Subcooling for Long Duration In-Space Cryogenic Propellant Storage

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Cryogenic propellants such as hydrogen and oxygen are crucial for exploration of the solar system because of their superior specific impulse capability. Future missions may require vehicles to remain in space for months, necessitating long-term storage of these cryogens. A Thermodynamic Cryogen Subcooler (TCS) can ease the challenge of cryogenic fluid storage by removing energy from the cryogenic propellant through isobaric subcooling of the cryogen below its normal boiling point prior to launch. The isobaric subcooling of the cryogenic propellant will be performed by using a cold pressurant to maintain the tank pressure while the cryogen's temperature is simultaneously reduced using the TCS. The TCS hardware will be integrated into the launch infrastructure and there will be no significant addition to the launched dry mass. Heat leaks into all cryogenic propellant tanks, despite the use of the best insulation systems. However, the large heat capacity available in the subcooled cryogenic propellants allows the energy that leaks into the tank to be absorbed until the cryogen reaches its operational thermodynamic condition. During this period of heating of the subcooled cryogen there will be minimal loss of the propellant due to venting for pressure control. This simple technique can extend the operational life of a spacecraft or an orbital cryogenic depot for months with minimal mass penalty. In fact isobaric subcooling can more than double the in-space hold time of liquid hydrogen compared to normal boiling point hydrogen. A TCS for cryogenic propellants would thus provide an enhanced level of mission flexibility. Advances in the important components of the TCS will be discussed in this paper.

I. Introduction

The use of cryogenic propellants is crucial for exploration of the solar system because of their superior specific impulse (I_{sp}) capability. Future missions will require vehicles with the flexibility to remain in space for months to

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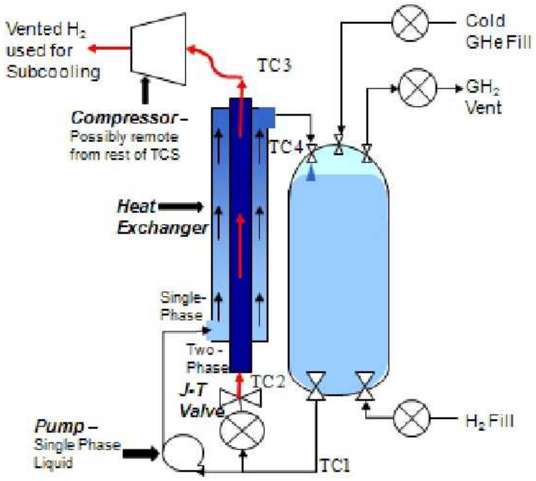


Figure 1. The TCS concept for isobaric subcooling of cryogens on the launch pad.

years, necessitating long-term storage of these cryogens. One powerful technique for easing the challenge of cryogenic fluid storage is to subcool them below their boiling point at atmospheric pressure prior to launch. Propellants such as liquid hydrogen have very large heat capacities. The heating of the chilled cryogens allows them to absorb the energy that leaks into the tank even with the use of the best insulation systems. During this period of heating of the subcooled cryogen there will be minimal need to vent the cryogen, thus extending its in-space 'hold-time'. This technique can substantially extend the orbital and transit storage of the cryogenic propellants.[1]

In recent years a novel technology has been proposed that uses the thermodynamic capabilities of the stored cryogen itself to carry out subcooling using a system known as the Thermodynamic Cryogen Subcooler (TCS). The TCS consists of valves, pumps, compressors and heat exchangers along with insulation enhancements to the subcooled propellant tank and the TCS. The power and footprint requirement will be significantly less than that of previously proposed launch-pad coolers of various configurations. In addition this system can be used to maintain or further lower the thermodynamic condition of the cryogen that is delivered to the launch pad, even if it has previously been densified or subcooled. There will be minimal, addition to the launched mass as the entire TCS will be ground support equipment (GSE).[1]

II. Thermodynamic Cryogen Subcooler

Figure 1 shows a notional configuration for the TCS that is being proposed for a launch pad subcooling system. The hydrogen that is being subcooled, will be extracted from the tank. Some of this extracted hydrogen will be passed through a Joule-Thomson (J-T) valve that isenthalpicly expands the hydrogen. The hydrogen on the upstream side of the J-T valve, at thermodynamic condition 1(TC 1), will be at the temperature of the hydrogen in the tank (initially 20.4 K). The hydrogen on the downstream side of the J-T valve (TC 2) will have the same enthalpy as the hydrogen on the upstream side, but at a lower pressure (~0.1 atm.) and substantially lower temperature (~15 K). While going through this expansion the hydrogen at TC 2 becomes a two-phase fluid. Most of the liquid hydrogen extracted from the tank at TC 1 will be pumped into the outside tube of a concentric tube heat exchanger - the single-phase tube. The two-phase hydrogen at TC 2 is passed into the center tube of the concentric tube heat exchanger — the two-phase tube. Since the hydrogen in the two-phase tube is at a lower temperature than the hydrogen in the single-phase tube it can extract heat from the hydrogen in the single-phase tube and thus subcool the propellant. The two-phase hydrogen will increase in vapor quality along the two-phase tube until it totally vaporizes and is vented (TC 3) to a flare stack through a compressor system. This compressor system will probably be the heaviest and most power intensive component of the TCS and hence it might be remote from the rest of the TCS. The subcooled hydrogen at the end of the single-phase tube (TC 4) is then fed back into the hydrogen tank. The portion of LH_2 that is expanded through the J-T device and vented will be replaced by a supply of make-up LH_2 to fill and maintain a full tank. As the bulk hydrogen in the tank is subcooled by this process, its density increases so the tank will be backfilled with non-condensable cold helium in order to prevent the tank from experiencing a compressive atmospheric load. The TCS components will be isolated from parasitic heat inputs by using a vacuum outer jacket and multi-layer insulation (MLI). By using the cooling enthalpy available in the cryogen that is being stored the need for a power intensive high-capacity refrigeration system is diminished.

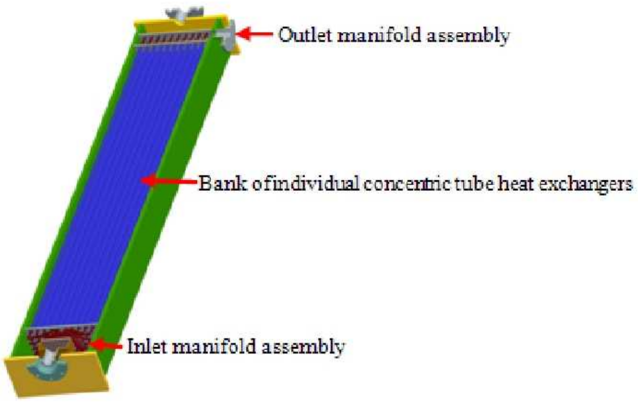


Figure 2. A notional TCS heat exchanger with a bank of concentric tube heat exchangers.

Drawing Credit: Matthew Kuhn – NASA/GSFC 2009 Intern

The important components of the TCS are the heat exchanger, the pump, the compressor, the Joule-Thomson valve, and the insulation system. The following sub-sections discuss the conceptual, modeling and experimental development of components undertaken by the TCS team since 2009.

A. Heat Exchanger

A major component of the TCS is the heat exchanger which will transfer heat from the higher temperature recirculated single-phase liquid cryogen that is being subcooled to the vented lower temperature two-phase cryogen that is performing the cooling. The performance of the heat exchanger will determine the mass and size parameters of the TCS, which are important for the appropriate packaging of this system on the launch pad. An actual TCS would probably consist of a bank of concentric tube heat exchangers that would allow the TCS to be packaged compactly. Figure 2 depicts a notional TCS heat exchanger with a bank of 200 individual concentric tube heat exchangers with a manifold splitting the flows near the inlet and another manifold rejoining the flows near the outlet. For an Earth Departure Stage (EDS) sized tank about 34 tons of hydrogen will have to be subcooled within a 12 hour period, leading to the necessity for high Reynolds number flows (10^5 – 10^6) through the heat exchanger to achieve a reasonably compact design. In the future these concentric heat exchangers may provide a baseline for

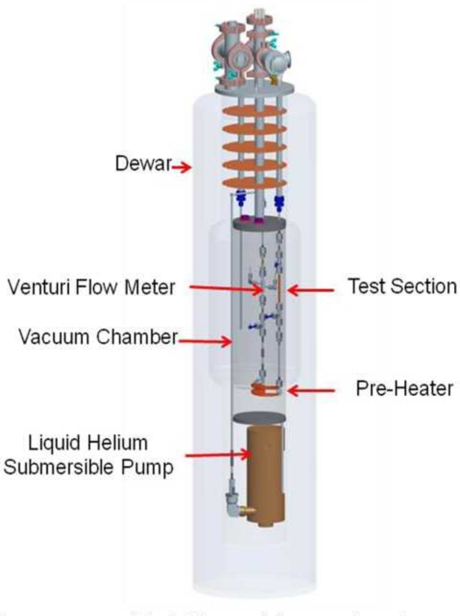


Figure 3. Experiment to measure high Reynolds number two-phase flow parameters.

Drawing Credit: Lee Kersting and Peter Oas – NASA/GSFC 2009-2010 Interns

more advanced compact heat exchangers that are difficult to model and scale.

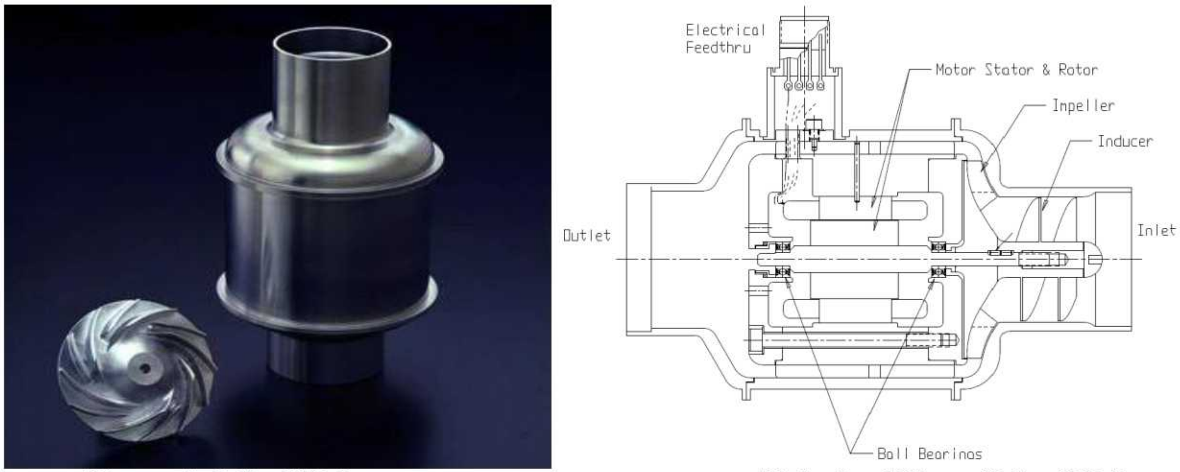
Goddard Space Flight Center (GSFC) is performing the first-step of the TCS heat exchanger development: measuring the high Reynolds number two-phase flow parameters or heat transfer coefficient and pressure drop. These measurements will enable the design of simple and scalable concentric tube co-flow heat exchangers. Figure 3 shows the experiment at GSFC to measure the important two-phase flow parameters. This experiment will be conducted using liquid helium as a simulant for liquid hydrogen. The dewar will be filled with liquid helium. A submersible liquid helium pump will be used to pump liquid helium in a controlled fashion into the experiment components located in the vacuum chamber. The flow from the pump will be routed through a venturi flow meter to measure the volumetric flow rate. The flow will then be directed through a pre-heater section. The quality of the two-phase fluid is set in this section. The pump-venturi combination and the pre-heater section will allow independent variation of the flow rate and the quality of the flow respectively. The heat transfer coefficient and pressure drop in the test section will be measured for various flow rates and flow qualities. Temperature and pressure measurements will be made to define the thermo-physical properties of the fluid at various locations along the experiment.

Once the two phase flow parameters have been measured, this data will be used to design a subscale version of the heat exchanger shown in figure 2, possibly with 4 concentric tube heat exchangers. The performance of a subscale TCS with this subscale heat exchanger, J-T, pump and compressor will lay the groundwork for a full-scale TCS demonstration leading the TCS to a technology readiness level (TRL) of 6

B. Pump

A cryogenic liquid pump will be required by the TCS to facilitate liquid flow through the single tube heat exchanger for subcooling before re-injection into the tank. The liquid flow rate is quite large with a relatively small head rise so the pump is a mixed/axial flow device that is a larger version of the pump shown in Figures 4. This pump can be installed directly in the liquid hydrogen lines with insulation installed around it. The pump shaft has the motor rotor and pump impeller/inducer directly attached and riding on special ball bearings. These bearings utilize a teflon/molydisulfide cage that lubricates the ball bearing and races in the poor lubricity liquid hydrogen. The bearings have stainless steel races and ceramic balls. These bearings have been used extensively in liquid hydrogen, liquid helium and liquid nitrogen applications. The ball bearings and the motor are both kept cool by the liquid hydrogen. The heat load from the bearings is minimal with respect to the liquid hydrogen. The liquid hydrogen flows in and out of the pump in the same axis allowing for ease of installation. The pump is controlled by a variable frequency drive (VFD) that provides a wide range of possible performances through changes in speed.

Other cryogenic pumps such as the liquid oxygen loading pumps at NASA-KSC use mechanical seals which are prone to failure in cryogenic applications. This pump uses no dynamic seals thus eliminating this failure mechanism.



(a) An Inline LH_2 Pump (b) Sectional View of Inline LH_2 Pump

Figure 4. A subscale version of the inline liquid hydrogen pump.

Credit: Barber-Nichols

Figure 5. A cryogenic hydrogen compressor.
Credit : Barber-Nichols

C. Compressor

The hydrogen expanded across the J-T valve must be compressed prior to venting to the atmosphere after passing through the two-phase tubes of the heat exchanger. The hydrogen that is initially two-phase directly after passing through the J-T valve will be completely vaporized by the time it passes through the heat exchanger. The compression system must take the gas at very low pressure (approximately 13.1 KPa) and discharge above atmospheric pressure (near 105 KPa). This very large pressure ratio will require multiple stages of compression and large volumetric flow rates at the first stage inlet. Each stage resembles the compressor shown in Figure 5. The lower portion of each of the compressors is installed in an insulated vessel while the water-cooled motors are open to the atmosphere. VFDs control each stage at elevated speeds to optimize performance.

In the late 1990's a prototype four stage compression system for propellant densification was tested at NASA-Glenn Research Center (GRC) under similar conditions. Four stages were used due to the fact that the blowers rotated on grease-packed ball bearings that have limited life at high speeds. The mean time before failure (MTBF) of these high speed machines with grease-packed ball bearings was low. Investigation of bearing alternatives for this application will be undertaken as part of the TCS development effort. As it is critical that this design use a hermetic solution, the two best possible bearing solutions are foil (gas) or magnetic. Both have been used successfully in similar cryogenic applications and as neither solution has wear components under normal operation it also has the possibility of greatly improving compressor system reliability. Both bearing options are capable of operating reliably at very high speeds surpassing 100,000 rpm. The number of stages could possibly be reduced to 2 from the current requirement of 4-5 (using ball bearings) by increasing the speeds (specifically impeller tip speeds) of each machine. Fewer machines with no wear parts should greatly increase system reliability.

D. Joule-Thomson Valve

The J-T valve is used to reduce the temperature of a fluid as it undergoes isenthalpic expansion through an orifice with a positive Joule-Thomson coefficient. The cold output stream of the J-T is passed into the heat exchanger where the two phase flow is divided into as many as 200 two-phase flows and routed through the concentric tube heat exchanger assembly where it heat exchanges and cools the bulk liquid that is re-circulated into the cryogen tank as described in Section A. J-T valves have been extensively tested on the ground in conjunction with thermodynamic vent systems and industrial refrigeration systems. They have been flight qualified for the Shuttle and the Centaur but never flown. It is of course not necessary for the J-T valves to fly for this TCS application, although the TCS J-T valve will be developed for a flight launch pad application.

Previous experimental investigations[2,3] conducted at NASA/GRC have indicated that J-T devices, such as Visco Jets and straight orifices, became clogged when flowing standard industrial grade LH_2 and operating at a temperature range from 20.5 K to 24.4 K for longer than 20 minutes. Above or below this temperature range, no clogging was detected. Densified liquid hydrogen at 18.2 K has been flowed through J-T devices without any clogging for short durations. Longer duration tests with subcooled liquid hydrogen would provide useful validation of this TCS component. It has been postulated that the clogging occurs due to a trace amount of neon that exists in the regular LH_2 supply. It has been further proposed that at temperatures between 20.5 K and 24.4 K, neon exists in a metastable, super-cooled liquid state. When impacted on the face of an orifice, the neon solidifies and accumulates. In time, flow blockage occurs from accretion of solid neon on the orifice significantly reducing the flow rate through the orifice and eventually resulting in complete blockage of the orifice.

This clogging may pose a threat to operation of the TCS if LH_2 fluid conditions fall in the range of planned operation. The TCS is designed to chill liquid hydrogen from approximately 20.4 K to 16 K. This is below the reported range of concern for clogging. However, if liquid hydrogen is initially loaded into a propellant tank at normal boiling point conditions (liquid saturated at one atmosphere), it would be reasonable to assume that the propellant tank is rated for some slight pressure above atmospheric to assure that positive pressure could be maintained to avoid collapse of the tank. This being the case, the liquid hydrogen may initially be at some slightly elevated temperature corresponding to that pressure, and could as a result fall in the region of concern for clogging, although for J-T devices with larger flow rates, clogging was not reported.[4] The TCS operating envelope will be reviewed and a determination will be made regarding the potential risk for J-T clogging, If required, solutions will be proposed to mitigate this risk.

Different J-T devices are available, with the only real requirement being to provide a sufficient pressure drop at the desired design flow rate. This could be accomplished with a straight orifice, throttling valve or other similar device. Much work has been done using Visco Jet ™ flow restrictors in cryogenic fluid systems. The Visco Jet is a multiple orifice device that provides a larger flow capacity than a single orifice with a comparable pressure drop. It also has the advantage with its multiple orifice design of being more robust – plugging appears to be mitigated by virtue of the redundancy afforded by the multiple orifices. However, for the projected TCS flow rates, available Visco Jets are significantly undersized, making them unsuitable for this application. A more suitable option would be the use of a throttling valve with a suitable flow coefficient (C_V) that could pass the required flow rate.

Consideration must be given to determine the flow rate through the J-T device. A two-phase mixture can be choked at its sonic limit through the J-T orifice. Computing the sonic velocity in a two-phase flow cannot be done by ideal gas relations, but can be determined by considering the thermodynamic properties of the mixture. For a given upstream pressure, the downstream pressure can be varied for an isenthalpic process, and a plot of the mass flow rate versus the downstream pressure will yield the pressure which results in a maximum mass flow rate. The choked flow pressure and the sonic velocity, is a byproduct of this calculation. The required flow rate through the J-T diminishes with time as the propellant in the tank reduces in temperature. The maximum flow rate would be required during initial portion of TCS operation, when the bulk liquid hydrogen is at its warmest As the bulk hydrogen subcools, the temperature of the hydrogen at the J-T valve inlet also drops, the valve is then throttled back to maintain the reduced flow rate requirement. Figure 6 shows the reduction in the required mass flow rate through the J-T and the required J-T orifice diameter with time – as these follow the J-T inlet hydrogen temperature drop.

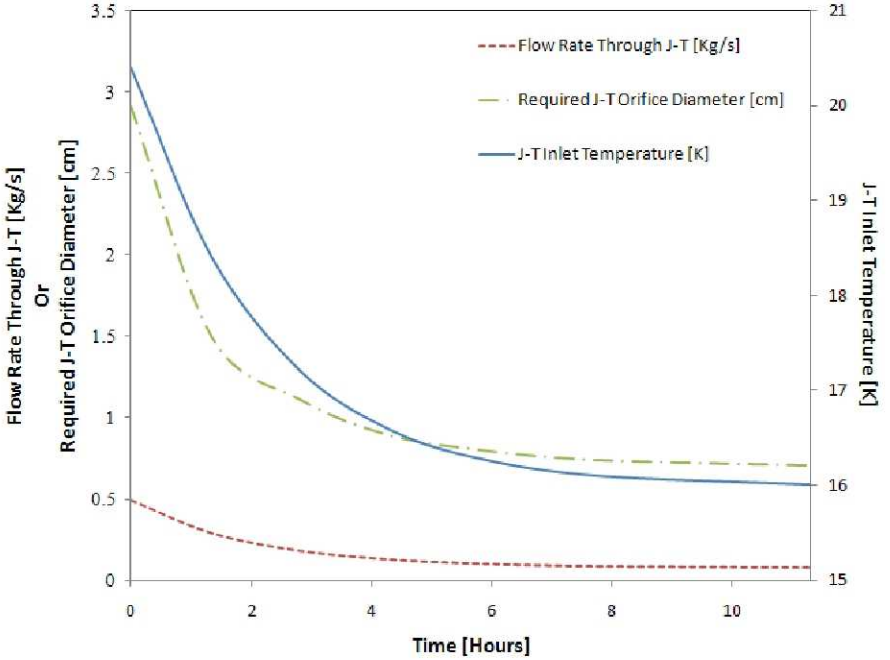


Figure 6: Variation of flow rate, required J-T orifice diameter and J-T inlet temperature with time.

There are a number of suitable cryogenic valves available for ground support systems, and qualifying one of these valves for the TCS should be easily accomplished.

E. Insulation for Test Tank and TCS Components

Insulation is the key for every cryogenic application. A failure to correctly size the insulation, especially for propellant conditioning operations can ruin the efficiency of the entire system. The TCS insulation system consists of the vacuum jacketed (VJ) piping that connects the tank sump to the heat exchanger inlet, the heat exchanger, the VJ piping that connects the heat exchanger outlet to the top of the tank, the flight tank itself (with all of its disconnects), and the piping running the subcooling process hydrogen from the heat exchanger outlet through the compressor systems to the hydrogen burn stack. Due to restrictions on the launch tower (especially if it is a mobile platform, clean pad architecture), there may be significant distances between the launch vehicle and the heat exchanger, even if the heat exchanger is located on the launch structure, piping distances could be as long as 50 m. Umbilical plate disconnects and the heat exchanger connections are generally hot spots within such a system and must be carefully paid attention to.

Tank insulation has been heavily researched, generally insulation materials are good for either ambient pressure or high vacuum, not both as is required for launch vehicles. Lewis Research Center, currently the Glenn Research Center, did a careful study of several different types of high performance insulation and came to the conclusion that foam underneath the MLI was the appropriate method for insulating high performance hydrogen propellant tanks. Subsequently, Marshall Space Flight Center (MSFC) tested the foam/ MLI combinations and showed a heat flux as low as 63 W/m^2.[5] Foam insulations can have heat loads on the order of several hundred[6] W/m^2 while helium purged MLI systems can have even higher heat loads than that.[7] The advantage of the foam underneath the MLI is the use of nitrogen gas. Nitrogen generally evacuates much better than helium and has a thermal conductivity that is roughly 5 times lower than helium. Several systems proposed by United Launch Alliance (ULA) using helium purged MLI underneath insulation that departs at staging have been investigated analytically by Kennedy Space Center (KSC), with resulting steady state heat fluxes as low as 50 W/m^2 (depending on the thickness and performance of the staged insulation). However, the difference in helium versus nitrogen evacuation once on orbit could lead back to the thick foam and MLI solution tested at MSFC. Another consideration is that the helium purge would increase the heat load on the oxygen tank (since it would normally be kept under a nitrogen purge), proper sizing of the foam would give a surface temperature of roughly 90 K (the normal boiling point of oxygen and above the air liquefaction point) and allow for a nitrogen purge on both tanks.

The VJ piping is also important, in that the performance of the pipe will play directly into the minimum temperature achievable by the conditioning system. The larger the pipe diameter is the lower the pumping power requirement will be, however this has to be optimized against the increased heat load for a larger diameter VJ pipe. Another factor to consider is that the fluid will be flowing at very high velocities at the peak flow rate, minimizing the heat picked up in the line; however the residency time in the piping will still be on the order of tens of seconds.

In order to subcool about 3.3 Kg/s of hydrogen, the hydrogen will be run through a heat exchanger consisting of 200 concentric tube heat exchangers each with an external diameter of 2.25 cm and about 3.8 m long. These 200 tubes can be placed in a 20x10 array that is 0.93 m x 0.48 m. A 4.25 m long VJ tube can be used to contain this array of heat exchangers. The best method for insulating the actual heat exchanger will be to build a vacuum jacket around the heat exchanger and then either fill the vacuum jacket with glass bubbles, or attempt a complex MLI wrap. Further thermal analysis would be needed to determine the better solution. However, this will be a heavy solution and might require moving the heat exchanger off of a mobile launch tower onto the pad surface. The insulation must be accounted for in the system trades and thus the entire system (including the insulation) can be properly sized and accounted for in the system's propellant conditioning performance.

F. TCS Thermal Fluids Modeling

A one-dimensional numerical model of the Thermodynamic Cryogen Subcooler (TCS) will be developed in Thermal Desktop®. Thermal Desktop is a thermal modeling program based on SINDA/FLUINT, a standard thermal-fluid analyzer that can be used to build, analyze, and post process steady state and transient thermal-fluid models. In Thermal Desktop an abstract network of the system to be analyzed is developed using finite difference and finite element modeling methods. FloCAD®, a module of Thermal Desktop, generates flow networks and calculates convective heat transfer rates. RadCAD®, another Thermal Desktop module, calculates radiation exchange factors and orbital heating rates.

FloCAD has the capability of modeling two-phase flow systems which can be used for thermal-fluid modeling of the two-phase hydrogen in the TCS system heat exchanger. In addition, FloCAD allows modeling of fluids with multiple constituents. This feature will be employed in analyzing the thermodynamic state of the subcooled propellant storage tank where both hydrogen and helium will be present.

In addition to modeling the heat exchanger and the storage tank, other components of the TCS will also be modeled in FloCAD. These include compressors, pumps, fill and vent valves, the J-T valve, and the associated plumbing that connect them.

The RadCAD component of Thermal Desktop will be employed to analyze radiation heat loads from the environment on the various components of the TCS system. Included in this analysis will be the insulation materials such as MLI which may be applied to minimize the environmental heating rates.

Once the various components of the TCS are developed in Thermal Desktop the parameters for each component will be adjusted to represent the physical system under study. As such, the two phase flow heat transfer coefficient obtained experimentally will be an input to the heat exchanger model.

A parametric analysis of the TCS system will then be performed in Thermal Desktop. The model results will be compared to those obtained experimentally. The comparison will be the basis for further adjustments to the thermal model and/or the TCS hardware.

G. Subcooling Demonstration Test Tank

The United Launch Alliance owns two Centaur tanks that could be the center pieces of a cryogenic test facility at KSC that would be ideal for demonstrating the subcooling of cryogenic propellants in the Florida launch environment. One of the tanks is available as a loan from ULA and the other would be donated to the Florida Institute of Technology (FIT):

- **Centaur III tank** (Atlas V Centaur) is available as a loan. ULA just finished using this tank to qualify the switch from fixed foam to spray-on-foam insulation (SOFI).
- **Centaur II tank** (Atlas II Centaur) is being donated to FIT. This is a damaged flight article that is no longer flight worthy but is ideal for supporting a wide range of ground cryogenic testing including testing with subcooled propellants. The tank is currently being prepared for shipment to FIT.

Several pictures of the actual Centaur III tank for loan and Centaur II tank for donation are shown in Figure 7 and Figure 8, respectively.

Figure 7: ULA's Centaur III Tank.

Figure 8: ULA's Centaur II Tank.

III. Conclusions

This paper outlines the development in the concepts for the thermodynamic cryogen subcooler and its components. The goal for this team is to demonstrate subcooling on a flight-like tank in the Florida launch environment. The TCS will provide an effective method for isobaric subcooling of cryogenic propellants on the launch pad with a relatively small system that does not require a very large electrical power supply. A demonstration such as this would provide confidence in implementing this subcooling technology on the launch pad to provide extended hold times for cryogenic propellants in space. The extended hold times would significantly benefit launch logistics of the Exploration architecture, allowing for longer in-space hold times for upper stages, propellant depots; long duration human missions to asteroids and to Mars, and other high ΔV robotic planetary science missions.

Acknowledgments

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