Thermal Switching Cryogenic Heat Pipe

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ABSTRACT

This paper describes a thermal switching cryogenic heat pipe, which is needed to thermally manage two CCD cameras within the ABC instrument on the NASA/JPL SIM Lite telescope. The primary requirement is to transport 12 W from the 150 K CCD cameras to a 140 K primary radiator 1.4 m away. The heat pipe is a 1.5 cm OD Al axial groove design with methane as the working fluid, which provides 75 W-m of transport capacity at 140 K. A secondary requirement is to periodically heat (decontaminate) the CCD cameras to 293 K with minimal heater power. To meet the decontamination requirement, the heat pipe was modified to provide thermal switching by using small diameter SS tubing to connect it to a liquid trap (LT) cooled by a small secondary radiator (SR) which is thermally isolated from the primary radiator (PR). The LT is a scaled-up version of the LTs used on the CRISM flight system. During normal operation, a small heater keeps the LT filled only with vapor. During decontamination, the LT heater is turned OFF, the PR is heated by midsized heaters and/or heat pipe conduction, the SR-cooled LT captures the working fluid effectively turning the heat pipe OFF, and a small evaporator heater raises the instrument temperature to 293 K. When the LT heater is re-enabled, the system returns to normal operation. This paper describes the design, fabrication, and testing of this demonstration system.

INTRODUCTION

In the summer of 2009, JPL contacted ATK and described a need for a heat transport system (HTS) to link two CCD cameras, within the Astrometric Beam Combiner (ABC) instrument on the SIM Lite Astrometric Observatory,[1] to a cryoradiator. Formerly the Space Interferometry Mission (SIM), SIM Lite will utilize optical interferometry to determine the positions/distances of stars much more accurately than any previous program.

The JPL HTS thermal requirements are as follows: (1) hot-side temperature of 150 K, (2) a hot-side heat load of 6-12 W, (3) cold-side cryoradiator at 140 K, (4) transport length of 1.4 m, (5) periodic hot-side decontamination heating to 293 K with minimal heater power, (6) modest flight heritage, and (7) low cost/manufacturing complexity. This paper describes the novel solution that was developed to meet the aforementioned requirements.

CONCEPT

The solution that was developed to meet the HTS thermal requirements is a cryogenic heat pipe with thermal switching capability. This type of device is very similar to a cryogenic diode heat pipe (CDHP), which allows heat to flow only in one direction (forward mode). A common CDHP imple-

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mentation involves positioning a cold-biased liquid trap (LT) on the evaporator end so that if the condenser becomes hot, the LT removes fluid from the heat pipe so as to prevent (condenser-to-evaporator) reverse mode heat flow. In a thermal switching cryogenic heat pipe, the LT is positioned on the condenser end and it has its own cooling source. During normal operation, the small LT heater keeps the LT warm enough so that it is filled with vapor while the heat pipe is ON. To turn the heat pipe OFF, the LT heater is turned off and all the working fluid migrates to the LT. While the heat pipe is in the OFF condition, just a small amount of heater power is required on the evaporator end to achieve a significant (decontamination) temperature rise. The heat pipe can be turned back ON by simply repowering the LT heater.

To develop the system described herein, thermal switching capability was implemented by appropriately modifying an Al axial groove heat pipe. Methane was used as the working fluid. The heat pipe modifications included the addition of: (a) a small secondary radiator (SR) thermally isolated from the primary radiator (PR), (b) an LT plumbed to the cryogenic heat pipe with small diameter tubing and thermally coupled to the SR with a low conductance shunt (note: the LT is similar in design/implementation to the LTs used on the CRISM[2] and the Three-Color Experiment[3] methane CDHPs flying on the Mars Reconnaissance Orbiter [MRO] and an early Defense Support Program [DSP] satellite, respectively), (c) a small liquid trap heater, and (d) an ambient tank (AT) to reduce the fill pressure. Figure 1 illustrates the concept (AT omitted).

TRADES

The important system design features that were traded to develop the solution that would best meet the requirements and the key issue(s) associated therewith are listed below. Design selections are indicated in italicized type. Brief comments on items 1-10 follow below.

1.	working fluid	ethane vs. *methane*
2.	heat pipe architecture	*axial groove* vs. non-axial groove
3.	flight heritage	CRISM vs. *Three-Color Experiment*
4.	fill pressure	*ambient tank* vs. high pressure heat pipe
5.	transport capacity	small diameter/margin vs. *large diameter/margin*
6.	radiator sizing	small radiator/long test vs. *large radiator/fast test*
7.	shunt conductance	*low G/Q, long cooldown* vs. high G/Q, short cooldown
8.	evaporator/condenser lengths	*JPL lengths of 15cm/71cm* vs. longer or shorter
9.	parasitics simulation in test	*heaters* vs. temperature controlled shroud
10.	decontamination	*liquid trap* vs. no liquid trap

With regard to the working fluid, methane is the superior choice as its liquid transport factor ($N_T = \sigma\Delta H/n$) is roughly equal to that of ethane at 140 K, but methane experiences a steep fall-off in transport capacity above 140 K, becoming zero at its critical temperature of 191 K; thus, decontamination power is lower with methane. With regard to the heat pipe architecture, the axial groove

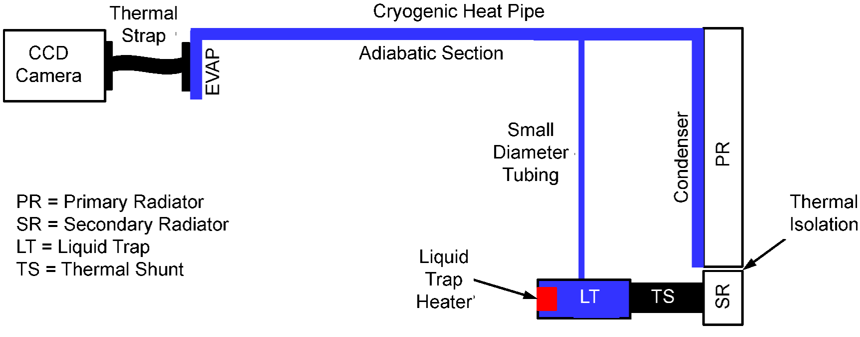

Figure 1. Concept for a Thermal Switching Cryogenic Heat Pipe

design is the simplest, least costly, highest TRL approach. With regard to flight heritage, features of both CRISM and the Three-Color Experiment CDHP systems were combined, ensuring the selected approach would have significant flight heritage. With regard to fill pressure, using an ambient tank reduces the fill pressure by 5 times or more, improving system durability, reliability, safety, and flight-qualifiability. With regard to transport capacity, a larger diameter heat pipe (than necessary) provides design margin if transport requirements grow. With regard to radiator sizing (for testing), using a larger radiator than flight expedites characterization testing and modestly reduces development cost. With regard to shunt conductance (G), the lower OFF-state heater power of a low G shunt arguably outweighs the faster cooldown rate afforded by a high G shunt. With regard to evaporator and condenser lengths**,** the initial design lengths selected by JPL provide acceptable margin on the HTS thermal requirements. With regard to parasitics simulation (during testing), the simplicity of using heaters outweighs the flight system accuracy of a temperature-controlled shroud. Lastly, with regard to (ease of) decontamination, the lower heater power and thermal switching efficiency of having an LT greatly outweighs the design simplicity of not having an LT.

DESIGN

Figure 2 illustrates the design features of the thermal switching cryogenic heat pipe. The key design features are as follows: (a) heat pipe extrusion (6063 Al, axial groove, 1.5 cm OD, 10 cm ID, 75 W-m capacity with 140 K methane); (b) evaporator (15 cm x 5 cm flange); (c) adiabatic section (1.4 m length); (d) condenser (71 cm x 5 cm flange); (e) ambient tank (stainless steel, 1000 cc), (f) primary radiator (6061 Al, 0.95 m x 0.95 m x 0.6 cm, black paint on both sides, isolated from Al honeycomb panel with Delrin rods); (g) secondary radiator (6061 Al, 0.1 m x 0.6 m x 0.6 cm, black paint on both sides, isolated from primary radiator by Delrin pins); (h) heat pipe supports (Delrin isolators, Al honeycomb panel with cutout for radiators, Delrin isolators underneath panel); (i) pressure transducer (0-6.9 MPa); (j) valves (for fill/vent, removed before shipment to JPL); (k) liquid trap (6063 Al, CRISM LT design); (l) LT shunt (stainless steel, 0.05 W/K), and (m) working fluid (99.999% methane, 4.1 MPa fill pressure).

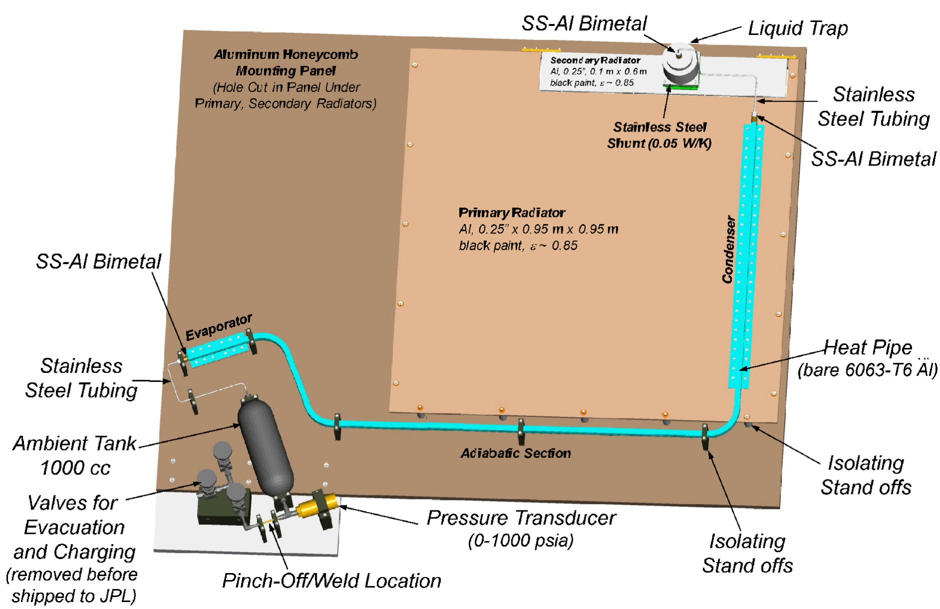

Figure 2. Design of the Thermal Switching Cryogenic Heat Pipe

TESTING

After the thermal switching cryogenic heat pipe was manufactured and assembled in accordance with the Figure 2 design at the ATK manufacturing facility in Beltsville, MD, the unit was then configured for thermal vacuum testing. Figure 3 illustrates the overall test setup, thermocouple locations, heater placement, and MLI coverage (note: heater labels are preceded by the letter "H" and MLI is depicted by the dotted red lines). The unit was mounted in ATK Chamber E, which has a full 360° LN_2-cooled, box-shaped shroud. Figure 4 illustrates the thermal vacuum chamber used at the ATK test facilities in Beltsville, MD.

After the placement of the thermal switching cryogenic heat pipe assembly on the flat interior bottom surface of the shroud, a transit and ruler were used to level the unit so that it would have a slightly adverse tilt. The arbitrary tilt specification specified in the test plan required that the evaporator would be 1.3 +/- 0.5 mm above the condenser.

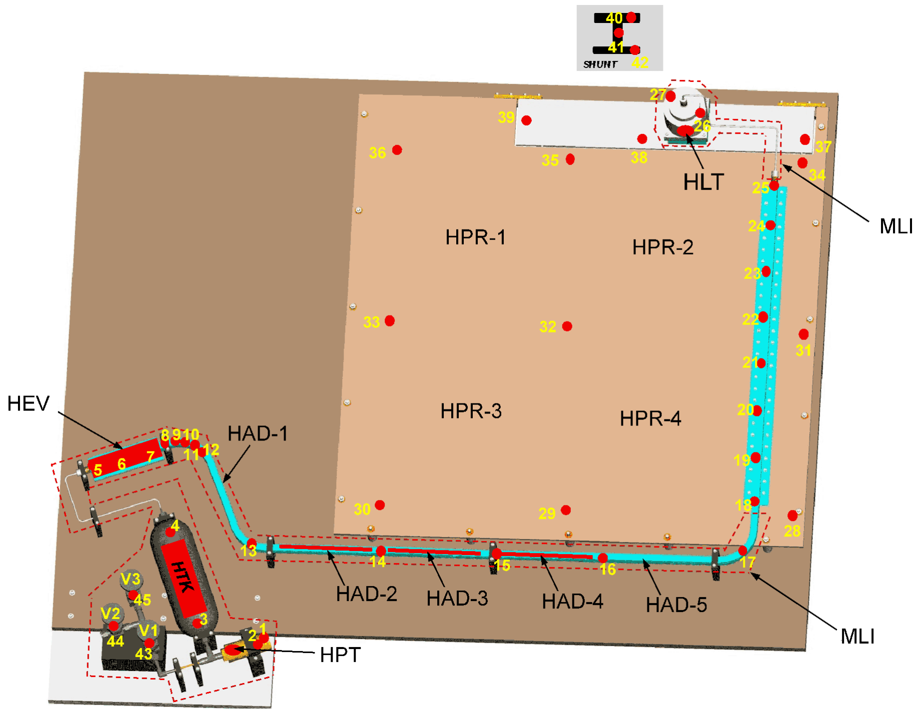

Figure 3. Test Setup for the Thermal Switching Cryogenic Heat Pipe

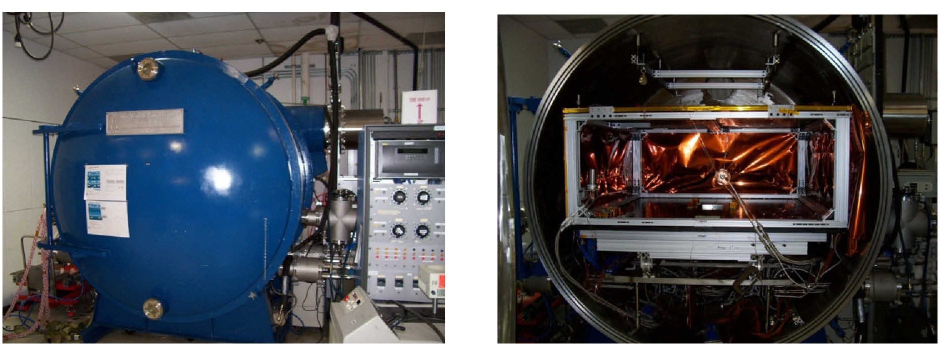

Figure 4. ATK Thermal Vacuum Chamber E

The initial test plan called for three primary performance characterization/acceptance tests: (1) Test 1- Cooldown/ON-OFF-ON (during which the heat pipe would be cooled down from ambient temperature to an ON condition, turned OFF with the LT, then turned back ON); (2) Test 2 - Normal Operation (during which evaporator and parasitic heater powers up to the maximum HTS requirement would be utilized); and (3) Test 3 - Decontamination (during which three different decontamination heating options would be utilized).

With regard to Test 3, the three decontamination heating options consisted of the following: (i) Decontamination Option 1 – high power (120 W) heating of the primary radiator to 191 K plus a small amount of evaporator heater power; (ii) Decontamination Option 2 – modest power (40 W) heating of the evaporator so that it would deprime and the transport capacity of the heat pipe would fall as the primary radiator temperature rose; and (iii) Decontamination Option 3 – low power (3-5 W) implementation of the LT as explained in the earlier part of the paper plus a small amount evaporator heater power. Table 1 lists the original test matrix.

Due to project schedule constraints, JPL decided that only tests 1-1, 1-2, 2-6, and 3-11 would be carried out (unless opportunities arose during testing to carry out additional tests without adversely impacting project schedule). In addition, due to a slower than expected cooldown rate of the LT during testing (which occurred due to an analysis oversight wherein the transient cooldown of the thermally shunted LT was not included in pretest thermal predictions), the abridged test program indicated by Table 1 was further modified.

The actual tests that were carried out over a 31.75 hour period beginning at 6 am on 4/24/10 are listed below. As indicated, Test 1-2 was eliminated and modified versions of Test 3-13 and Test 3-7 as well as a repeat of Test 2-6, which is denoted below as Test 2-6r, were carried out. The temperature and methane pressure time-histories corresponding to each of the tests listed below are provided in Figures 5-10.

Test 1-1 (t = 0.00 – 10.25 hours; test duration 10.25 hours)
Test 2-6 (t = 10.25 – 11.25 hours; test duration 1.00 hours)
Test 3-13 (t = 11.25 – 15.00 hours; test duration 3.75 hours)
Test 3-7 (t = 15.00 – 18.75 hours; test duration 3.75 hours)
Test 3-11 (t = 18.75 – 29.75 hours; test duration 11.00 hours)
Test 2-6r (t = 29.75 – 31.75 hours; test duration 2.00 hours)

Initial cooldown and turn ON of the thermal switching cryogenic heat pipe is illustrated in Figures 5a and 5b. Figure 5a is a zoomed-out view to show the variation in methane pressure from the fill pressure value of 4.1 MPa (600 psi) to the operational value of 1.0 MPa (145 psi) when temperatures had steadied out. Figure 5b is a zoomed-in view to better illustrate the heat pipe temperatures. At the conclusion of Test 1-1, with an evaporator heater power of 10 W vs. the planned 8 W, the thermal switching cryogenic heat pipe had started up successfully.

Table 1. Test Matrix (Original Unabridged Plan)

Test #	Steady State #	Description	QEVAP (W)	QCOND (W)	QLTRP (W)	QPARA (W)	TIME (HRS)
1	1	Initial Cooldown	0 ramp to 8	Q(TPR = 140 K)	2	0	10+1=11
	2	Turn-Off	Q (TEVAP = 293 K) ~ 3	Q(TPR = 145 K)	0	0	3+1 = 4
	3*	Turn-On	3 ramp to 8	Q(TPR = 140 K)	2	0	3+1 = 4
2	4*	Normal Oper. Min, no QP	6	Q(TPR = 140 K)	2	0	1+1 = 2
	5*	Normal Oper. Max, no QP	12	Q(TPR = 140 K)	2	0	1+1 = 2
	6	Normal Oper. Max, QP	12	Q(TPR = 140 K)	2	2.5	1+1 = 2
3	7*	Decontam. Option 1	Q (TEVAP = 293 K) ~ 3	Q(TPR = 191 K)	2	2.5	3+1 = 4
	8*	Normal Oper. Max, QP	12	Q(TPR = 140 K)	2	2.5	3+1 = 4
	9*	Decontam. Option 2	Q (TEVAP = 293 K) ~ 40	0	2	2.5	3+1 = 4
	10*	Normal Oper. Max, QP	12	Q(TPR = 140 K)	2	2.5	3+1 = 4
	11	Decontam. Option 3	Q (TEVAP = 293 K) ~ 3	Q(TPR =100 K)	0	2.5	3+1 = 4
	12*	Low Temp. Operation 1	Q (TEVAP = 110 K)	0	2	0	3+1 = 4
	13*	Low Temp. Operation 2	Q (TEVAP = 120 K)	0	2	0	3+1 = 4
		Test Completion				TOTAL	53

** OPTIONAL TESTS PER JPL DIRECTION*

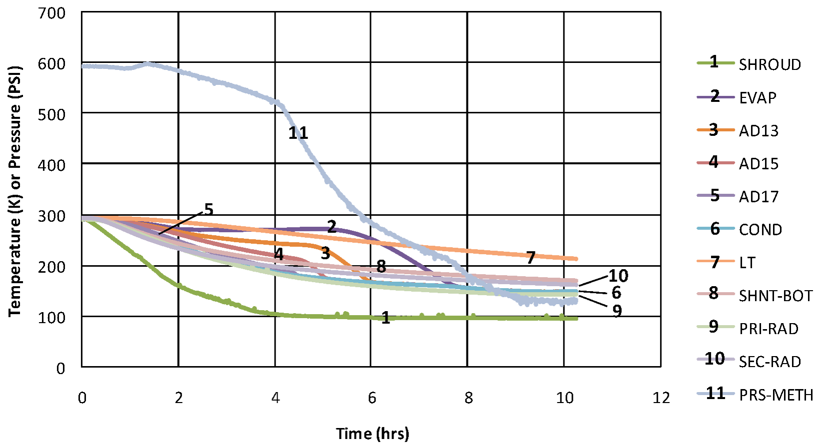

Figure 5a. Initial Cooldown and Turn ON: *Test 1-1 Zoomed-Out View*

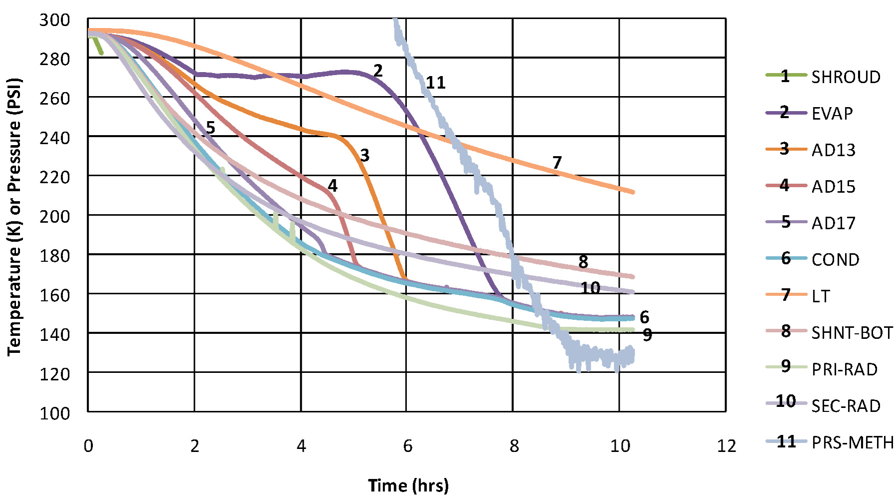

Figure 5b. Initial Cooldown and Turn ON: *Test 1-1 Zoomed-In View*

Two anomalies were observed during Test 1-1 that should be mentioned before proceeding. First, due to the closeness of the evaporator and adiabatic temperatures, it was hypothesized that thermocouples 5-7 may have been placed on the unheated side of the evaporator. After reviewing the assembly photos, that hypothesis was confirmed. Thus, in the remainder of the figures presented herein, the evaporator temperatures will be slightly lower than they should be. The likely temperature underestimation, considering only evaporative film resistance, should be roughly 3 K for a 12 W heat load. Second, the resistance of the evaporator heaters (five small heaters wired in parallel) at room temperature was about 4 ohms. However, when the system had cooled to 150 K, the resistance was only about 2 ohms. This resistance change was verified by the data acquisition equipment and by hand measurements. The cause of this change (decrease) is unknown, but it might be due to either CTE effects (increased clamping force at the junction where the five evaporator heaters were wired in parallel) or the presence of ultra high purity copper traces in the heaters (which may exhibit temperature dependent electrical resistance). It is assumed that the data acquisition equipment was correct and that there was not simply an error in measuring the heater resistance and the corresponding evaporator heater power.

Figure 6 illustrates the results of Test 2-6, the normal operation test. Overall, Test 2-6 demonstrates successful normal operation of the thermal switching cryogenic heat pipe at a primary radiator temperature of 140 K, a condenser temperature of 150 K, an evaporator temperature of 151 K, a maximum evaporator heat load of 12 W, and a parasitic heat load (spread evenly over the adiabatic section of the heat pipe) of 2.5 W. The curve at the top of Figure 5 is the LT. Based on the slow LT cooldown, a decision was made to deviate from the (abridged) test plan and proceed to Test 3-13 (the low operating temperature test).

Figure 7 illustrates the results of Test 3-13, the low operating temperature test. As indicated, the low operating temperature target of 120 K indicated in Table 1 was modified to 135 K so that enough time would be available to carry out Test 3-7, decontamination option 1. Overall, Test 3-13 demonstrates successful low temperature operation of the thermal switching cryogenic heat pipe at a primary radiator temperature of 127 K, a condenser temperature of 135 K, an evaporator temperature of 135.5 K, and heat loads identical to Test 2-6.

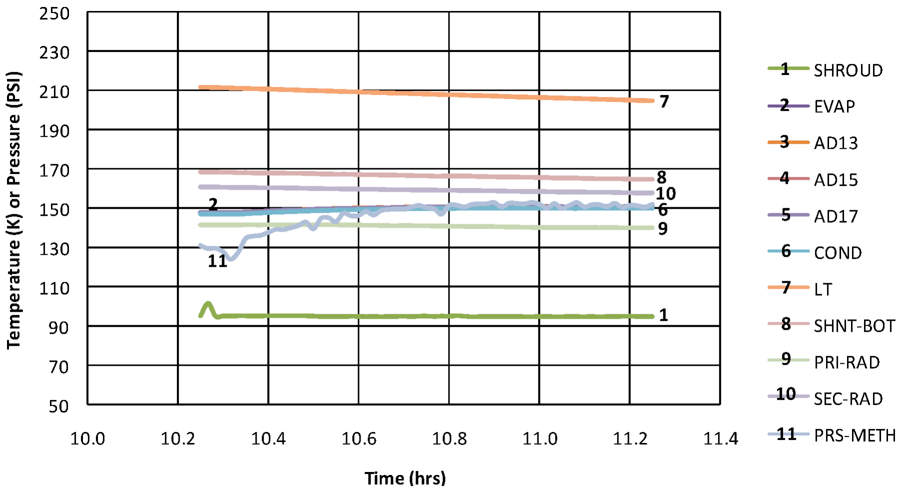

Figure 6. Normal Operation: *Test 2-6*

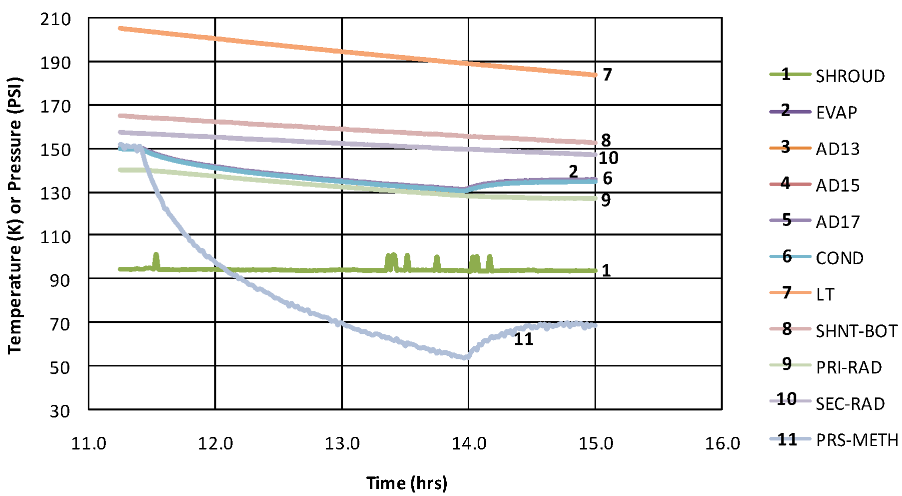

Figure 7. Low Temperature Operation: *Test 3-13*

Figure 8 illustrates the results of Test 3-7, the decontamination option 1 test. The planned test procedure was to heat the condenser to 191 K to deactivate the heat pipe. To implement this procedure, the LT needed to be heated along with the condenser to prevent liquid trapping. However, given the slow cooling rate of the LT, doing so would surely have added test time and jeopardized project schedule. So, decontamination option 1 was modified as explained below. Initially, 150 W was applied to the primary radiator at just after 15 hrs. At just after 17 hrs, the 175 K condenser temperature had just risen above the LT temperature. Shortly thereafter, well before the condenser was at 191 K, the evaporator deprimed, as the LT had begun trapping fluid. At 17.75 hrs, the primary radiator heater was turned off. At 18.25 hrs, evaporator heater power was increased to 26 W. Shortly thereafter, at 18.75 hrs, the evaporator was at 293 K. This test thus demonstrated a new hybrid decontamination procedure that would be utilized to carry out Test 3-11 as described below.

Figure 9 illustrates the results of Test 3-11, the decontamination option 3 test (note: the roughly 10 hr delay in conducting this test following the previous test was necessary to wait for the LT to cool down to the required temperature). Based on the discussion above, the originally planned decontamination option 3 procedure was modified to the following four steps: (1) turn off the LT

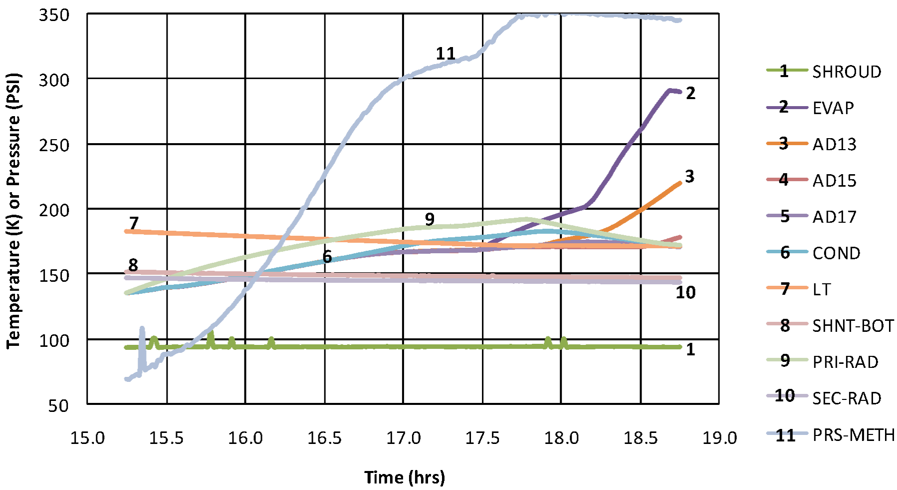

Figure 8. Decontamination Option 1: *Test 3-7*

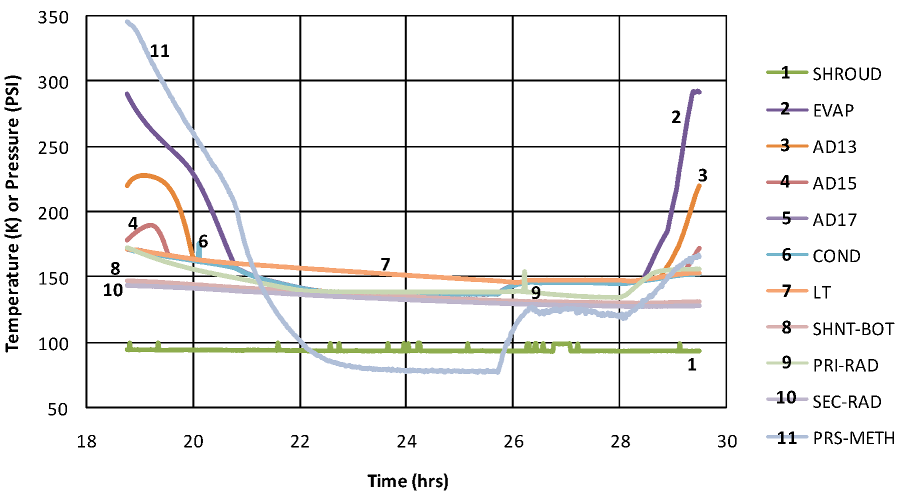

Figure 9. Decontamination Option 3: *Test 3-11*

heater; (2) heat the primary radiator so that the condenser is above the LT temperature (note: primary radiator heater power is only that necessary to raise the condenser temperature to, or slightly above, the LT temperature); (3) heat the evaporator to rapidly raise its temperature to 293 K (note: if heat up time is not of paramount importance as it was in this test, lower evaporator heater powers, resulting in a longer heat up times, can be used); and (4) once the evaporator is at 293 K, reduce the heater power to maintain temperature. As can be seen in Figure 9, this procedure worked very well and it is recommended that this procedure be utilized to carry out decontamination heating in future ground tests and in the flight system.

Figure 10 illustrates the results of Test 2-6r, a repeat of the normal operation test. The purpose of this test was to demonstrate how quickly the system returns to normal operation after a hybrid decontamination procedure. One advantage of having an LT is that decontamination can be carried out without appreciably altering system pressure. As seen in Figure 10, the methane pressure changes by only 0.3 MPa (40 psi) in transitioning from the decontamination condition to the normal operating condition. Without an LT, the pressure variation and time to return to normal operation would have been greater. The test closest to simulating a non-LT system is Test 3-7 (see Figure 8). As seen, the high 2.4 MPa (350 psi) peak pressure during decontamination about doubles the time necessary to return to normal operation (see Figure 9).

CONCLUSIONS

The two main conclusions of this effort are as follows: (1) the thermal switching cryogenic heat pipe functions very well as a heat transport system (HTS) and easily meets all JPL heat transport, operating temperature, and temperature stability requirements (note: the +/-2 K/hr temperature stability requirement was not expressly addressed in this paper because it was so easily achievable), and (2) the thermal switching cryogenic heat pipe functions very well as a thermal switch by utilizing the working fluid capturing capability of the LT. It is recommended that the hybrid decontamination procedure developed and demonstrated during the test program be utilized in future ground testing and in the flight system. The hybrid decontamination procedure, which combines primary radiator heating, LT fluid capture, and evaporator heating, is a very fast and efficient way to turn the thermal switching cryogenic heat pipe OFF and heat the evaporator to 293 K for CCD decontamination. Turning the thermal switching cryogenic heat pipe back ON from the OFF state is a very fast and efficient process as well.

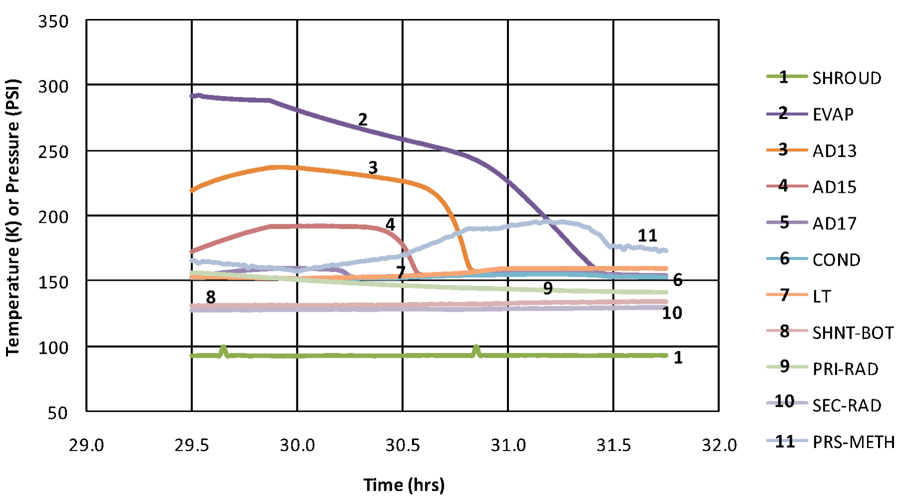

Figure 10. Normal Operation Repeat: *Test 2-6r*

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REFERENCES

1. Goullioud, R., Catanzarite, J., Dekens, G., Shao, M., Marr, J., "Overview of the SIM Lite PlanetQuest Light Mission Concept," Proc. SPIE 7013, (2008), pp. 7013-177.
2. Bugby, D., Garzon, J., Beres, M., Stouffer, C., Mehoke, D., and Wirzburger, M., "Cryogenic Diode Heat Pipe System for Cryocooler Redundancy," Proc. SPIE 5877, (2005), pp. 321-329.
3. Misselhorn, J., Brennan, P., and Fleischman, G., "Application of Heat Pipes to a Cryogenic Focal Plane Space Experiment," AIAA-87-1648, 22nd AIAA Thermophysics Conference, Honolulu, HI (1987).