ATMOSPHERIC PRESSURE EFFECTS ON CRYOGENIC STORAGE TANK BOIL-OFF

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ABSTRACT

The Cryogenics Test Laboratory (CTL) at the Kennedy Space Center (KSC) routinely utilizes cryostat test hardware to evaluate comparative and absolute thermal conductivities of a wide array of insulation systems. The test method is based on measurement of the flow rate of gas evolved due to evaporative boil-off of a cryogenic liquid. The gas flow rate typically stabilizes after a period of a couple of hours to a couple of days, depending upon the test setup. The stable flow rate value is then used to calculate the thermal conductivity for the insulation system being tested. The latest set of identical cryostats, 1000-L spherical tanks, exhibited different behavior. On a macro level, the flow rate did stabilize after a couple of days; however the stable flow rate was oscillatory with peak to peak amplitude of up to 25 percent of the nominal value. The period of the oscillation was consistently 12 hours. The source of the oscillation has been traced to variations in atmospheric pressure due to atmospheric tides similar to oceanic tides. This paper will present analysis of this phenomenon, including a calculation that explains why other cryostats are not affected by it.

INTRODUCTION

Cryostats are regularly used at the CTL to determine the thermal performance of various insulations. Tests are conducted in small 10-L cylindrical cryostats or large 1000-L spherical tanks. Both tanks are double walled and contain insulation in the annulus. The 10-L cylindrical cryostats are used for initial material testing, such as thermal conductivity, vibrations, and boil-off, over a short time frame. The 1000-L tanks are used to determine boil-off rates and thermal cycling performance over a longer duration, providing a better demonstration of performance. The 10-L and 1000-L tanks are shown in **FIGURE 1**.

While undergoing a long duration test in a 1000-L tank an unforeseen change occurred in the tank's boil-off rate. The gas flow oscillated up to 25% of its nominal value. The peak to peak amplitude of the oscillation was 12-1/2 hours. These oscillations shared characteristics with barometric pressure changes and ocean tide levels. The average pressure change (ΔP) for Cape Canaveral, FL is +/- 3 millibars. The ΔP is concurrent with the local tides levels, which also change from high tide to high tide every 12 hours and 25 minutes.

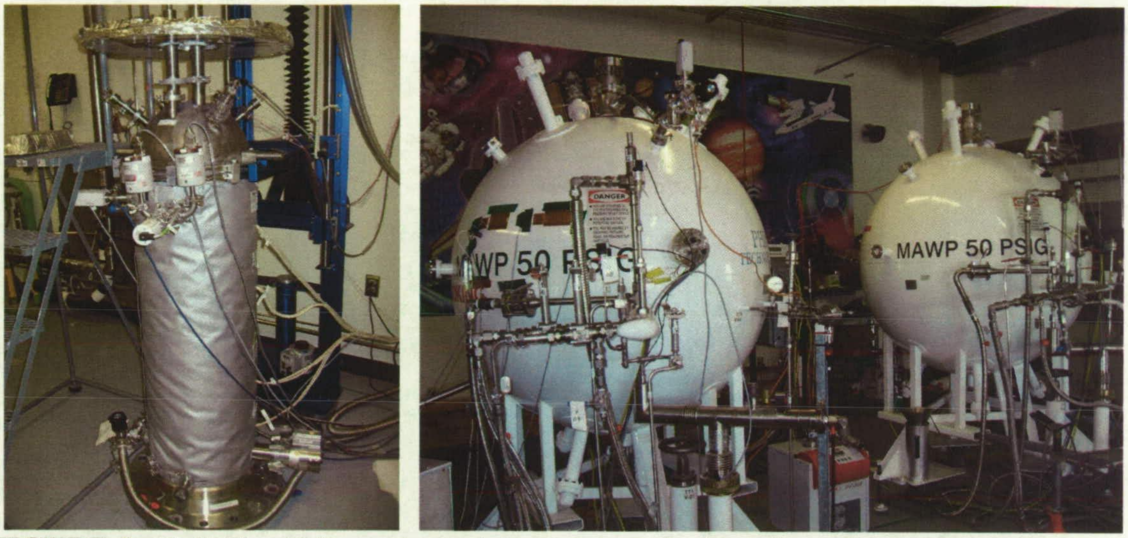


FIGURE 1. *(Left)* The 10-L cryostat tank is used for gathering information on materials. *(Right)* The 1000-L is used for boil-off test and demonstration runs.

EXPERIMENTAL

Steady-state liquid nitrogen boil-off calorimeter methods developed by CTL were used during this experiment. Longer duration boil-off tests were performed in the 1000-L tanks. These tanks are scaled versions of the propellant storage tanks used on the shuttle launch Pads 39 A/B for liquid hydrogen. The liquid level of the tank was 90 percent filled with liquid nitrogen. After filling, it takes several hours to a couple of days for the tanks boil-off to stabilize, as shown in **FIGURE 2**. The tank can be pulled to high, soft or no vacuum. For this experiment a high vacuum level of below $1*10^{-4}$ torr was used.

Tank boil-off is measured inside the tanks vent line by two flow meters. One is for high volume and the other for low flow. Only the high volume flow meter can be used at high vacuum. The 1000-L tanks also have a series of sensors and multiple scales to determine the tank's liquid conditions. Equipped inside are 12 liquid level/temperature sensors at different depth levels, shown in **FIGURE 3**. The tank also sits on three scales, determining the mass of the remaining liquid. Knowing the mass and internal conditions helps calculate the volume of liquid left in the tank. By comparing the liquid volumes from day to day and using the flow meters the boil-off of liquid nitrogen is determined.

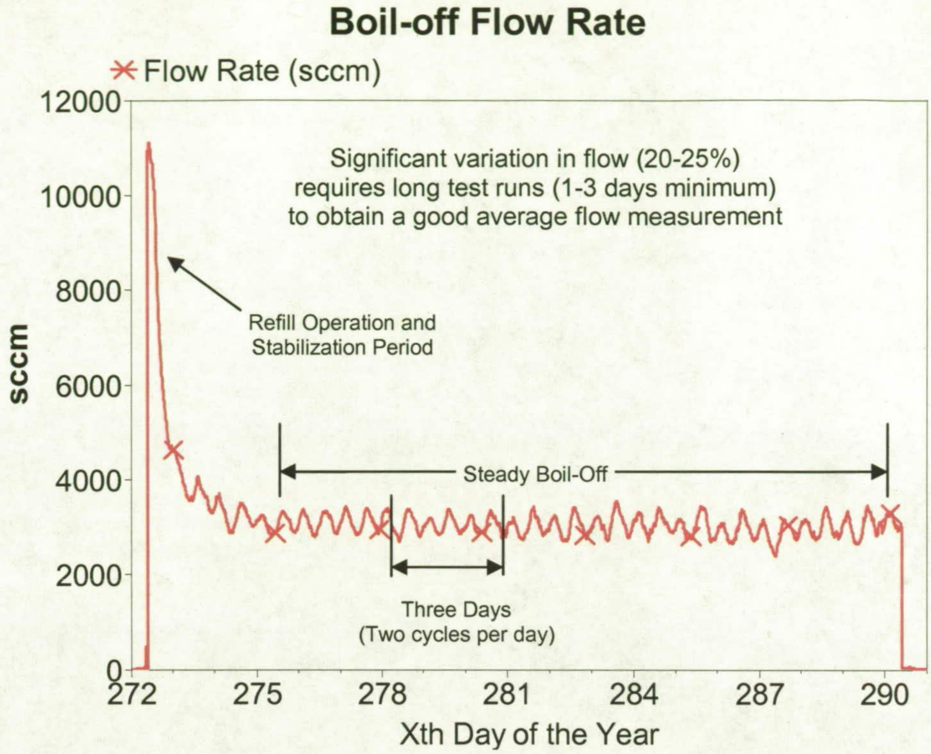


FIGURE 2. Graph showing typical data collected during a boil-off test.

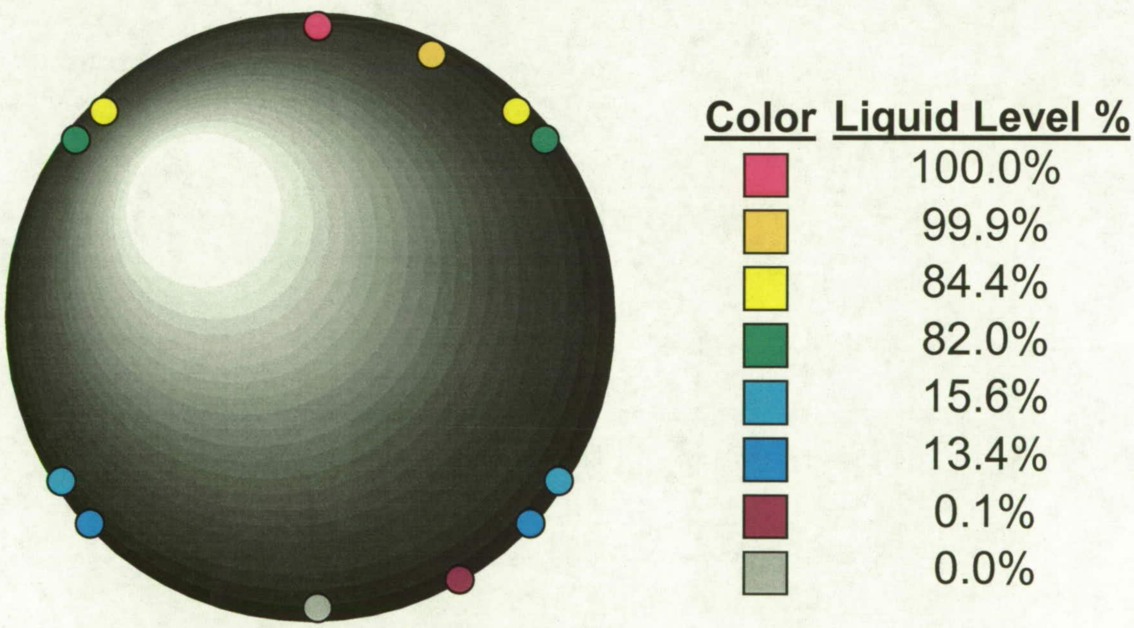


FIGURE 3. Diagram of 1000-L tank liquid level sensor locations.

RESULTS

The boil-off test was run for 30 days in the 1000-L tank. During testing the flow rate oscillation was discovered. It was also observed that liquid nitrogen temperatures inside the tank were fluctuating in a similar pattern. Both tanks are in an air conditioned environment, reducing the ambient temperature affecting the liquid. Further research lead to the collection of barometric pressure data from NOAA buoy **#41009**, 20 nautical miles off the coast of Cape Canaveral, Florida. Graphing the buoy's data showed a pressure oscillation occurring every 12-1/2 hours peak to peak. This shared characteristics with the liquid temperature and flow oscillations, see **FIGURE 4**.

The data gathered shows a relationship between the pressure, temperature and gas flow rate. The increase in barometric pressure raised the liquid temperature. The liquid temperature increase lead to a higher flow rate, after the liquid nitrogen turned from liquid to gas. The state change naturally affects the boil-off since the ratio of liquid to gas is 1:694 at 68ºF. This also explains the small lag in time between the temperature and flow. The temperature of liquid nitrogen is -320ºF, the gas slowly increases in both temperature and volume as it evaporates. This change takes time and the graphs show the delay from the nitrogen changing state.

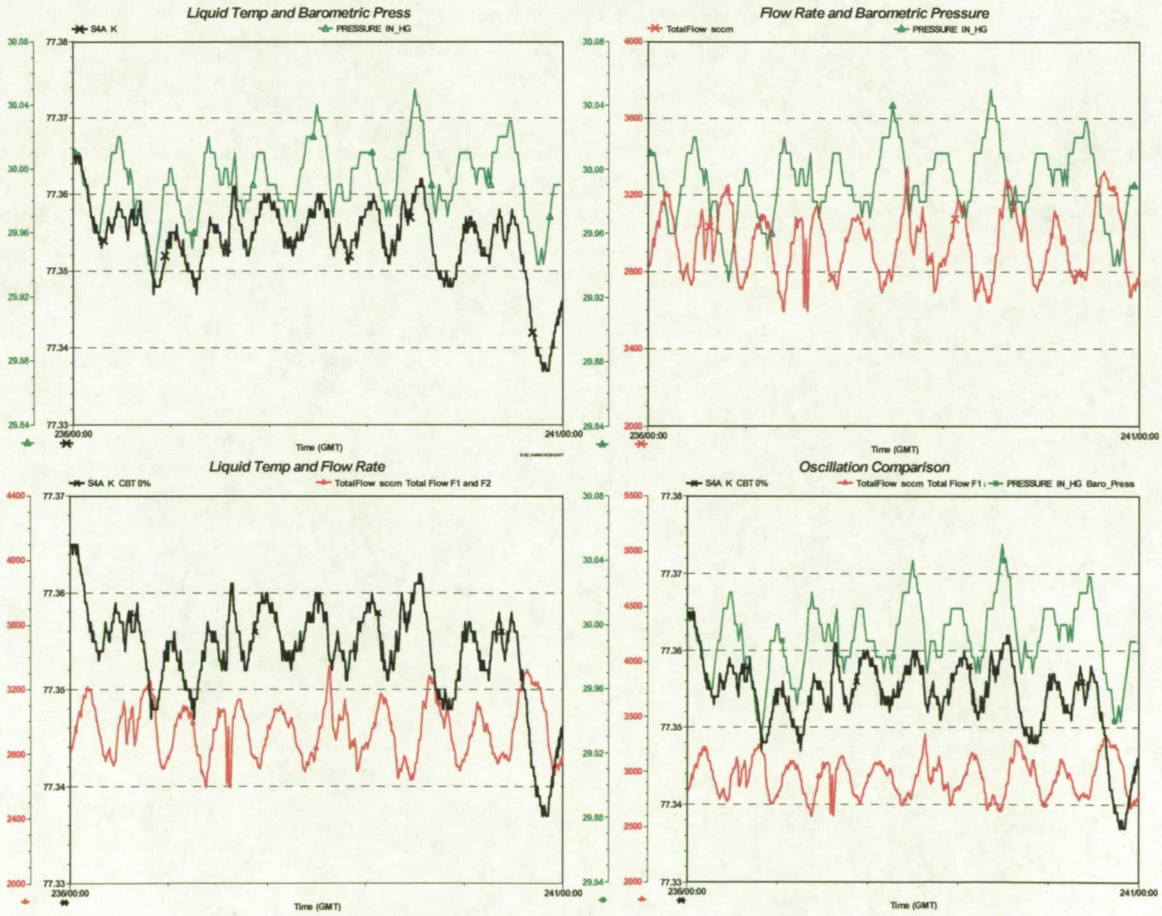


FIGURE 4. (Upper Left) Tank Liquid Temperatures Barometric Pressure. (Upper Right) Flow Rate vs. Barometric Pressure. (Bottom Left) Tank Liquid Temperature vs. Flow Rate. (Bottom Right) Pressure, Temp and Flow oscillations.

The oscillations on the graph are similar to each other. The flow of gaseous nitrogen has a small phase shift compared to the liquid temperature. Even with these shifts the plotted flow of the nitrogen closely resembles the plotted temperature in several locations. With an increase in cryogenic liquid temperature the amount of boil-off will naturally increase as the element changes states from liquid to gas.

One justification for a change in liquid temperature is pressure. Any temperature can be directly affected by pressure. A pressure change might affect temperatures enough to fluctuate flow; consequently creating an oscillation in boil-off.

The barometric pressure is directly affecting the temperature in of the liquid. Constantly the liquid temperature and pressure rise and fall together without a phase shift. This is most apparent toward the end of the graph at JCD 240 (2.04E+06 seconds). Here there is a steady increase in both temperature and pressure, followed by a decline, increase and a rapid decline towards the end. Keep in mind that these measurements were taken from transducers over 20 nautical miles away and have stunning consistency.

With the plots of temperature and pressure being similar, it can be expected that the plot of pressure and flow will be much like the plot in **FIGURE 4**. Barometric pressure and the nitrogen flow from the storage tank have the same peak to peak amplitude of 12 and a half hours. Similar to the plot of temperature and flow, the flow peaks do not occur at the same time as the pressure peaks; however they are not opposite of each other. The pattern with the pressure and flow indicates a small phase shift. A few hours after the pressure reaches a high the flow will peak before the pressure again comes to a low. This can be seen in **FIGURE 6**. This can be explained as the time it take for the barometric pressure to effect the liquid nitrogen, warm it and have it boil-off from a liquid to a gas.

The consistency with the amplitude show that the flow rate oscillation is directly associated with the liquid temperature and the barometric pressure. However, it has not been explained as to why this oscillation has been seen in the 1000-L tanks and not the 10-L or even the LH2 tanks on the shuttle launch pads.

DISCUSSION

Cryogenic boil-off has been largely attributed to ambient temperatures, none steady state storage tanks conditions, pour insulation, and low tank liquid levels. While examining the problem none of the suspected causes showed a relationship to the oscillation.

Tides Effects on Barometric Pressure

Atmospheric pressure can change from rain storms, hurricanes, tropical depressions and so forth. Although the pressure can be changed by several things only one entity has the ability to adjust the pressure on a regular and stable time interval. The moon continuously orbits the earth and takes over 27 earth days to complete one lunar day. Despite its long elliptical orbit, its gravitational forces continue to pull on earth.

Gravity affects all substances differently. The moons gravity continually pulls on earth deforming the planets solid core, but its major effects are shown in the oceans. The tides that are experienced occur daily and from high to high tide is 12 hours and 25 minutes. Although tides overall height can change depending on location on earth and where the moon is in its orbit, the interval that effects the tides never changes. Tides are always different from day to day by 50 minutes.

Along with the effect the moon has on the earth's oceans the moon also affects the atmospheric pressure. This occurrence occurs with the same amplitude as the tides. The barometric pressure and oceans tides for Cape Canaveral, FL can be seen in **FIGURE 7**. Viewing the graph it can be seen that the rise and fall of the tides coincides with the rise and fall of the barometric pressure. When the pressure reaches a high the ocean is at a high tide. When the pressure is at a low the ocean is at a low tide.

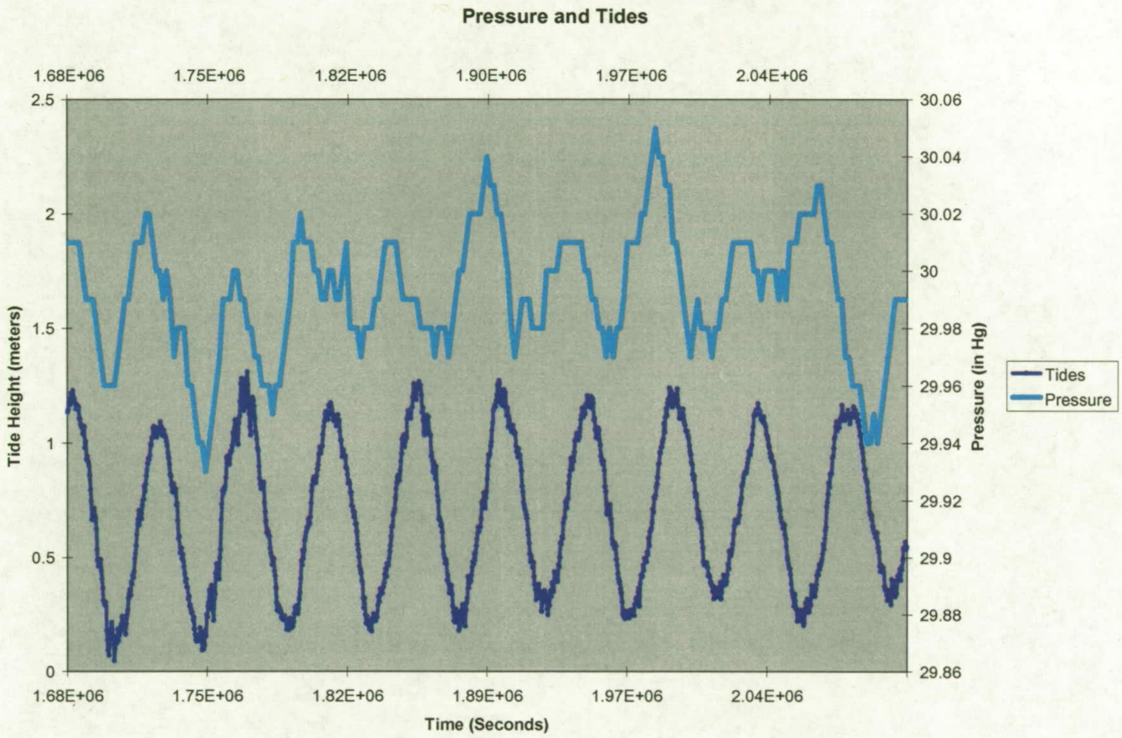


FIGURE 7. The graph shows the tide height and barometric pressure. (X-axis: JCD 236 at 0:00:00 GMT to 241 0:00:00 GMT)

ANALYSIS

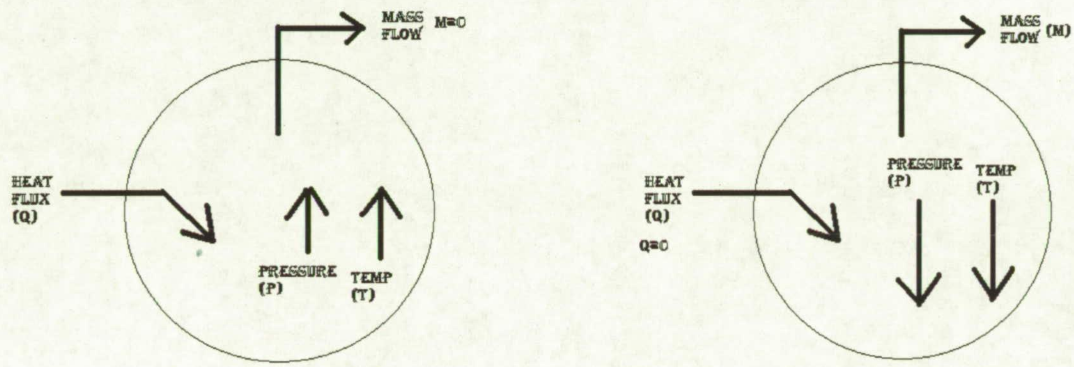
A model was completed in MathCad representing the oscillation for the storage tanks. The model addressed at three scenarios.

1. Liquid nitrogen in the 1000-L tank.
2. Liquid nitrogen in the 10-L tank.

3. Liquid hydrogen in the shuttle launch Pad 39-A/B tanks.

The scenarios were solved by using steady state conditions of thermodynamics. Each tank was evaluated using two different conditions. The conditions are shown below in **FIGURE 8**. With the conditions, the tanks calculated flow rates of sccm (standard cubic centimeters per minute) could be calculated for the gas escaping each tank through its vent line. After this the flow rate can be converted to a volume loss of liquid per day. This is accomplished by assuming the liquid in the tank is saturated and the state of the liquid is under the conditions seen from the barometric pressure change.

The calculated and actual results determine whether the barometric pressure changes have an effect on a tanks liquid volume, inevitably leading to an increase of boil-off. If the calculated number is below the known number of boiloff we can conclude that the pressure change does affect the tank. If the calculated value is above what we know to be the tank boil-off, then obviously the pressure change does not affect the liquid volume in the tank. A table of these results can be seen in **FIGURE 9**. From this it can be seen that the barometric pressure change does not affect extremely large storage tanks. However the smaller cryostats of 10-L and 1000-L are affected. The amount of calculated boil-off for the 10-L is small enough that, it is without the range of accuracy for the flow meters in the cryostat to detect.



CONDITION 1

- Assume $M_{dot}=0$
- Pressure of liquid is increasing.
- Temperature of liquid is warming.
- Solve for the Heat Flux Q_{dot}.

CONDITION 2

- Assume $Q_{dot}=0$, $M_{dot}\neq 0$.
- Pressure of liquid is decreasing
- Temperature of liquid is cooling.
- Find flow in sccm and liter/day.

FIGURE 8. This gives a brief explanation of the assumed conditions used to calculate the rate of boil-off.

Tank Size	Known Boil-off Rate	Calculated Boil-off Rate	Does Press. Effect it?
1000-L	3.8 liter/day	.363 liter/day	Yes

10-L	**2.16 liter/day**	**4.4*10-3 liter/day**	**Yes**
850-kgal	**400 gal/day**	**800 gal/day**	**No**

FIGURE 9. Table of calculated values compared to known historical boil-off rates.

CONCLUSION

Testing on the 1000-L tanks has shown that barometric pressure changes are effecting the boil-ff of cryogenic liquids. These rates vary depending on weather, global location and the moon's location in its orbit around the earth. Although this problem has not been seen in larger storage dewars, it does effect dewars with a lower liquid volume. A small change of pressure in these tanks will have a larger result because of the lesser liquid volume. In small dewars the oscillations are still present, but are very minor. This limits what can be recorded since the amount can be so slow that at is within the range of uncertainty for some transducers.

The research and calculations performed will help personal in the future understand any detected variations in boil-off and reduce the uncertainty that is associated with the instruments used to collect the data.

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