Venting of a Water/Inhibited Propylene Glycol Mixture in a Vacuum Environment – Characterization and Representative Test Results

Eugene K. Ungar

Lisa R. Erickson

NASA/Johnson Space Center

Abstract

A planned use of the Orion space vehicle involves its residence at the International Space Station for six months at a time. One concept of operations involves temporarily venting portions of the idle Orion active thermal control system (ATCS) during the docked phase, preventing freezing. The venting would have to be reasonably complete with few, if any, completely filled pockets of frozen liquid. Even if pockets of frozen liquid did not damage the hardware during the freezing process, they could prevent the system from filling completely prior to its reactivation.

The venting of single component systems in a space environment has been performed numerous times and is well understood. Local nucleation occurs at warm, relatively massive parts of the system, which creates vapor and forces the bulk liquid out of the system. The remnants of the liquid will freeze, then evaporate over time through local heating. Because the Orion ATCS working fluid is a 50/50 mixture of water and inhibited propylene glycol, its boiling behavior was expected to differ from that of a pure fluid. It was thought that the relatively high vapor pressure water might evaporate preferentially, leaving behind a mixture enriched with the low vapor pressure propylene glycol, which would be vaporization-resistant. Owing to this concern, a test was developed to compare the evaporation behavior of pure water, a 50/50 mixture of water and inhibited propylene glycol, and inhibited propylene glycol.

The test was performed using room temperature fluids in an instrumented thin walled stainless steel vertical tube. The 1 in x 0.035 in wall tube was instrumented with surface thermocouples and encased in closed cell polyurethane foam. Reticulated polyurethane foam was placed inside the tube to reduce the convection currents. A vacuum system connected to the top of the tube set the pressure boundary condition.

Tests were run for the three fluids at back pressures ranging from 1 to 18 torr. During each test, the mass of the test article was measured as it changed over time, as was its temperature and backpressure.

The tests were successful. Somewhat surprisingly, the results showed that the evaporation behavior of the three fluids had more similarities than differences. The 50/50 mixture evaporated similarly to the pure water – albeit at a slower rate. The test results indicate that our extensive space-based experience with venting of single component fluids can be applied to the problem of Orion ATCS venting as long as the appropriate puts, takes, and caveats are applied.

VENTING OF A WATER/INHIBITED PROPYLENE GLYCOL MIXTURE IN A VACUUM ENVIORNMENT – CHARACTERISATION AND REPRESENTATIVE TEST RESULTS

Eugene K. Ungar, Lisa R. Erickson
NASA – Johnson Space Center

ABSTRACT

A planned use of the Orion space vehicle involves its residence at the International Space Station for six months at a time. One concept of operations involves temporarily venting portions of the idle Orion active thermal control system (ATCS) during the docked phase, preventing freezing. The venting would have to be reasonably complete with few, if any, completely filled pockets of frozen liquid. Even if pockets of frozen liquid did not damage the hardware during the freezing process, they could prevent the system from filling completely prior to its reactivation.

The venting of single component systems in a space environment has been performed many times and is well understood. Because the Orion ATCS working fluid is a 50/50 mixture of water and inhibited propylene glycol, its boiling behavior was expected to differ from that of a pure fluid. A test was developed to compare the evaporation behavior of pure water, a 50/50 mixture of water and inhibited propylene glycol, and inhibited propylene glycol.

The test was performed using room temperature fluids in an insulated thin walled stainless steel vertical tube. Reticulated polyurethane foam was placed inside the tube to reduce the convection currents. A vacuum system connected to the top of the tube set the pressure boundary condition. The mass of the test article was measured as it changed over time, as was its temperature and backpressure.

The tests were successful. Somewhat surprisingly, the results showed that the evaporation behavior of the three fluids had more similarities than differences. The 50/50 mixture evaporated similarly to the pure water – albeit at a slower rate. The test results indicate that our extensive space-based experience with venting of single component fluids can be applied to the problem of Orion ATCS venting.

INTRODUCTION

A planned use of the Orion space vehicle involves its residence at the International Space Station for six months at a time. One concept of operations involves venting portions of the idle Orion active thermal control system (ATCS) for the duration of the docked phase, preventing freezing. The venting would have to be reasonably complete and no sections of the system could be filled with pockets of frozen liquid. Sections of freezing liquid could damage the hardware and pockets of frozen coolant could prevent the system from filling completely prior to its reactivation.

The venting of single component systems in a space environment has been performed numerous times and is well understood. Local nucleation occurs at warm, relatively massive parts of the system, creating vapor and forcing liquid out of the system. Remnants of the liquid in the system freeze and then evaporate over time owing to local heating.

Because the Orion ATCS working fluid is a 50/50 mixture of water and inhibited propylene glycol, its boiling behavior was expected to differ from that of a pure fluid. It was thought that the higher vapor pressure water might evaporate preferentially, leaving behind a mixture enriched with the lower vapor pressure propylene glycol, which would be vaporization-resistant. Owing to this concern, a simple test was developed to compare the evaporation behavior of three fluids: inhibited propylene glycol, pure water, and a 50/50 mixture of water and inhibited propylene glycol.

The test was performed using room temperature fluids in an instrumented 14 inch long vertical thin-walled stainless steel tube. The 1 in x 0.035 in wall tube was instrumented with surface thermocouples and encased in closed-cell polyurethane foam. Reticulated polyurethane foam was placed inside the tube to reduce the convection currents. A vacuum system connected to the top of the tube set the pressure boundary condition.

Tests were run for the three fluids at backpressures ranging from 1 to 18 torr. During each test, the mass of the test article was measured as it changed over time, as was its backpressure and temperature profile.

The tests were successful. Somewhat surprisingly, the results showed that the evaporation behavior of the pure water and the 50/50 mixture had more similarities than differences. After a short initial transient, the 50/50 mixture evaporated with a similar rate to the pure water. The test results indicate that our extensive space-based experience with venting of single component fluids is relevant to the case of Orion ATCS venting.

TEST APPARATUS

A schematic of the vacuum venting test apparatus is shown in Figure 1. The vacuum system was capable of maintaining pressures below 1 torr. A cold trap protected the vacuum system by capturing evaporant before it could flow into the vacuum system. An 8 gallon reservoir plumbed upstream of the cold trap provided an auxiliary vacuum volume. Four manual ball valves were present in the system to drain the test cylinder, to isolate the test cylinder from the vacuum system, to provide a vent to atmosphere, and to allow isolation of the vacuum system.

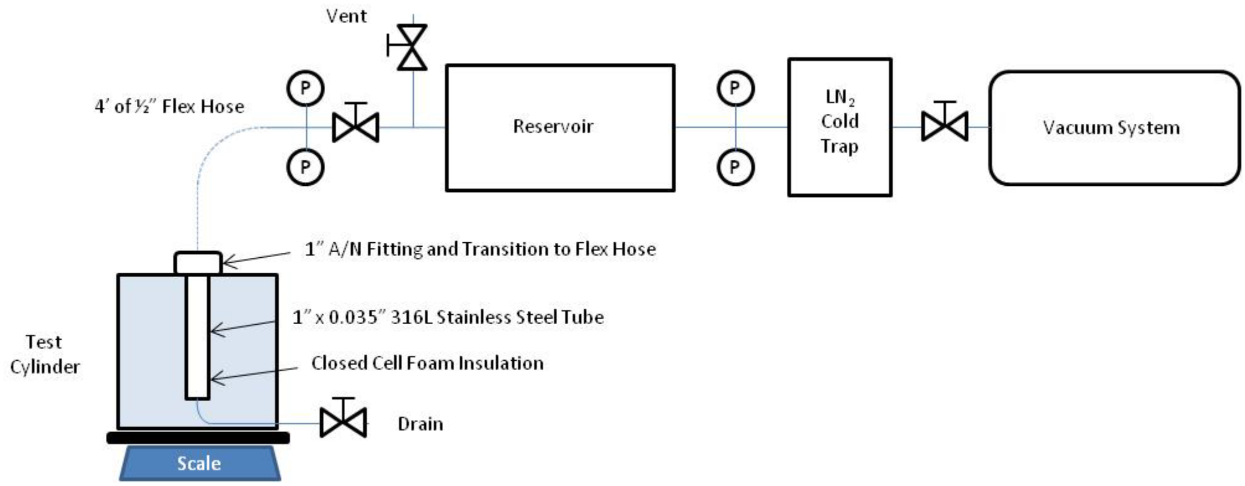

Figure 1. Schematic of test apparatus.

Pressures upstream and downstream of the reservoir were sensed by pairs of MKS Baratron model 220CA pressure transducers (0-1 torr and 0-1000 torr ranges - both with an accuracy of ±0.15% of the reading). Eleven copper - constantan thermocouples (TCs) were surface mounted along the tube to measure the fluid's temperature at each location. Their positions are shown in Figure 2. A low point drain valve allowed the test cylinder to be drained and flushed between test runs. The tube rested on an A&D FX-3000i precision balance (0-3000g with ± 0.01g readability). All test data (mass, pressure, and temperature) was recorded at a rate of 1 Hz.

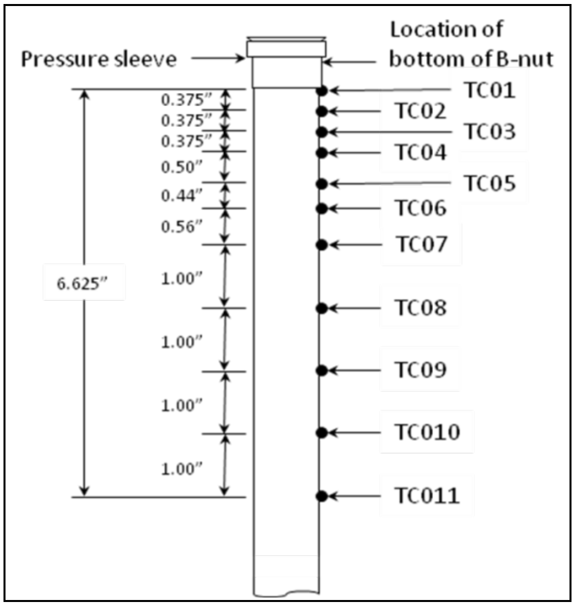

Figure 2. Test cylinder thermocouple locations.

The test cylinder was configured to make the vacuum-induced evaporation as microgravity-representative as possible. The test cylinder was a 14 inch length of 1 in x 0.035 in wall 316L stainless steel tube. A thin wall stainless steel tube was chosen because its low thermal conductance would inhibit axial heat flow – both from the environment and along the test cylinder. The test cylinder was oriented vertically to minimize liquid carryover. The tube was encased in 3 inches of closed cell polyurethane foam insulation to limit heat leak from its surroundings. 10 pore per inch reticulated polyurethane foam[1] was placed within the tube to reduce gravity driven convection during the test.

TEST OPERATION

Multiple test runs were performed to characterize the behavior of Dowfrost HD, water, and a 50/50 mixture of the two when exposed to various vacuum backpressures. A total of twelve test points (TPs) were performed. The first three tests were performed with pure water to check the

---

[1] The in situ void fraction of the reticulated foam is 92.6%, based on void fraction measurements.

functionality of the test apparatus. The other nine tests investigated the vacuum induced evaporation:

- at several different backpressure ranges,
- with and without the reticulated foam in the tube.
- in water, Dowfrost HD inhibited propylene glycol, and in a 50/50 mixture of the two.

All the non-checkout tests were performed with the same procedure. First, the test cylinder was filled with the desired quantity of working fluid (typically to a level 1/8" above TC02), tapped to dislodge any trapped bubbles, connected to the test apparatus, and placed on the scale. The cold trap was then cleaned and charged with liquid nitrogen. The hand valve at the flex hose was closed and the vacuum chamber and reservoir were pumped down. The pressure in the test cylinder was then reduced to a value (typically 30 torr) somewhat above the test fluid saturation pressure by venting through the flex hose hand valve. The valve was closed once the desired pressure was reached.

After stability was obtained, data recording was begun and the flex hose hand valve was opened quickly. The test was declared complete once the measured mass and temperatures began to level off (after 15 to 30 minutes). The vacuum system was then isolated and the test cylinder was repressurized and opened. The final liquid level was measured by pushing the reticulated foam below the liquid surface and, inserting a dipstick, and measuring the resulting liquid level with a ruler (accuracy of ± 0.0625 in). The foam was then pulled up to the starting liquid height and the test cylinder was drained, flushed, and filled for the next test.

ASSESSMENT OF APPARATUS AND EVAPORATION PHYSICS

Several analyses and tests were performed to assess the ability of the test cylinder to mimic the physics of 0-g evaporation. They are discussed in turn below.

Temperature Drop Across the Tube Wall

Since test article thermocouples were mounted externally, the temperature drop across the tube wall was assessed. The tube wall was 0.035 inch 316L stainless steel. The characteristic conduction time, τ, of the tube wall can be calculated from the tube wall thickness, t=0.035 in, and the thermal diffusivity of 316L stainless steel, $\alpha=4.0\times10^{-5}$ ft^2/s.

$$\tau = \frac{t^2}{\alpha} = 0.21\ s$$

Because the wall time constant is 4 orders of magnitude shorter than the test duration of 15 to 20 minutes, the temperature drop across the tube wall can be neglected.

Characterization of the Average Fluid Temperature at a Given Location

As demonstrated above, there was negligible temperature drop between the thermocouple measurement and the fluid in contact with the tube wall. An additional assessment was performed to determine whether an appreciable difference existed between the fluid temperature at the wall and the average fluid temperature at that axial location. Conduction in a cylindrical solid following a step change in wall temperature was assessed to determine the time constant for the average temperature response. The characteristic time[2] of the transient was determined analytically using the equivalent thermophysical properties for the fluid/foam[3] combination. The effective thermal diffusivity and calculated time constants for each fluid are shown in Table 1. The largest time constant, which corresponds to Dowfrost HD, is 2.8 minutes. This is reasonably short compared to the 15 to 30 minute test point length. Therefore, we conclude that the measured temperatures were representative of the average fluid temperature.

Table 1. Thermal Diffusivities and Time Constants for each Liquid Plus Foam Combination

Fluid	Effective Thermal Diffusivity (ft^2/hr)	Time Constant (min)
Dowfrost HD	0.0037	2.8
Water	0.0060	1.7
50/50 Mixture	0.0045	2.3

Convection Reduction in the Tube

Tests were performed to assess the buoyancy-suppression efficacy of the reticulated foam insert. Three test points (TP06, TP07, and TP08) were run with similar back pressures. The foam was installed for TP06 and TP08, but was removed for TP07. The back pressures for these three test points are shown in Figure 3 and the final temperature profiles are shown in Figure 4. The temperature profiles show that the thermal transient penetrated further into the test cylinder fluid when no foam was present. The foam reduced the natural convection.

---

[2] The time required for 63% of the transient to pass.

[3] Thermophysical properties were calculated with Maxwell relationship from Thermal Conductivity of Solids by J.E. Parrott and Audrey D. Stuckes, Pion Ltd., London, 1975.

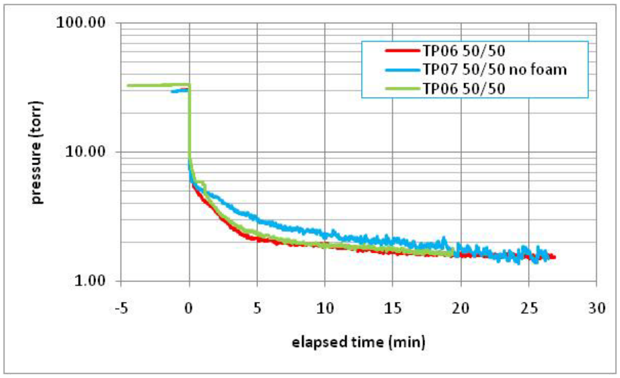

Figure 3. Pressure downstream of flex hose for TP06, TP07, and TP08.

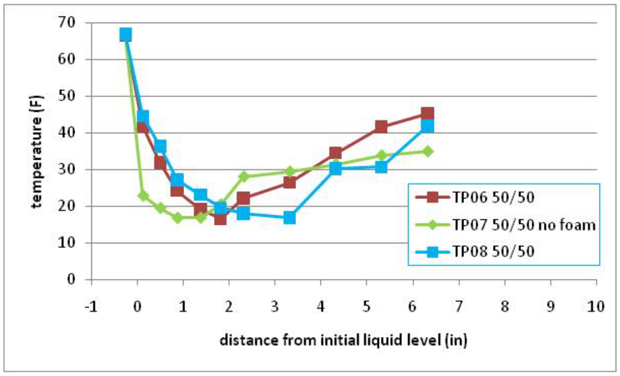

Figure 4. Temperature profiles for TP06, TP07 and TP08 – 19.4 minutes after start.

The degree of reduction in the natural convection was further assessed by analyzing heat conduction into a stagnant fluid. A simplified semi-infinite analysis was performed based on a step change in temperature at the location of the final measured fluid level for TP08. The step change was from the initial measured temperature to the final measured temperature at that depth. This analysis would tend to over predict the temperature penetration depth, since the temperature at that depth actually underwent a gradual transition to the final temperature. The analytical results are compared with the test results in Figure 5. The figure shows that the foam did not eliminate natural convection in the test cylinder. Boiling in the warmer fluid deep in the test cylinder caused a significant amount of unavoidable fluid movement in the test cylinder.

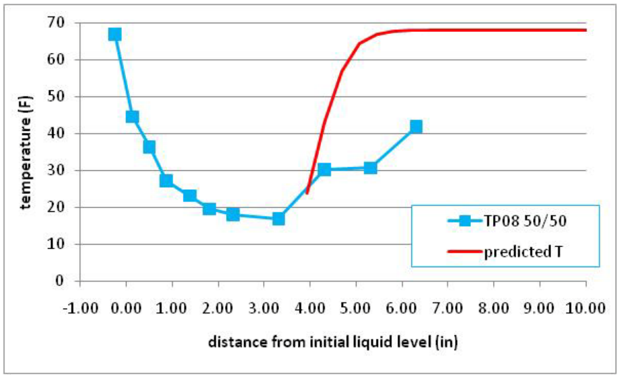

Figure 5. TP08 final measured temperature profile and stagnant liquid temperature prediction.

TEST RESULTS

Test Point Summary

The vacuum vaporization test points test points are summarized in Table 2. The table lists the evaporant, the time under vacuum, and the vacuum level. The mass losses as measured using the scale and dipstick (where available) are also listed[4].

Table 2. Test Points

Test Point	Fluid	Duration (min)	Final Pressure (torr)	Dipstick Δ Mass (g)	Scale Δ Mass (g)	Comments
1	Water	3.4	18.5	-	6.6	checkout
2	Water	3.6	15.9	-	1.2	checkout
3	Water	3.2	3.1	-	8.7	checkout
4	50/50	25.2	2.3	20.0	13.0	
5	50/50	23.7	5.0	15.9	12.3	constant 5 torr
6	50/50	26.9	1.6	-	9.0	
7	50/50	26.4	1.5	23.7	20.0	no foam
8	50/50	19.4	1.6	44.8	13.3	
9	50/50	15.9	0.9	22.0	13.4	
10	50/50	21.7	1.0	23.6	16.1	
11	Water	30.5	1.7	-	22.2	
12	Dowfrost HD	21.5	1.0	15.1	12.4	

---

[4] No dipstick measurement was obtained for the non-checkout pure water test point as the cylinder was frozen at the end of the test.

Comparison of the Behavior of the Three Fluids

Test points 9, 10, 11, and 12 were performed after the checkout and assessment test points. They provide a direct comparison of the evaporation behavior of pure water, Dowfrost HD, and a 50/50 mixture of the two. The pressures measured downstream of the flex hose for TP09, TP11, and TP12 are plotted as a function of time in Figure 6. The pressure profiles are similar: an initial drop to less than 5 torr with a gradual decay to a final pressure of approximately 1 torr.

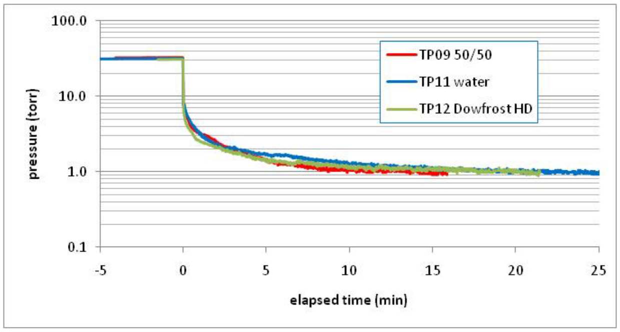

Figure 6. Pressure downstream of flex hose.

Figure 7 shows the temperature transients for each liquid. The saturation temperature at the pressure measured downstream of the flex hose is also included in the figures for water[5] and the 50/50 mixture[6]. The local saturation temperature in the test cylinder would be higher owing to the pressure drop of the flex hose. The saturation temperature for pure Dowfrost HD is not plotted in the figures because it would be off-scale high. Its published[7] saturation pressure at 68°F is 0.22 torr – well below the minimum pressure of 1 torr measured in the test (pure propylene glycol has an even lower saturation pressure, 0.07 torr at 68°F[8]). However, the temperature profiles clearly show that evaporation did occur – perhaps caused by the vaporization of the more volatile components of the inhibitor package that comprises 5% of the Dowfrost HD volume.

---

[5] REFPROP, Reference Fluid Thermodynamic and Transport Properties, E. W. Lemmon, M. D. McLinden, M. L. Huber, NIST Standard Database, Version 7.1, 2003.

[6] Dow Answer Center http://dow-answer.custhelp.com/app/answers/detail/a_id/4821/~/lttf---vapor-pressure-of-aqueous-dowfrost-and-dowfrost-hd---english-units, accessed 04/15/2011.

[7] Dowfrost HD MSDS.

[8] Marks Handbook.

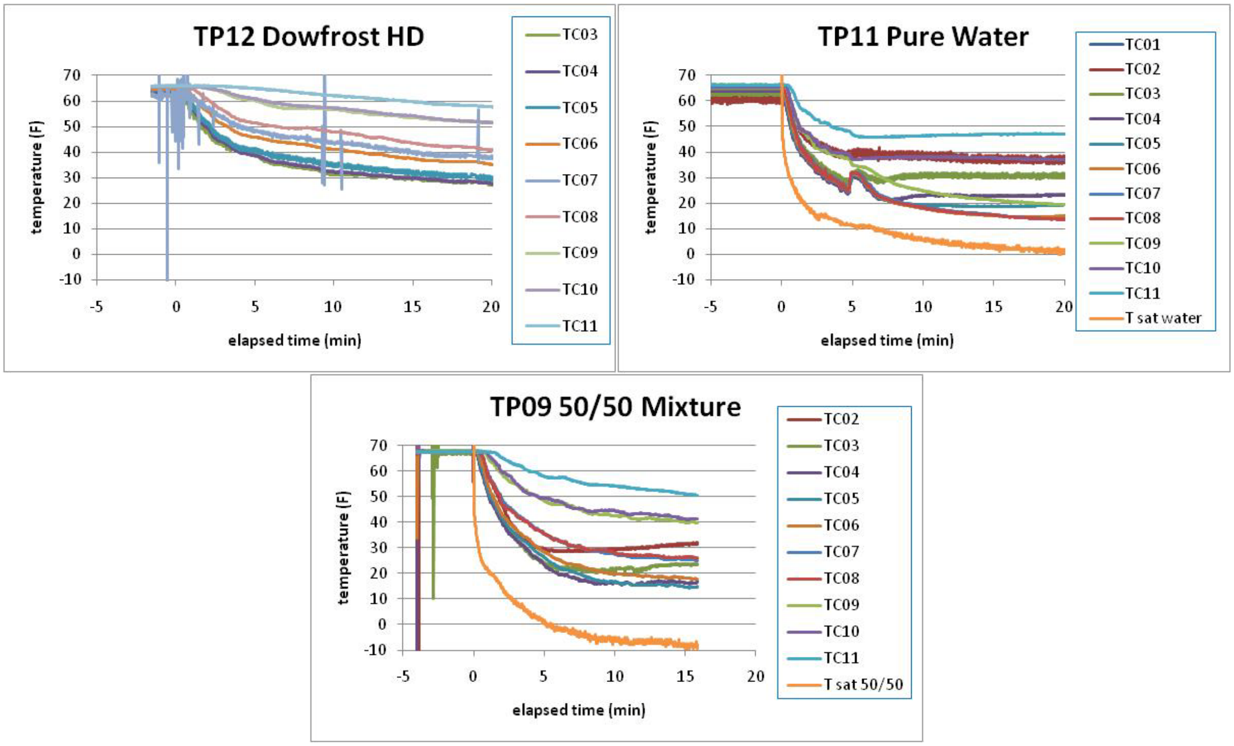

Figure 7. Transient temperature measurements.

Figure 7 also shows that, as might be expected, there is a large temperature variation in the test cylinder fluid. Much of fluid is superheated and susceptible to boiling.

The temperature profiles for the three liquids at different times during the transient are shown in Figure 8. The Dowfrost HD and the 50/50 mixture plots also show the final liquid level[9]. For the water and the 50/50 mixture, the point of maximum temperature depression precedes deeper into the tube as the depressurization proceeds. The minimum measured temperature for Dowfrost HD is always located at the same location near the top of the test cylinder.

---

[9] Measured with the dipstick and corrected for the foam void fraction.

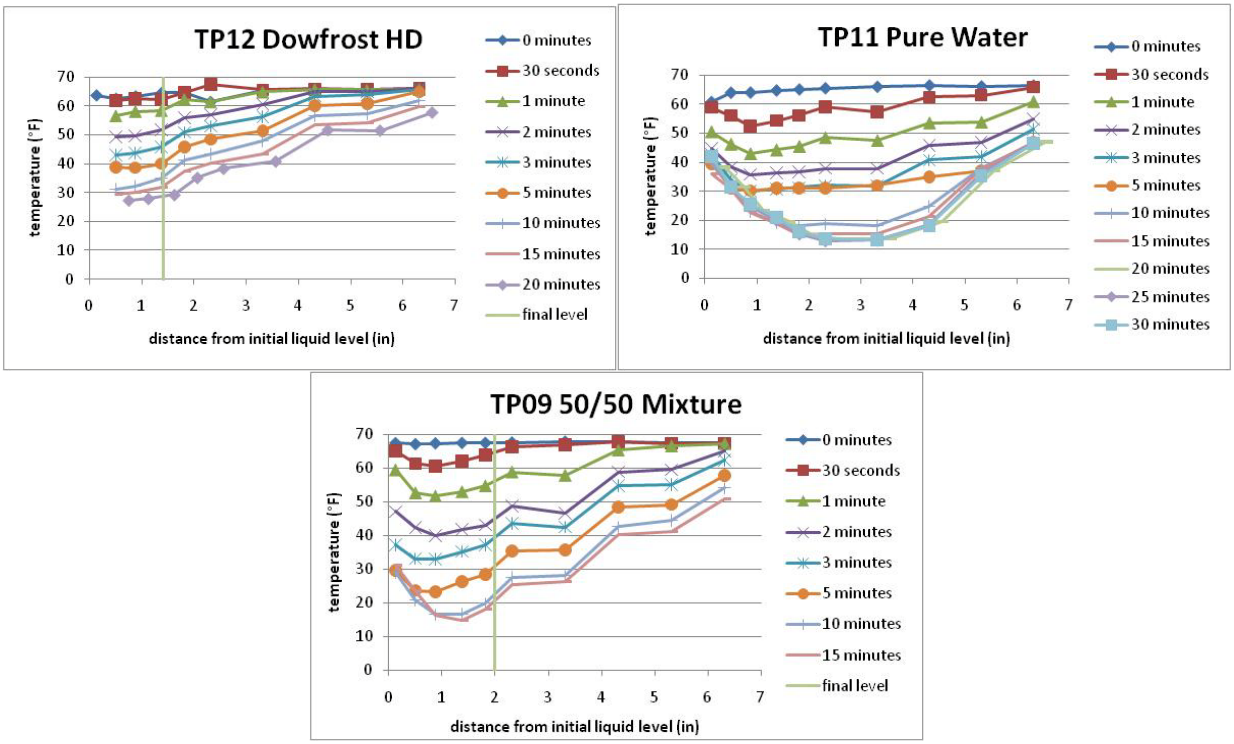

Figure 8. Temperature profiles.

For the 50/50 mixture, the point of maximum temperature depression at the end of the test is higher than the final liquid level. Since the temperature minimum would be expected to correspond to the top of the liquid, this suggests that the dynamic liquid level may have been higher than the static liquid level measured at the end of the test.

Figure 9 shows a comparison of the measured temperature profile after 15 minutes for the three liquids. The depth of temperature penetration was highest for the water and lowest for the Dowfrost HD. This suggests that the evaporation process was most vigorous for the pure water and least vigorous for the pure Dowfrost HD. The 50/50 mixture fell in between the two.

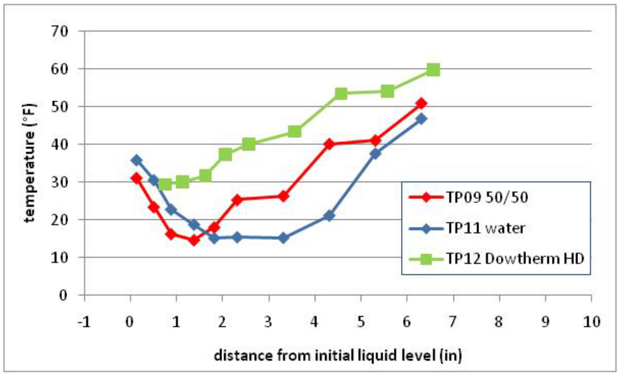

Figure 9. Temperature profiles at 15 minutes.

Figure 10 shows a comparison of the mass measured by the scale during the evaporation of the three fluids. Once the initial transient had passed, the shapes of the curves are similar. At each point in the transient, the water has lost the most mass and the pure Dowfrost HD has lost the least. The 50/50 mixture again falls between the two.

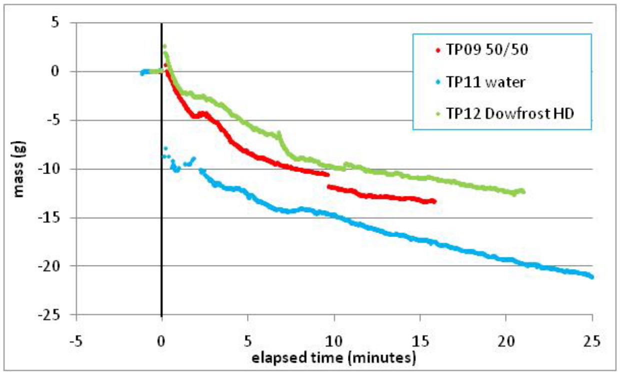

Figure 10. Transient measured mass change.

The ranking of temperature penetration depth and mass loss are the same: water, the 50/50 mixture, and pure Dowfrost HD. This corresponds to the ranking of the vapor pressure of the fluids.

Accounting for Evaporated Mass

The amount of liquid evaporated was measured in two ways, a continuous mass measurement from the scale and a pre and post-test liquid level comparison using a dipstick and ruler. The total mass loss measured using the dipstick was always greater than that measured using the scale (as shown in Figure 11). This discrepancy suggests that the boiling process entrained liquid droplets in the vapor stream. Entrained liquid that left the test cylinder, but was deposited in the flex hose bend could still be sensed by the scale. This conclusion is supported by the fact that liquid often dripped out when the flex hose was disconnected between tests.

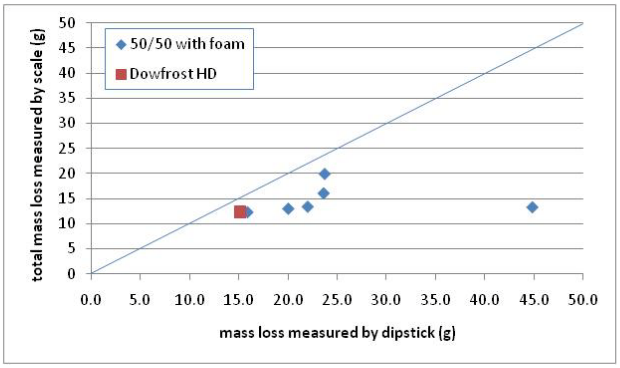

Figure 11. Mass loss measurement comparison.

Accounting for Energy

The 50/50 test data was also analyzed using energy bookkeeping. The energy difference between the initial and final states of the test cylinder[10] was assessed and compared to the energy that would be required to vaporize the mass of liquid that had left the test cylinder during the test. The drop in internal energy of the test cylinder was less than 10% of the energy that would be required to evaporate the volume of liquid that had exited. This suggests that upwards of 90% of the liquid mass that left the test cylinder did so by being entrained in the vapor stream. There was substantial entrainment.

Flex Hose Pressure Drop

A scoping analysis was performed to assess the magnitude of the pressure drop in the flex hose and its effect on the pressure in the test cylinder. The flex hose pressure drop was calculated using the Lockhart-Martinelli/Chisholm correlation for two-phase flow.[11] For convenience, the flow through the flex hose was assumed to be pure water vapor with entrained 50/50 liquid. The mass flow rate was based on the scale measurements – proportionately increased to agree with the overall fluid loss measured with a ruler. The flow quality was held constant over the transient.

When the quality of the flex hose flow was set at 4.6%, the minimum measured temperature was slightly higher than the saturation temperatures associated with the calculated test cylinder's pressure. The analysis showed that the pressure in the test cylinder during venting was on the order of 1.4 torr higher than the pressure measured downstream of the flex hose. Therefore the saturation temperature was higher than shown in Figure 7. Figure 12 shows a re-plot of TP09 assuming a flex hose quality of 4.6%. The saturation temperature corresponding to the calculated pressure in the test cylinder is denoted by Tsat*.

---

[10] The change in liquid volume between the initial and final states was based on the dipstick measurements. The initial and final temperature profiles were based on the thermocouple measurements - temperatures beyond the thermocouple locations were extrapolated linearly.

[11] Chisholm, D., 1967, "A Theoretical Basis for the Lockhart-Martinelli Correlation for Two-Phase Flow," *Int. J. Heat and Mass Transf.*, Vol. 10, pp. 1767-1778.

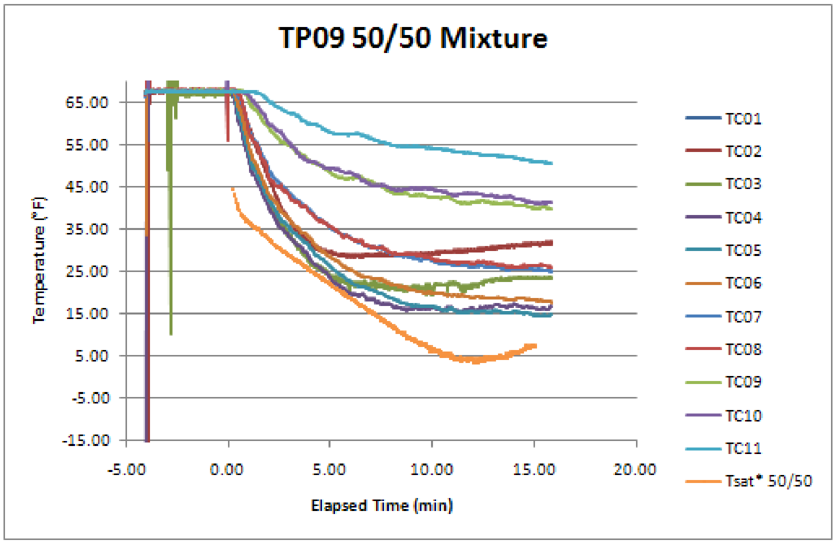

Figure 12. Transient temperature measurements.

SUMMARY

Several key points can be gleaned from the test data and analyses:

- The reticulated foam in the test cylinder reduced, but did not eliminate natural convection.
- The ranking of the fluids in the order of evaporation vigor is water, 50/50, and Dowfrost HD. This order is corresponds to the ranking of the fluid vapor pressure.
- The evaporation of the 50/50 mixture was energetic enough
    - that it resulted in significant entrainment and carryover,
    - that it increased the dynamic liquid level over the static value owing to boiling-induced foaming in the test cylinder.
- The 50/50 mixture and the pure water had similar evaporation characteristics. There was no indication that the evaporation process was inhibited by increased concentrations of Dowfrost HD at the liquid/vapor interfaces. Of course, the likely presence of boiling in the bulk fluid and the resulting fluid mixing would tend to mitigate against a local buildup of Dowfrost HD. However, the overall similarity of the evaporation processes suggests that local preferential evaporation would not be an issue on-orbit.

CONCLUSIONS

Contrary to expectations, the 50/50 mixture evaporated in a fairly similar fashion to the pure water. There was no noticeable reduction in the evaporation rate that might be caused by local propylene glycol enrichment of the liquid. The test result was affected by the unavoidable presence of fluid mixing owing to buoyancy. However, the vigor of the 50/50 mixture evaporation suggests that on-orbit venting of a water/inhibited propylene glycol loop is likely to fall within the experience database of pure fluid venting.