

Figure 2 shows the Pump design, with the overall dimensions displayed. Note the Start-Up Heater Mount at the vapor-outlet end of the Evaporator and the Thermostat Mounts on the Reservoir. The following heaters are mounted on the Evaporator and Reservoir:

Start-Up Heaters	1 prime & 1 redundant	10W	chassis mount, mounted to Evaporator Saddle
Control Heaters	1 prime & 1 redundant	6.5W	polyimide tape, wrapped around Reservoir
Shutdown Heater	1	5W	polyimide tape, wrapped around Reservoir

The Start-Up Heater power level was selected on the high side relative to the FPA heat load to ensure that the circulation started on the “right hand side” of the LHP performance curve. The Control and Shutdown heat loads were chosen empirically based on values that resulted in effective control of the LHP.

Also note the Liquid Return Line Brace on the Reservoir. It supports the Liquid Return Line as it approaches the Reservoir.

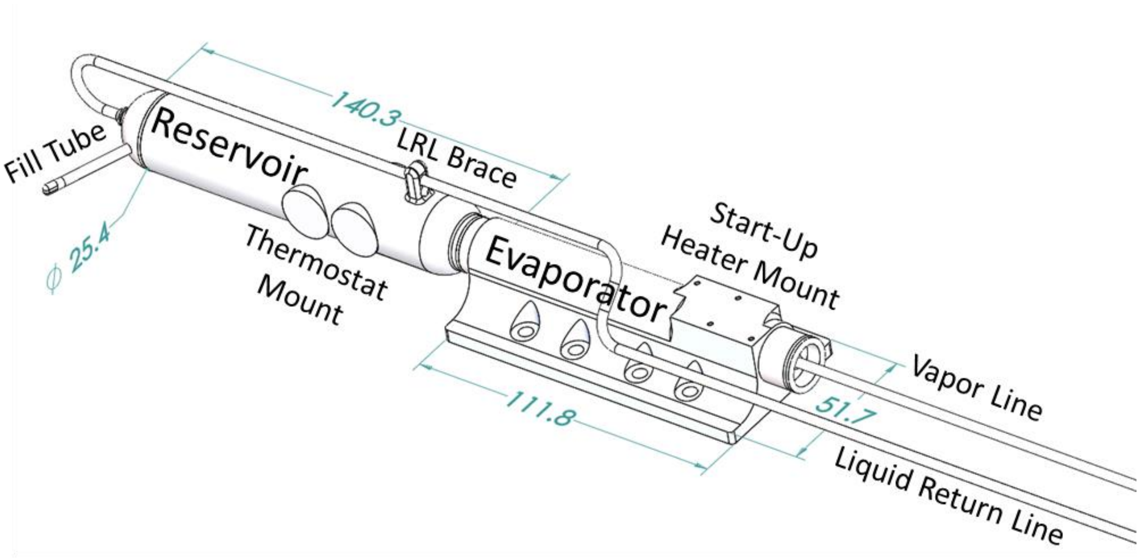

Figure 2. Evaporator/Reservoir Pump Geometry (Dimensions are in mm).

The Radiator utilized the stainless steel Transport Line soldered into a serpentine groove in an aluminum plate. The aluminum was nickel plated to allow solder adhesion to the Radiator. Figure 3 shows the design of the VISNIR Radiator, with the Condenser Line highlighted in blue. Figure 4 shows the actual solder joint, with a good meniscus between the tube and the groove.

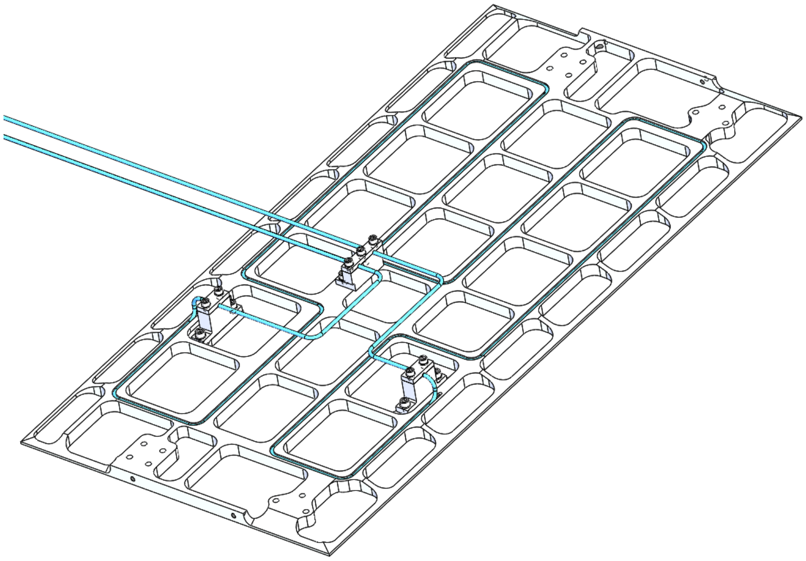

Figure 3. Condenser Section of the Transport Line Soldered into the Serpentine Groove in the VISNIR Radiator Panel

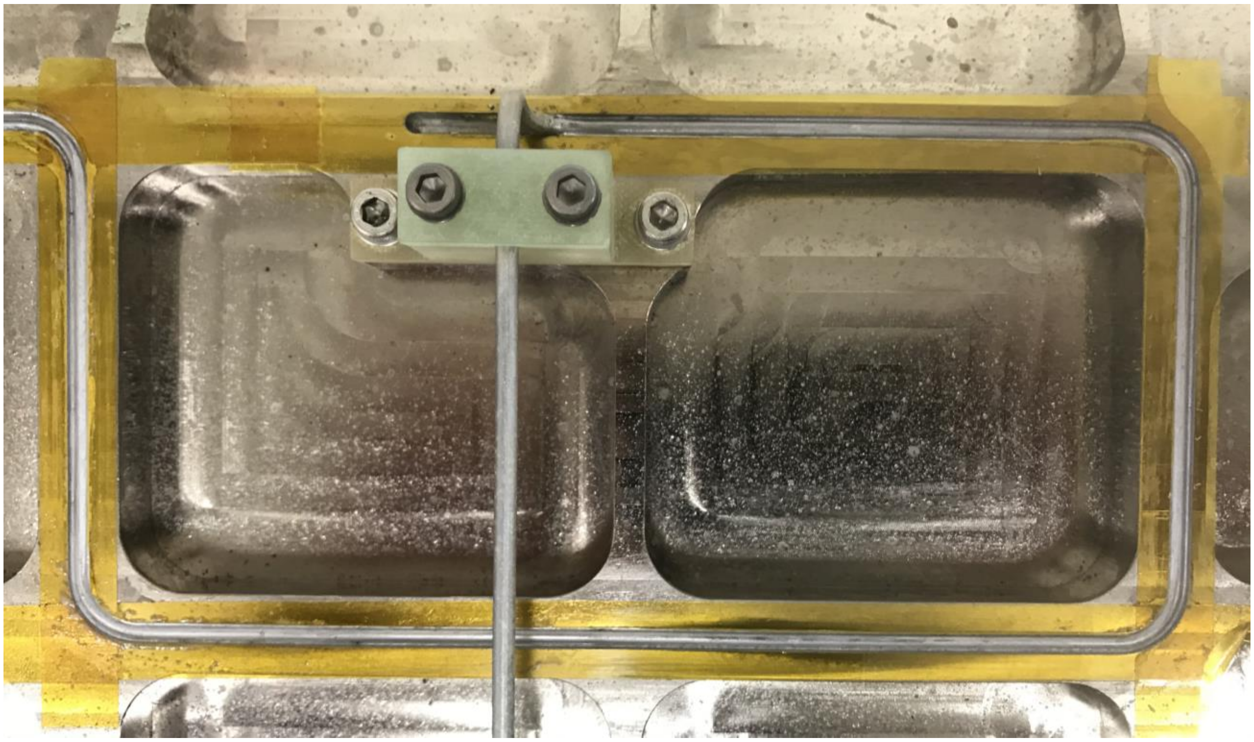

Figure 4. Condenser Section of the Transport Line Soldered into the Serpentine Groove in the Radiator Panel, with a G10 Tube Support Mount

The Radiators for the two LHPs are very similar, being the same width and height, and being machined aluminum plates with an “egg carton” construction and having a serpentine path for the Condenser Line. The LHPs are shown side-by-side in Figure 5. It can be seen there that the basic serpentines are very similar. For the UVVIS the Transport Lines from the Evaporator enters offset to the side, while with the VISNIR the Transport Lines enter closer to the middle of the Radiator. Both designs use G10 Tube Mounts to control the height of the Transport Lines and reduce pull-out stress where the Transport Lines enter the solder groove. The two designs’ major difference is the distance between the Evaporator and the Radiator, as shown by the dimensions in Figure 5. This differential accommodates the differing placements of the FPA heat sources and the radiator mounting. Figure 6 shows the final bend shapes and the relative mounting. The longer tubes of the UVVIS make a negligible difference in the pressure drop of the fluid flow through the LHP. They do require slightly more working fluid for the UVVIS, 26 grams vs 25 grams.

Three pairs of LHP were constructed and tested:

UVVIS	VISNIR
SN001	SN002
SN004	SN003
SN006	SN005

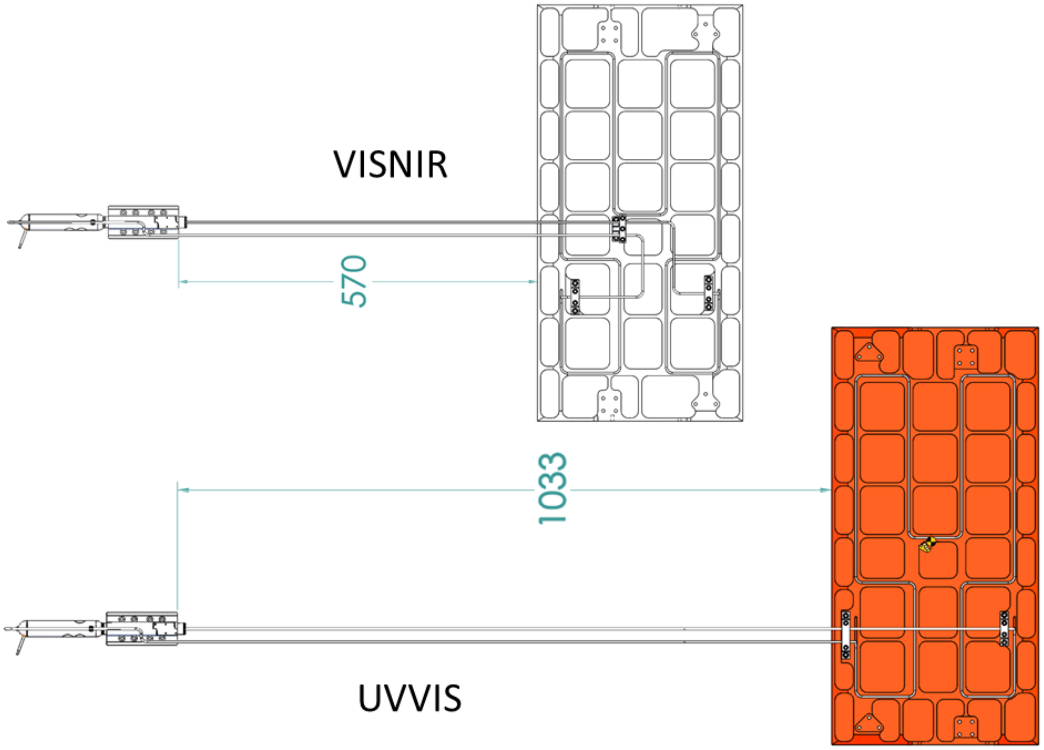

Figure 5. LHPs in the Flat Configuration, Showing Relative LHP size

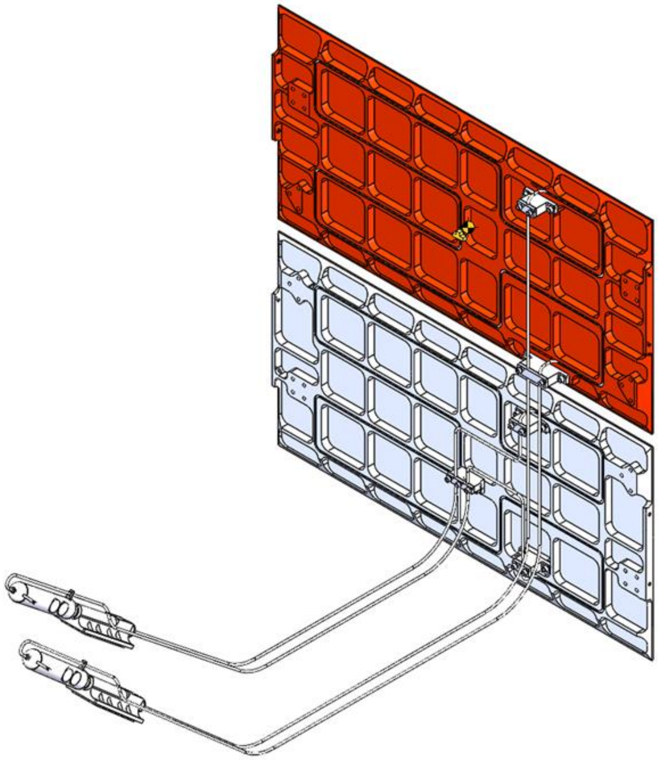

Figure 6. The Final Bent Shape of the LHPs, and their Relative Placement

I. Fabrication Procedures

A. Primary Wick

The Wicks were sintered in-house from stainless steel powder into ingots ~20mm diameter and ~20cm length. The Wick was qualified by taking a sample off the top of the ingot to use for pore radius and permeability tests. The pore radius is a “last bubble” tests where the Wick sample is saturated with acetone, pressure applied to one side of the sample and a bubble flow through the sample is established. The pressure is allowed to gradually decay. When the bubbles cease to flow then the corresponding pressure is used to calculate the effective pore radius of the Wick. Aavid has a tradition of using a “last bubble” test rather than “first bubble”, as the “last bubble” test is more conservative. Its result is a slightly lower pressure than the “first bubble”, which leads to a slightly larger estimate of pore radius. Also the “last bubble” test is more repeatable. It does not depend on a transient vapor wave front progressing through the saturated porous media. Additionally a simple permeability test is done by correlating a pressure drop to a flow rate of acetone through the sample. If the measurements meet the standard for the Loop Heat Pipe design then the Wick is machined from the sintered ingot.

B. Evaporator Saddle

The machined Wicks are inserted into stainless steel Sleeves, which are then inserted into aluminum Saddles. Each of these joints is an interference fit, giving a hard squeeze between the parts and a low thermal resistance for heat conducting across the joint. After the Sleeve-into-Saddle insertion the final machining of the Saddle and Sleeve are done.

C. Reservoir and Secondary Wick

The Secondary Wick assembly is constructed from very fine stainless steel screen. Different parts are fitted around the Bayonet Tube, an extension of the Liquid Return Line, and the inner surface of the Reservoir. Next the Bayonet Tube is fitted into the Reservoir and welded in place. A bubble test is done on the screen wick. The Fill Tube is welded to the Reservoir.

D. Evaporator/Reservoir Pump Assembly

The Reservoir has a knife edge cut into the end that interfaces with the Evaporator. After carefully checking alignment, the Bayonet Tube is inserted into the central bore of the Primary Wick. Insertion continues until the knife edge cuts into the Primary Wick and the Reservoir shoulder mates with the Sleeve. Those parts are then welded together to make a fully integrated Evaporator/Reservoir Pump assembly. Another bubble test is done.

E. Radiator/Transport Lines

After machining, the Radiator is nickel plated. In parallel the stainless steel Transport Line is bent into the corresponding shape to fit into the serpentine groove in the Radiator. The parts were mated together with Sn63/Pb37 solder. A thorough cleaning is required to remove flux residue. A Vapor End Cap that fits onto the vapor end of the Evaporator is welded onto the vapor line end of the Transport Line. A Ferrule is welded to the end of the Liquid Return Line portion of the Transport Line.

F. Evaporator/Condenser Integration

The final steps are to weld the Ferrule to the end of the Reservoir, connecting the Bayonet Tube to the Liquid Return Line, and weld the Vapor End Cap to the open end of the Evaporator. At that point fabrication is complete.

G. Contamination Control

Throughout the fabrication process care is given to contamination control. The presence of contaminants inside any heat pipe can lead to unwanted chemical reactions resulting in non-condensable gas that can degrade performance. Material Certifications are required of all materials. Project materials are stored in dedicated shelving. Dedicated work spaces are used to limit the introduction of unwanted materials. Particular care was taken during the sintering and machining of the Wicks and processing with the working fluid to exclude contaminants. Sintering is done in dedicated molds. Machining of Wicks takes place on a specially cleaned lathe, with no cutting fluids and only Wicks being machined for the duration. Processing is done on a dedicated processing rig with all new tubing and valves. Leak checking is done each time a Loop Heat Pipe is attached. Vacuum bake-out steps and multiple fill/vent cycles are included in the procedure to eliminate contaminants.

MECHANICAL TESTING

Various tests were done on the units as they progressed through the assembly process. Included were:

- Pore Radius Bubble Tests on the subassemblies; Wick, Secondary Wick, Knife Edge Seal & Evaporator.
- Transport Line Flow Restriction.

- Mass Spectrometer Helium Leak Checks to the subassemblies; Evaporator, Reservoir, and Transport Line, and the complete assembly.
- Vibration Tests; Evaporator/Reservoir Pump subassembly and Transport Line/Radiator subassembly.
- CT Scan of Knife Edge Seal and Wick, before and after vibration test.
- X-Ray examination of Transport Line solder joint into the Radiator after vibration test.
- Proof Pressure (3.3 MPa) test on the complete assembly and Thermal Proof Pressure (75C/3.4 MPa) test on the propylene charged assembly.
- Pinch-off Leak Check via RGA check with the sealed assembly in the vacuum chamber.
- Secondary Wick Heat Transport Capability test.

THERMAL TESTING

Thermal Vacuum Thermal Performance testing was done on each delivered unit at the Aavid facility in the flat configuration. NASA conducted further thermal performance testing in the flat and the bent configurations for the first pair, and for the bent configuration for the second pair. In Aavid’s thermal testing an electrical resistance heater was mounted to the Evaporator to control the heat load. A chiller-cooled cold plate was mounted to the Radiator, with a simple bolted interface, with Chomerics Chotherm Thermal Interface Material mounted between the cold plate and Radiator. 40 type-T thermocouples were located at locations on the Evaporator, Reservoir, Radiator and Transport Lines. A tape heater was wrapped around the Reservoir, in the aft section near the Fill Tube. This was used at low power to control the Reservoir temperature, and at a higher power to cut off circulation, One DC power supply drove the heat load to the Evaporator, and a second DC power supply drove current through the Reservoir heater. These two power supplies were controlled by the datalogger to adjust heat loads and control Reservoir temperature in the various stages of the test. The thermocouples were connected to a PC-based LabView datalogger. The datalogger collected temperatures from the thermocouples and voltages and currents from these 2 power supplies. It also exercised temperature control of the Reservoir heater and over-temperature shutdown. A third power supply drove the Start-Up heat; this one was not under logic control from the datalogger.

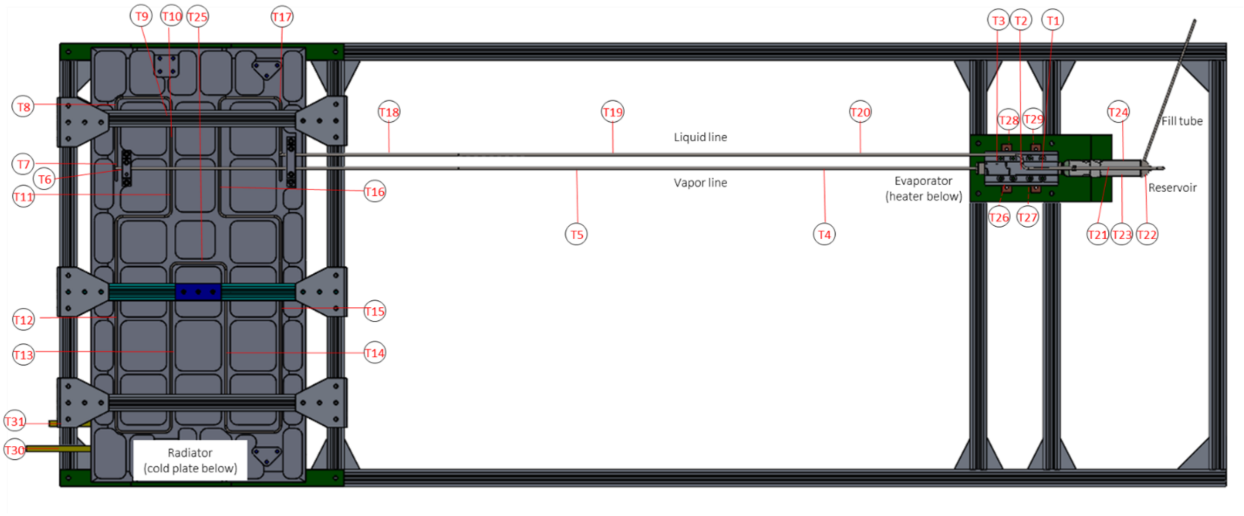

Figure 7. Thermocouple Map

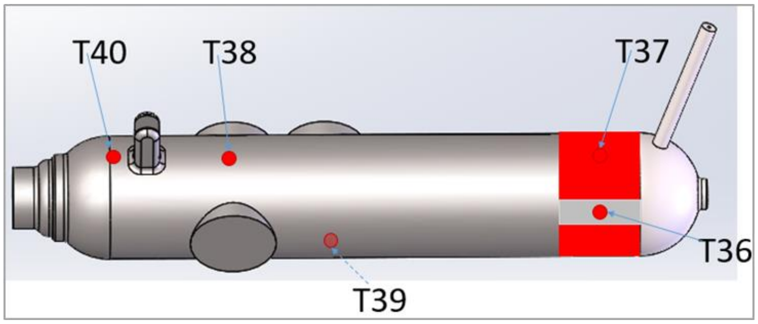

Figure 8. Reservoir, with Tape Heater and T36, the Control Thermocouple

The Evaporator and its heater block are shown in Figure 9. Note the large mass of the heater block, which is intended to replicate the mass of the FPA being cooled. Cartridge heaters are used to apply heat.

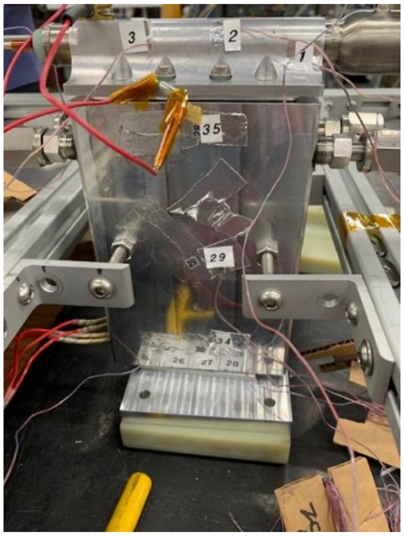

Figure 9. Evaporator Heater Block

Aavid’s vacuum chamber is 65cm in diameter and 3m in length and is driven by a diffusion pump. The chamber is shown in Figure 10. Typical vacuum level was about 1 x 10^{-5} hPa. The loop heat pipes were mounted in the chamber and carefully leveled with a calibrated inclinometer. MLI wrapped the entire LHP assembly.

Figure 10. Thermal Vacuum Chamber, with Loop Heat Pipe Mounted Inside

LOOP HEAT PIPE ACCEPTANCE TESTS

Thermal Vacuum Tests were conducted by Aavid on Loop Heat Pipes in the flat, horizontal orientation. After delivery NASA conducted further TVac testing, in both flat, horizontal, and bent, upright configurations.

1) **Cold Start Test**
   With the chiller circulating at -60C, apply 10W to the Start-Up Heater. Observe that the circulation commences by noting the rise in temperatures along the Vapor Line and drop in temperatures along the Liquid Return Line to below -50C. See Figure 11.

2) **Shutdown**
   While the LHP is circulating remove heat from the Evaporator and Start-Up heaters. Set the Reservoir Control Heater to 0C and power it with 5W. Note when the Reservoir temperature exceeds the Evaporator temperature. This indicates that the vapor pressure in the Reservoir is greater than in the Evaporator, causing cessation of circulation. See Figure 11.

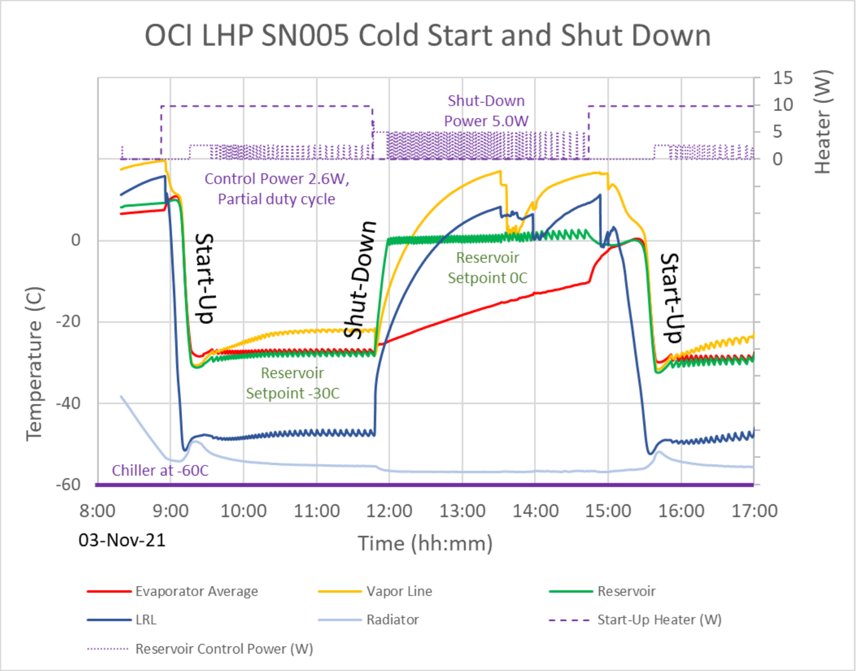

Figure 11. Cold Start Test and Shutdown Test

3) Day-in-the-Life at 15W

With 15W applied to the Evaporator, cycle the chiller temperature from -40C to -50C, back to -40C, and finally to -60C. The duration at each temperature is long enough for the LHP to come to steady state. This replicates the sort of heat sink temperature cycle the satellite is expected to see in orbit. The Reservoir temperature controller setpoint is set at -30C, though the Reservoir doesn't get that cold at the -40C chiller settings. See Figure 12. All the LHPs managed the sequence without their Primary Wick drying out.

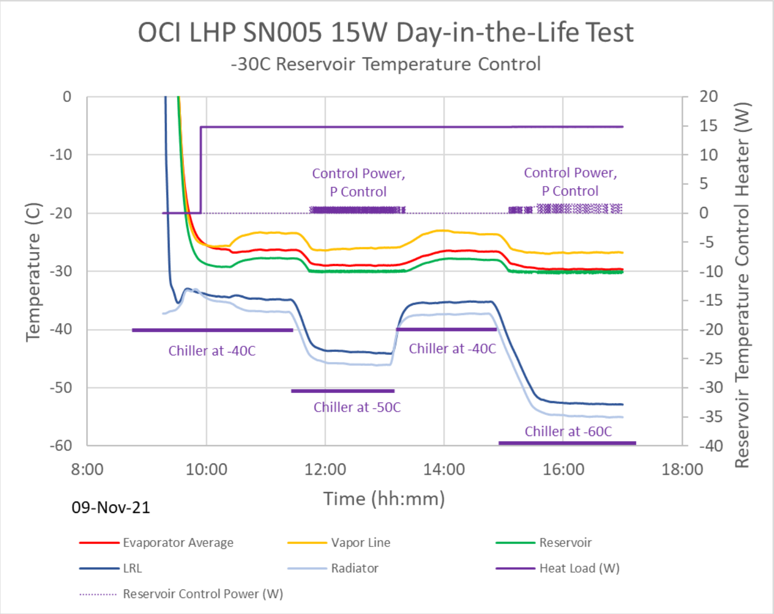

Figure 12. 15W Day-in-the-Life Test

4) Day-in-the-Life at 25W

With 25W applied to the Evaporator, cycle the chiller temperature from -40C to -50C, back to -40C, and finally to -60C. The duration at each temperature is long enough for the LHP to come to steady state. This replicates the sort of heat sink temperature cycle the satellite is expected to see in orbit. The Reservoir temperature controller setpoint is set at -30C, though the Reservoir doesn't get that cold at the -40C chiller settings. See Figure 13. All the LHPs managed the sequence without their Primary Wick drying out. Note that the waviness of the Evaporator and Vapor Line temperatures in the 12:00 to 16:00 time period were induced by the Reservoir temperature controller. Different control parameters and coefficients were tested out during this time period, some of which did not result in steady temperatures.

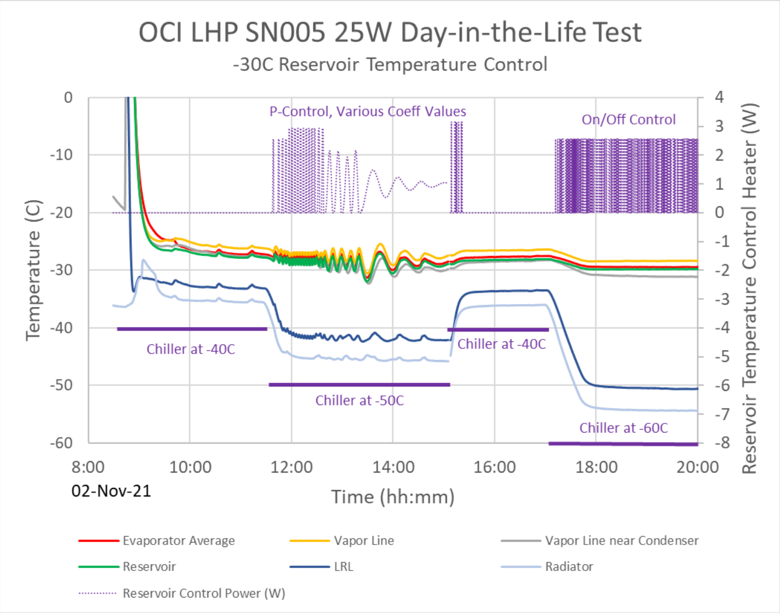

Figure 13. 25W Day-in-the-Life Test

5) Maximum Heat Transport Capability

With the LHP circulating and the chiller set at -40C the heat load applied to the Evaporator is stepped up in increments until the Evaporator temperature diverges from the Reservoir temperature, indicating dry-out in some location of the Evaporator. This shows the maximum heat load that the LHP can carry. See Figure 14 for SN005 test results.

The Loop Heat Pipes had the following Maximum Heat Transport Levels:

SN001	200W
SN002	180W
SN003	180W
SN004	160W
SN005	180W
SN006	155W

The measured maximum heat transport exceeds the FPA heat load by a very significant factor, at least 7.7. This extra margin was intentional to cover an estimated transient Cold Start heat load of 60-90W, when extra-cold liquid floods the Reservoir.

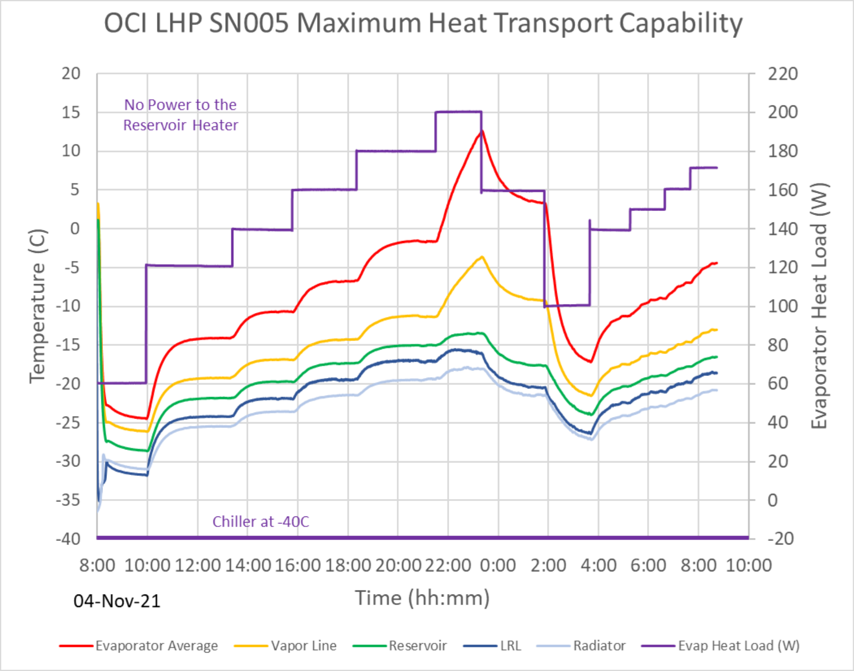

Figure 14. Heat Transport Capability Testing

6) Heat Load Step-Down Test

The Heat Load Step-Down Test stresses the Secondary Wick, whose job is to convey liquid from the Reservoir to the Evaporator during times when the mass flow of vapor out of the Evaporator exceeds the massflow of liquid returning in the Liquid Return Line. This happens when the Evaporator heat load drops from a high value to a low value, as the Condenser goes from being mostly filled with vapor to being mostly filled with liquid. The Step-Down exercise included these steps:

130W to 15W
130W to 50W
65W to 15W
65W to 25W

The test was done while the LHP was tilted in a slightly adverse configuration, with the tip of the Evaporator 5mm above the tip of the Reservoir. All units successfully managed the Step-Down transitions without their Primary Wick drying out. See Figure 15 for SN005 test results.

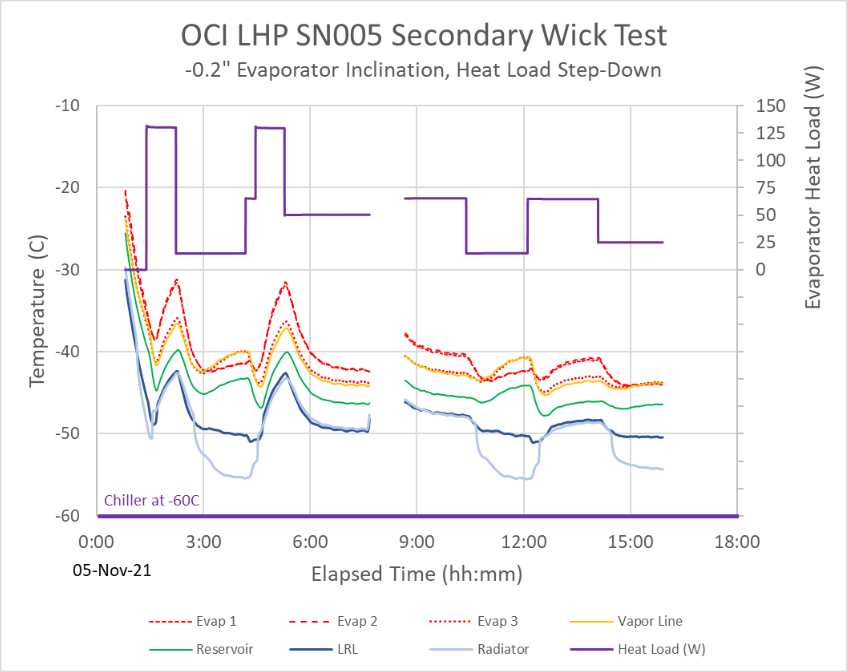

Figure 15. Secondary Wick Step-Down Test

CONCLUSION

A family of Loop Heat Pipes has been designed, fabricated and tested for a NASA flight application for the Ocean Color Instruments on the PACE satellite. There were UVVIS and VISNIR versions of the LHP. They shared the same Evaporator designs, had similar Radiators, but differed in the length of their Transport Lines. The LHPs are to carry 5W to 20W in the -40C to -20C temperature range. Three pairs of LHPs were delivered, all having met the heat transport, conductance, and change-of-state transitional requirements. Of particular note, the units were fabricated and tested in the flat configuration and delivered to NASA. After NASA testing in the flat, two of the three pairs were bent into their final shape and then retested. NASA's testing did not include the detailed thermal performance and heat transport capability tests but followed the the "Day-in-the-Life" model. Because in their bent configuration the units were slightly gravity aided, their performance was not exactly equivalent. Their results were qualitatively similar to those shown here, and there was no anomalous behavior.

ACKNOWLEDGMENTS

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REFERENCES

1. Maydanik, Y.F., "Loop heat pipes," *Applied Thermal Engineering*, Vol. 25, No. 5-6, 2005, pp. 635, 657.
2. Faghri, A., *Heat Pipe Science and Technology*, Taylor & Francis, Washington D.C., 1995, Chap. 9.