EXPERIMENTAL RESULTS OF INTEGRATED REFRIGERATION AND STORAGE SYSTEM TESTING

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ABSTRACT

Launch operations engineers at the Kennedy Space Center have identified an Integrated Refrigeration and Storage system as a promising technology to reduce launch costs and enable advanced cryogenic operations. This system uses a close cycle Brayton refrigerator to remove energy from the stored cryogenic propellant. This allows for the potential of a zero loss storage and transfer system, as well and control of the state of the propellant through densification or re-liquefaction. However, the behavior of the fluid in this type of system is different than typical cryogenic behavior, and there will be a learning curve associated with its use. A 400 liter research cryostat has been designed, fabricated and delivered to KSC to test the thermofluid behavior of liquid oxygen as energy is removed from the cryogen by a simulated DC cycle cryocooler. Results of the initial testing phase focusing on heat exchanger characterization and zero loss storage operations using liquid oxygen are presented in this paper. Future plans for testing of oxygen densification tests and oxygen liquefaction tests will also be discussed.

KEYWORDS: Liquid Oxygen, Refrigeration, Storage

INTRODUCTION

Launch operations engineers at the Kennedy Space Center have identified a Integrated Refrigeration and Storage system as a promising technology to reduce launch costs and enable advanced cryogenic operations. This system uses a close cycle Brayton refrigerator to remove energy from the stored cryogenic propellant. This allows for the potential of a zero loss storage and transfer system, as well and control of the state of the propellant through densification or re-liquefaction. However, the behavior of the fluid in this type of system is different than typical cryogenic behavior, and there will be a learning curve associated with its use. A 400 liter research cryostat has been designed, fabricated and delivered to KSC to test the thermofluid behavior of liquid oxygen as energy is removed from the cryogen by a simulated DC cycle cryocooler.

In typical cryogenic storage tanks, heat leak from the ambient environment enters the tank via conduction down the length of the structural supports and the associated plumbing as well as convection and radiation across the surface area of the tank. This heat transfers via convection to the cold fluid from the tank walls. The natural convection in the liquid creates a boundary layer along the tank walls, with an upward convection current due to buoyancy forces. The warmer fluid rises and accumulates in a layer at the top of the liquid, where it reaches saturation temperature and then evaporates. This process is shown pictorially in Figure 1a. Over time, this saturation layer reaches deeper into the tank, the temperature stratification disappears, and the liquid in the tank will eventually reach a fairly constant temperature. If there is refrigeration integrated into the liquid region, heat is removed from the liquid in a similar natural convection process. In this case, the fluid is cooled, resulting in a downward current at the heat exchanger location. This can result in a circulation pattern in the fluid as shown in Figure 1b. The intent of the first phase of the IRAS testing is to experimentally determine the physical effect of the heat exchanger position and configuration on the liquid in the tank. In particular, the IRAS cryostat is designed to measure the horizontal and vertical temperature gradients in the liquid, the level of subcooling provided by the refrigeration. The system pressure response to changes in refrigeration power. In addition, a model of the system is being created using Fluent CFD software. This model will be validated using the experimental results. The first year of testing is only planned to include zero boil off operations. Four different heat exchanger configurations are planned to be tested. A horizontal heat exchanger will be tested at three different heights, at approximately the 10%, 35%, and 60% fill locations. A vertical heat exchanger will also be tested. In the following year, oxygen liquefaction and densification operations will also be performed.

SYSTEM DESIGN

The general procurement solicitation for the IRAS test cryostat design and fabrication was released in the fall of 2007. The solicitation was left generally vague to allow for competing ideas on how to provide refrigeration into the system. The contract was awarded to Eden Cryogenics of Plain City, Ohio. Their design incorporates an open cycle liquid nitrogen cooling system to simulate a Brayton cooler, which could not be procured due to cost considerations. The vessel delivered has 400 liters of liquid storage, and the inner region included 34 RTD temperature sensors. The sensors are arranged to provide insight into thermal gradients in the horizontal and vertical direction, and includes an array of 10 sensors spaced within 2 inched at the fill level of 70% for greater resolution at a liquid to vapor interface. Additional temperature sensors were included to measure coolant nitrogen inlet and exit temperature as well as heat exchanger inlet and exit temperatures. Pressure sensors were included on the liquid oxygen and liquid nitrogen system, and the nitrogen flow is controlled by a bellows metering valve. A mass flow controller has been ordered to provide for automatic pressure control in the near future. There are three load cells used to measure the system mass. The entire inner assembly is designed to be removed for servicing or repair, by disconnecting the top flange, and the heat exchanger supply and return tubes have mechanical fittings to allow for replacement or repositioning of the heat exchanger. The entire wetted assembly is made of 304L stainless steel, and is designed to ANSI/ASME codes. The maximum allowable inner pressure is 65 psia and the minimum pressure is 1 psia, to allow for subatmospheric operation while in densification mode. A system mechanical drawing is shown below in Figure 2.

Due to the hazardous nature of oxygen testing, a safety and hazards analysis was performed at KSC during the design phase. Of primary interest was materials selection. The American Society of Testing and Materials [1,2] has published guidelines for materials usage in oxygen systems. There are two materials of concern in use in the inner vessel, the G10 epoxy glass laminate that is used for the temperature instrumentation rake and Kapton insulation around the RTD wiring. Neither of these materials is approved for general usage in oxygen systems at KSC. An ignition probability assessment was conducted which considered the following ignition sources; temperature, heat of compression, friction, mechanical impact, particle impact, contamination, static electricity, electrical arcing and resonance. Due to the system design, and low temperatures, pressures, and flowrates involved, chances of ignition were considered remote. In addition to materials selection, the hazards analysis also included basic safety guidelines such as training, protective equipment, cleanliness, operating procedures, facility planning, quantity distance relations, venting, transportation, and fire protection. The IRAS system was reviewed by KSC safety experts and it was determined the system met all the applicable KSC oxygen system specifications [3].

Qualification Testing

The cryostat was delivered from Eden Cryogenics LLC to Kennedy Space Center on June XX, 2008. The assembly was inspected for damage from shipping and placed inside the Cryogenic Test Laboratory for qualification testing with liquid nitrogen. The cryostat was filled with 340 liters of liquid nitrogen and a three day thermal stabilization period was begun with the vent valve open to atmospheric pressure. After the stabilization period, a boil off test was conducted to quantify baseline heat leak. Using a 10,000 sccm MKS flowmeter, the average boiloff rate over a 24 hour period was found to be 4253 sccm. This equates to a heat leak of 17.5 W. Qualification testing also found that two RTD's (T1 and T14) were damaged during shipping. Subsequent troubleshooting after the cryostat was drained and opened discovered the pin connections at the electrical feedthrough had disconnected. These pins were reconnected and the RTD's have been working properly since. The rest of the instrumentation was also tested, with no problems noted except for the load cells on the bottom of the cryostat feet. Interference between the cryostat legs and the weld bead on the base caused a preload on the base, which did not allow the full weight of the system to fall on the load cells. This interference was eliminated by shaving the corners of the cryostat legs and the load cells are now reading properly.

INITIAL TESTING

After qualification testing, the system was sent to a local vendor for additional cleaning to the Kennedy Space Center oxygen cleanliness specification. The pretest briefing was originally scheduled to be held January 8, 2009. However, an unrelated safety incident at KSC in December resulted in a temporary hold on all non-essential hazardous operations. Additional safety approval processes were implemented, resulting in a four month delay in the start of testing. During this approval process, procedural and test siting changes were also made. The test readiness review was held on May 5, and chilldown with LN2 was initiated immediately after this review. This LN2 chilldown was one of the procedural changes required by the contractor safety organization, it was felt that the Kapton and G10 materials would have less ignition succeptibility if they were at cryogenic temperatures when they were initially exposed to 100% oxygen.

After a two day cold soak period, the liquid nitrogen was drained from the cryostat and the system purged with gaseous oxygen. While the inner vessel was still cold, liquid oxygen was introduced. Liquid oxygen is supplied to the laboratory a 180 liter portable dewar. There is only one LOX portable dewar on site, so the LOX fill process took several days as the oxygen supply was delivered, transferred into the IRAS system, returned to propellants to be refilled and then delivered again. A total of five oxygen dewars were loaded into the IRAS system between May 7th and May 18th, and the IRAS fill level was approxiametly 75%.

The initial cooling test was scheduled to begin on June 19th, however on Saturday June 16th the IRAS burst disk failed prematurely and needed to be replaced. At the time of the failure the IRAS pressure was steady at xx psi, which is the set pressure of the primary relief valve. The burst disk was designed to burst at xx psi. In addition to prematurely failing, the disk did not fully rupture, but partially cracked open. The system maintained a backpressure of XX psi. The cryostat was vented to atmosphere and the burst disk was removed. Visual inspection revealed no corrosion and the disk was sent to the Materials Analysis Branch at KSC for failure analysis.

Test Initial Conditions

Prior to testing, the test team met to discuss the test protocols. The primary intent is to ensure that the initial test conditions and the test operations are identical between the four heat exchanger configurations. To ensure identical initial conditions, control of the state of the propellant has to be achieved. Pressure control is simple and there are three options to choose from. The IRAS vent valve can be opened, allowing the tank pressure to reach the normal boiling point subjected to the variations in local atmospheric pressure. This is undesirable since any positive cooling will create subatmospheric pressure in the tank. Second, the tank can ride on its primary relief valve, set at 60 psi. This would create the largest temperature gradient between the liquid oxygen and the liquid nitrogen coolant. However in practice this would not occur since the bulk liquid oxygen density would be relatively low at this pressure. This is undesirable for space launch applications. The final option is to install a secondary relief valve set at a pressure closer to the NBP. This option was chosen and an 8 psig relief valve was installed off the vent leg of the IRAS. Temperature control prior to the start of testing was accomplished by having a thermal stabilization periods prior to the start of each test. This time period is dependent on the vessel heat leak, internal volume, system fill level, and the initial and final pressure. Figure 3 shows the temperature and pressure response in the IRAS after the vent valve was closed. The pressure immediately reaches the saturation pressure that corresponds to the bulk liquid temperature, then quickly rises over the next 25 minutes to reach the relief valve set pressure around 8.3 psig. According to the temperature profiles, it takes an additional 37 hours for the temperature to de-stratify and the liquid to become fully saturated. At this point all the heat leak into the tank will be contributing to evaporation. This is the condition required to start the testing.

Zero Boil Off Test #1

Currently, the test team has only had the time to complete one set of preliminary tests with the heat exchanger in the lowest position. This testing was completed the week of

June 1, 2009. The primary intent of the first test was to gather experience in the operational characteristics of the system and to get a feel for the LN2 flow control required. After a 70 hour thermal stabilization period, the liquid oxygen in the tank tank had a fairly constant temperature of 94.9 K and a pressure of 8.6 psig. The liquid level was at 72%. Liquid nitrogen cooling was initiated at 9:16 am when the needle valve was opened 5 full turns. This high flowrate was necessary during the system chilldown. After liquid nitrogen temperatures were reached at the LN2 heat exchanger outlet, the flow was restricted to attempt to maintain a constant pressure. Liquid nitrogen cooling was provided for 2 days. The nitrogen supply vessel was only partially filled at the beginning of the test and needed to be replaced around the 27 hour mark. The replacement vessel was also only partially full and only provided 18 hours of cooling. During the 2 day test period that time the pressure stayed below the relief valve pressure and the oxygen was stored in zero boil off mode. Future testing will attempt to utilize multiple nitrogen vessels connected together and pressurized with external GN2 as opposed to autogenous pressurization. This will also allow the cooling temperature to be decreased to near 77 K, as opposed to the 84 K provided by 22 psig saturated condition.

Figure 4 shows the liquid nitrogen inlet temperature and selected oxygen temperatures during the first hour of the test. The oxygen pressure is also shown. The oxygen pressure started to decrease within 35 seconds of the start of coolant flow. The chilldown was complete within 10 minutes with the LN2 inlet temperature reaching 85K. It is not readily apparent why the oxygen pressure and temperature began to decrease prior to the completion of the LN2 chilldown as it can be seen when the nitrogen temperature reaches the liquid point. One possible explanation is there is a thermal lag associated with the chilldown of the thermocouple on the outside of the line. In general, the liquid nitrogen instrumentation was problematic and will be modified before further testing is accomplished. Instead of thermocouples attached to the outside of the line, feedthru type thermocouples will be used to measure the nitrogen temperature directly. In addition, a nitrogen pressure sensor will be added.

Figure 5 shows the liquid nitrogen flowrate and oxygen pressure over the two day test period. The periods of constant LN2 flowrate correspond to specific needle valve adjustment periods. Over the 45 hour period, the oxygen pressure never rose above 8 psig, so ZBO conditions were achieved. After chilldown, the needle valve was decreased to 0.5 turns open, or a flowrate of 35 slm. The dP/dt in the LOX dewar was positive, so the valve was opened slightly to the 0.625 turn open position. At this point the dP/dt was dropping sharply. Again the valve position was adjusted to 0.58 turns open and the cooling was allowed to continue overnight. The dP/dt was fairly constant (dropping slightly) for the first five hours, but then began to decrease more rapidly as the night progressed. In the morning the LOX pressure was below 1 psig. The cooling flow was further decreased with the valve repositioned to 0.48 openand the pressure started to increase The spike in pressure at the 27 hour mark corresponded to the first nitrogen supply dewar becoming empty. When the new vessel was connected the flow dropped from 33 to 31 slpm, but the dP/dt decreased. This may be explained by the new nitrogen vessel being stored at a slightly lower pressure and the liquid supplied is cooler. At this point the valve was adjusted to the 0.40 turn open position. Cooling power at first decreased but later started to increase. This eventually caused a drop in LOX pressure, reaching 0.01 psig the following morning. At this point the second vessel was also expended. It is worth noting that the this period also exhibited a variable flowrate for the nitrogen cooling, even though the valve position was unchanged. Figure 6 also shows the liquid oxygen temperatures during this timeframe. The degree of subcooling is evident during the time between hours 25 and 35.

When the cooling power was decreased and dP/dt was increasing, the lowest regions of the vessel did not immediately increase in temperature like the saturated regions did.

Initial Test Lessons Learned

Liquid oxygen pressure control is feasible using liquid nitrogen cooling in the lowest region of the liquid space. Pressure variations are evident almost immediately upon changing of the cooling flowrate. More testing needs to occur to determine the optimum cooling flowrate required. Several problems were noted with this initial test and the IRAS instrumentation and control system will be modified to account for the problems. Most importantly, better control and visibility is needed in the area of the nitrogen supply. A pressure transducer will be added to the nitrogen supply line, and feed thru thermocouples will be used to measure the nitrogen temperature directly. Also, better control of the nitrogen supply will be accomplished using multiple supply vessels ganged together, vented to the NBP, and pressurized with external gaseous helium. In addition, a nitrogen mass flow controller will be added to attempt automatic pressure control. Next, when the cryostat is opened up to relocate the heat exchanger, RTD's will be added in the top of the annulus to the liquid nitrogen supply lines to better understand the true heat transfer across the heat exchanger. Finally, better resolution on the oxygen system pressure is needed. True saturation conditions are difficult to calculate using a 0-100 psig transducer with no monitoring of the ambient pressure fluctuations. A 0-30 psia gauge will be added to the system.

CONCLUSIONS

Ground operations engineers at the Kennedy space Center are looking to develop advanced technologies to increase the efficiency of their cryogenic propellant loading systems. One technology under investigation is the integration of a refrigeration system into the liquid space of the cryogenic storage tank. This allows for the possibility of control of the state of the propellant, included zero boil off operations, propellant densification, and in situ liquefaction. A cryostat has been designed and fabricated to test the thermal fluid behavior of liquid oxygen, while it is being cool by the internal refrigeration. The initial test has been conducted with generally favorable results. Further testing is planned over the next several months, and lessons learned in the initial phase of testing will be incorporated.

ACKNOWLEDGEMENTS

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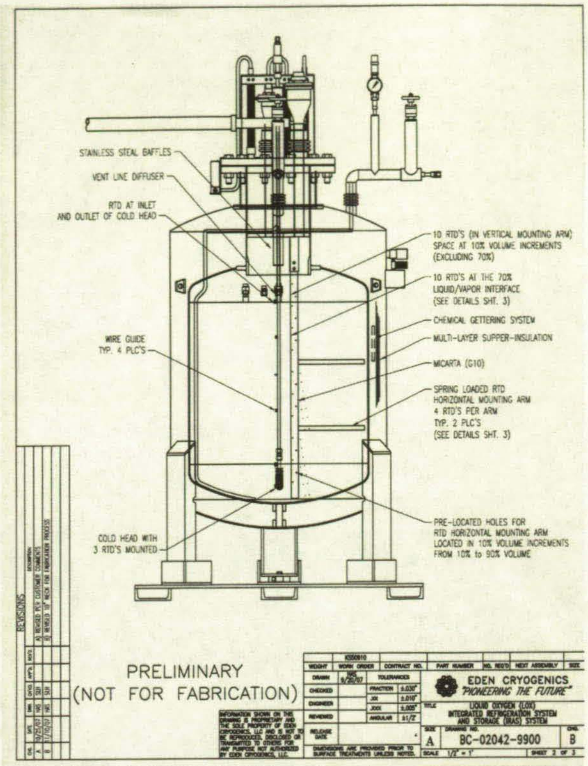

Figure 2) IRAS Mechanical Design Drawing

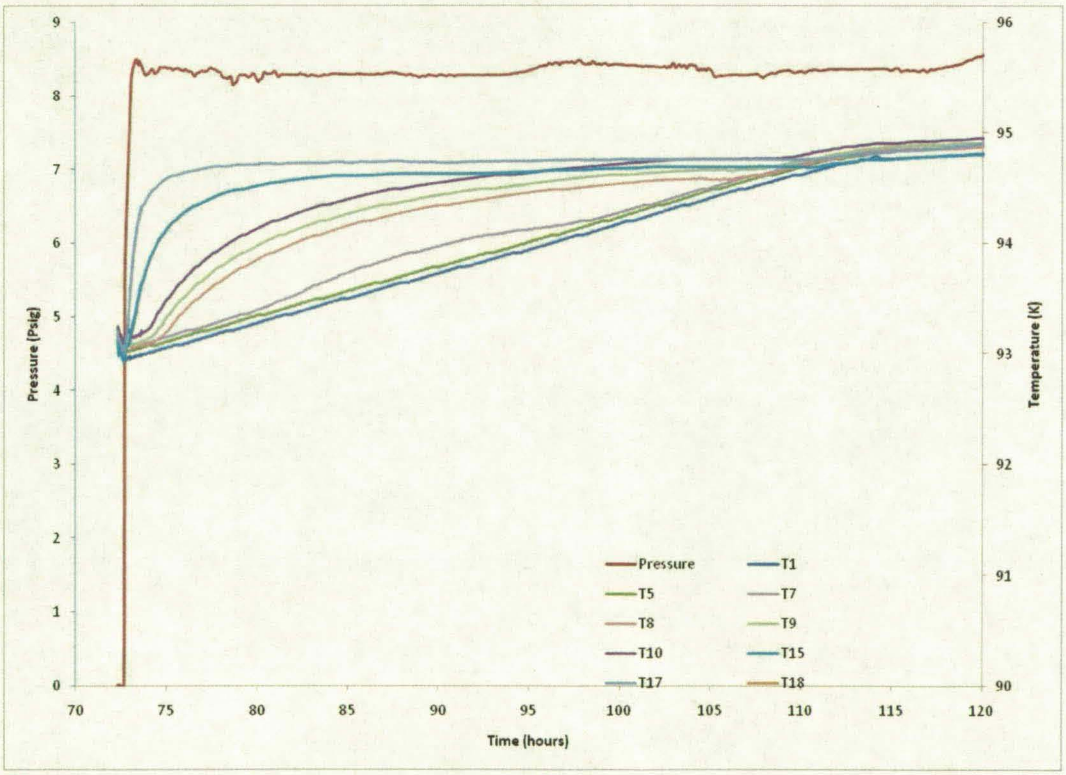

Figure 3) Pressure and Temperature Stabilization

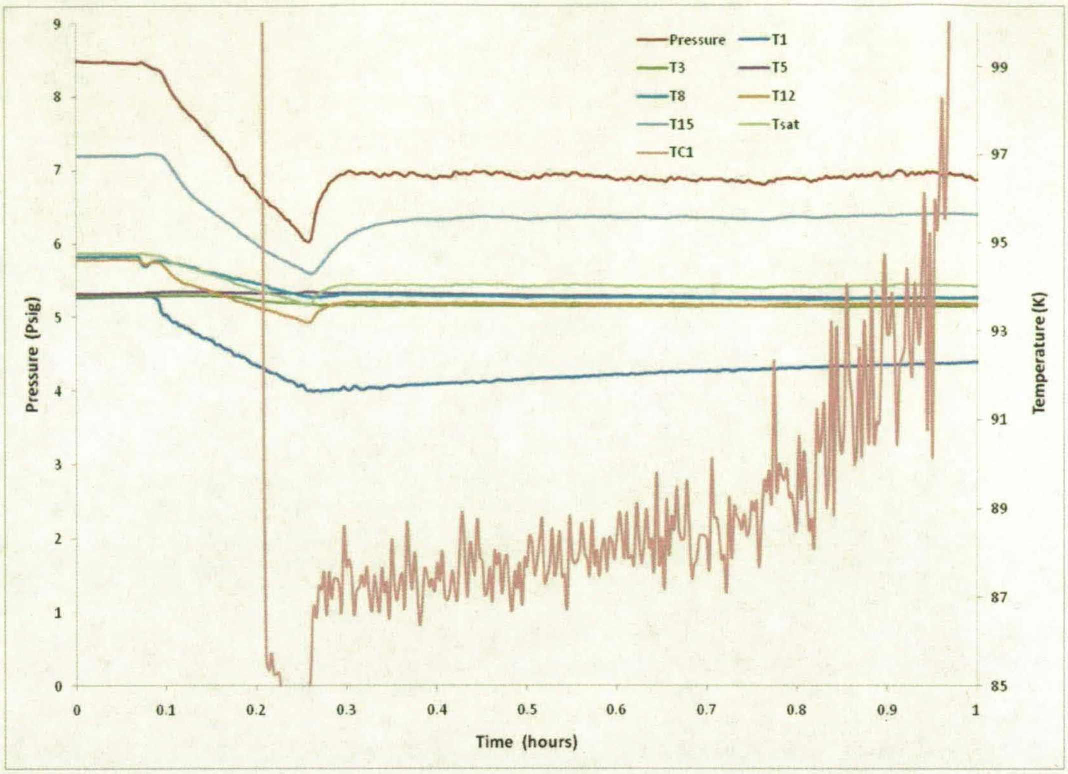

Figure 4) IRAS Response During LN2 Chilldown

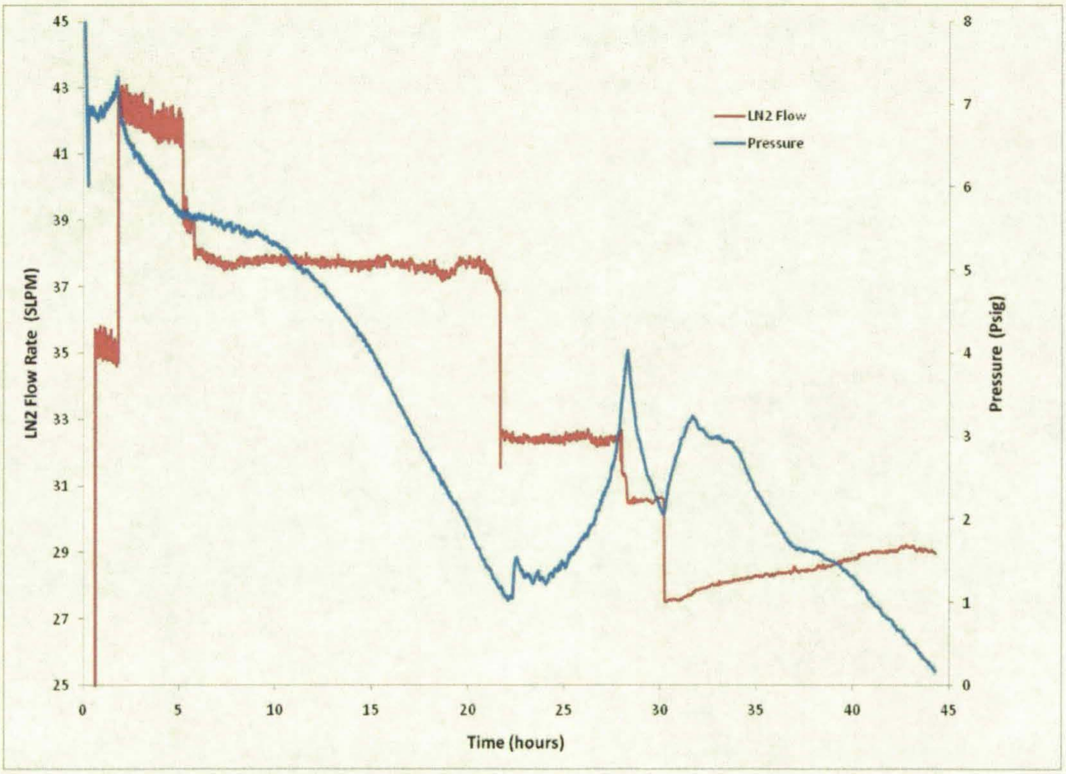

Figure 5) IRAS Pressure vs LN2 Flow Rate

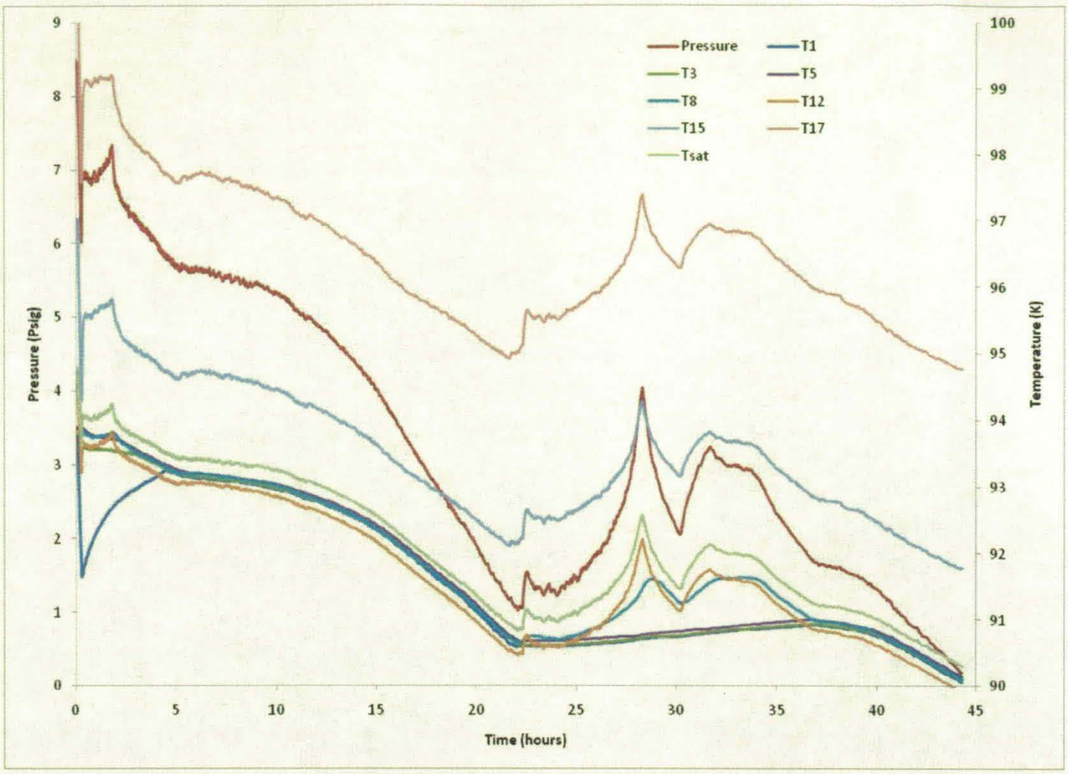

Figure 6) IRAS Oxygen Temperatures