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PROPELLANT DENSIFICATION WITHOUT USE OF ROTATING MACHINERY

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Abstract

In an effort to improve the thermodynamic properties of cryogenic propellants such as liquid oxygen and hydrogen, a variety of techniques for producing subcooled or densified cryogenic propellants have been explored and tested. Studies conducted by NASA and at Boeing have identified propellant densification as one of the enabling technologies for affordable, reliable and safe access to space. Vehicle performance studies have shown that Gross Liftoff Weight (GLOW) of a 2nd Generation RLV can be reduced significantly, which is achieved through the combined effect of increased propellant density and reduced vapor pressure. Increased density results in a reduction in the size of the propellant tanks, and the lower vapor pressure results in a lower tank operating pressure, which in turn reduces the tank weight and propellant residual weight. In an effort to advance the maturation level of this emerging technology, Boeing RSS (Reusable Space Systems) initiated a Densification Program to explore densification operations on a large-scale using LN2 subcooled to a temperature of ~120R. These tests which were performed at the Boeing Downey facility used LN2 as a surrogate fluid for LO2 due to the similar thermodynamic properties, increased safety, and reduced cost. This paper presents the test configuration and procedures, significant results, and analysis from this successful large-scale demonstration. Applications of this technology development program include booster and upper stage spacecraft design and as well as long-term cryogenic storage systems.

Introduction

In order to meet the goals of affordable and operationally efficient access to space, the next-generation reusable launch system will require a host of advanced technologies in the areas of Propulsion, Vehicle Structures/Airframe, Operations, Upper Stage, and Integrated Vehicle Health Management (IVHM). By synergistically incorporating these technologies into a 2nd generation launch platforms, vehicles with higher propellant fractions, lower structural weights, better performing engines, lower system maintenance, and increased reliability are achievable. To date, significant advancements have been made in the area of lightweight materials and structures. Examples include the filament wound composite fuel tanks for Orbital Science Corporation's X-34 and the advanced tank structures for the Lockheed-Martin X-33. Super-lightweight, aluminum-lithium tanks were also developed for the Shuttle ET to increase payload capability and to enable the construction of the International Space Station. Other examples of technology programs to reduce weight though material selection and structural design could be cited.

Propellant densification is a technology that can improve vehicle performance by enhancing the properties of the propellant. This is achieved by lowering the temperature of the cryogenic liquid (cryogen) below the Normal Boiling Point (NBP) temperature, resulting in a 7 to 10% increase in liquid density, thereby enabling a proportional reduction in the size of the propellant tank. Subcooling also results in a decrease in the propellant vapor pressure from 14.7 psia (1 atmosphere) to less than 2 psia. The combined effect of increased density and reduced vapor pressure will reduce the size and lower the operating pressure of the vehicle propellant tanks. Vehicle performance studies conducted at Boeing indicate that the use of densified LO2 and LH2 can result in a range of launch vehicle dry weight reduction from ~ 12% to 26%. In an independent study conducted by NASA Marshall Space Flight Center (MFSC), it was determined that the weight savings of an RLV using densified propellant could be as high as 30%. In addition to reducing vehicle weight the thrust level of the engines are also lowered by the same amount resulting in a smaller and lower cost engine. Densification technology is unique in that it provides the largest weight reduction benefit at the lowest cost.

For these reasons NASA presented the first "Turning Goals Into Reality" award in 1998 for propellant densification technology. Because of the significant performance and cost benefits offered by propellant densification the production and management of densified propellant has remained the focus of NASA and industry.

Historical Background

Although the advantages of using subcooled cryogenic propellant have been long understood, its application to an operational flight system has been limited. The North American X-15 research vehicle was among the first to successfully use subcooled LO2 in a flight environment. The X-15 used LO2 that was subcooled and was produced in-flight using the process of adiabatic evaporative cooling. LO2, which was loaded onto the vehicle at 1 atmosphere (~13.5 psia at Edwards Air Force Base) was free-vented from the vehicle during ferried flight. The process conditioned the LO2 to ~5 psia, the atmospheric pressure at the B-52 cruise altitude, producing densified LO2 with a bulk density increase of approximately 4%. The sacrificial LO2 lost in the evaporative cooling process was replenished from the B-52 mother ship thus ensuring a full tank at engine start.

Subcooled propellants were proposed for the second stage S-II during the Saturn V program, but this plan never progressed beyond conceptual design. During the National Aerospace Plane (NASP) program in the late 80s and early 90s, the contractor team (Rockwell, McDonnell Douglas, and General Dynamics) and the NASA Glenn Research Center (GRC, which was at the time called Lewis Research Center, or LeRC) investigated slush hydrogen generation and handling technologies. While the slush hydrogen effort was an overall success, the NASP program termination in addition to difficulties with mass quantity gauging, prevented slush from maturing into a practical technology.

In the early 90's, the SSTO propulsion team at Boeing (Rockwell) incorporated the lessons learned from the slush program and adopted triple point (TP) hydrogen and oxygen as the baseline, realizing that mass-quantity gauging of a single-phase fluid would be easier than gauging a two-phase fluid containing solid and liquid. However, it wasn't until the Shuttle Performance Enhancement Program in 1994, followed by the X-33 Densification Technology Development Program in 1996, that propellant densification began to mature and be recognized as a viable technology for a large-scale application. Boeing in a Cooperative Agreement with NASA GRC developed and tested the first generation LH2 densification system using a staged compressor during the X-33 Program.

Boeing was awarded a U.S. Government Patent in 1997 for Liquid Propellant Densification (No.5,644,920) for a densification system using a compressor and heat exchanger bath to subcool cryogenic propellants. Based on this patent Boeing in a Cooperative Agreement with NASA GRC developed and tested the first generation LH2 densification system using a multi-stage compressor during the X-33 Program. Later GRC built a second larger LH2 densifier and LO2 densifier using the compressor concept in support of the Lockheed-Martin X-33 program.

In CY1998, Boeing successfully performed a subscale LO2 Densification test program in which 13 loading tests with densified LO2 were conducted, demonstrating densified fill operations and close-loop recirculation operations using a free-boiling LN2 bath. The success of the subscale tests with LO2 led Boeing to embark on a Large-Scale LO2 densification test program in CY 2000, which is the focus of this paper. It was demonstrated during the course of the Large Scale test program that densified fill operations are feasible and that the Boeing patent-pending process of LH2 injection to subcool LO2 is safe, controllable, and operationally efficient.

More recently NASA has awarded three contracts under the Space Launch Initiative program to look at alternate means of producing densified LO2 and LH2 without the use of compressors or sub-atmospheric heat exchanger operation. These concepts include the generation of densified LO2 and LH2 through liquid evaporation into an inert gas, and low temperature production using pulse tube refrigeration concepts. Although these concepts are in development the consumable requirements (helium and power) appear to make these concepts not operationally efficient.

Boeing Densification Concept Description

Liquid oxygen can be subcooled with liquid nitrogen in a free boiling bath to ~140 °R without the use of a multi stage compressor or rotating machinery. Lowering the LO2 temperature to ~120 °R is more difficult and requires additional system complexities. Boeing has identified a simple propellant densification concept for LO2 that can subcool LO2 to the 120 °R temperature level without the complexities and costs associated with the use of rotating machinery, or large power requirement. The concept is based on using liquid hydrogen as a working fluid to maintain a constant liquid nitrogen heat exchanger bath temperature. Liquid hydrogen at ~40 °R is directly injected into the liquid nitrogen bath to maintain a constant temperature level. The heat capacity of hydrogen (latent heat & evaporative) is used to transport the heat from the heat exchanger. The liquid hydrogen rapidly evaporates at the liquid nitrogen temperature and absorbs the heat from the LN_2 through evaporation and super heating. The evaporated hydrogen is subsequently vented off and burned with small amount of nitrogen present in the exhaust gas. Because the heat transfer mechanism is through evaporation the heat exchanger bath operates above atmospheric pressure and therefore the concerns associated with air ingestion and contamination are eliminated.

The Boeing densification concept is presented schematically in Figure 1. The heat exchanger bath is filled with liquid nitrogen. The liquid level is maintained above the LO_2 heat exchanger tubes through the use of the LN_2 fill valve and liquid level sensor. The because only a small amount of nitrogen is lost during hydrogen injection the heat exchanger bath can be over designed to eliminate the need for active LN_2 liquid level control. LN_2 temperature is maintained constant through liquid hydrogen injection. This subcooled bath of nitrogen is used as a cold sink for a submerged tube bundle heat exchanger. By flowing LO_2 through the heat exchanger, the LO_2 is densified to ~ 120°R The amount of hydrogen injection is proportional to the amount of heat rejected into the heat exchanger bath by the LO_2 flow. Throttling the Lh2 valve results in temperature control over a wide range of heat load levels.

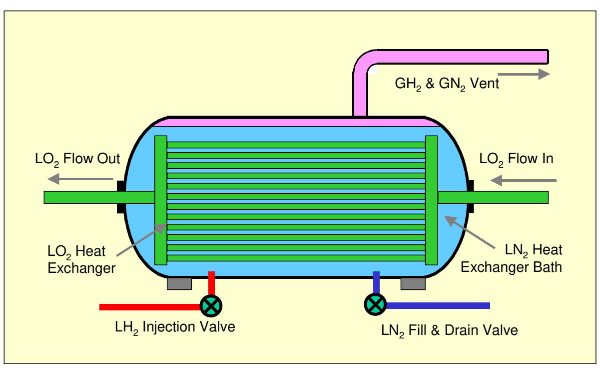

Figure 1 Boeing LO2 Densifier Schematic

The benefits offered by the Boeing LO2 densifier concept are significant:

- No rotating machinery (reliability)
- No external power except to operate valves
- Operates above atmospheric pressure
- Minimizes LN_2 storage tank size
- Simple control logic
- Compact portable design
- Low cost

Boeing LO2 Densifier Design Description

The LO2 Densifier concept described above was designed and manufactured by Cryogenic Technical Services, Inc. (Longmont, CO) per Boeing specifications which required an outlet temperature of 118°R at a maximum LO2 flow rate of 32 lbm/sec resulting in a heat rejection rate 600 Btu/sec. The densifier unit shown in Figure 2 is ~ 8 ft high by ~ 15 ft long, and is significantly smaller than the LO2 densifier built by GRC for the Lockheed-Martin X-33 program.

Figure 2. Boeing LO2 densification Unit

The design uses a liquid hydrogen injection process to sub-cool the nitrogen bath of the heat exchanger from the normal boiling point (NBP) of liquid nitrogen at one atmosphere (~140°R) to near the freezing point of the nitrogen (~116°R). The Densifier consists of a double-walled vacuum jacketed dewar (8-ft diameter x 16 ft long) which contains a tube-bundle heat exchanger in its interior and associated process plumbing and valves. The dewar and plumbing was designed and built per ASME code. The inlet header fill line branches into three lines, an inlet line, a re-circulation return line, and an overboard bleed line. The outlet header line provides the heat exchanger outlet. A fill and drain line is used to load the dewar with normal boiling point LN2 prior to operations.

A liquid hydrogen supply valve and injector manifold are used to inject LH2 into the dewar bath below the LN2 surface to sub-cool the LN2 bath by vaporizing and superheating the LH2. The evaporated LH2 is then vented from the top of the dewar via a 6-inch diameter line and vertical stack directly into the atmosphere. RTD temperature sensors are located throughout the dewar interior to monitor the bath temperatures and liquid level during the chill down and densification process. Interfaces flanges for the LO2 and LN2 side are standard 2-inch & 3-inch 150 lb class flanges with raised face concentric seal grooves. The LH2 interface is a 1 ½ inch CVI bayonet fitting which connects the transfer line from the LH2 trailer to the LH2 vacuum jacketed lines on the Densifier . The electrical and pneumatic control box is a NEMA-4 patch box with a GN2 purge.

Large Scale Densification Test System General Description

In order to prove that the LH2 injection process for LO2 densification is feasible on a large scale, Boeing conducted a research program in which a large scale LO2 densification unit was tested in an integrated system at the Boeing facility in Downey, CA. The key objectives of this large scale test demonstration were to:

- Demonstrate operations of the 2nd Generation Densifier using the Boeing LH2 injection process for real time production of 120R cryogenic fluid.
- Demonstrate propellant loading operations with densified fluid using a 12K gallon test tank as a simulated vehicle tank
- Establish the thermal gradient or stratification in the test tank during and after loading with subcooled propellant
- Define chill and fill operations and procedures for densified propellant
- Demonstrate off-nominal operations (vent, stop/restart, tank lockup)
- Determine the LO2 Densifier Heat Exchanger performance characteristics.

In order to reduce cost and increase system safety, it was decided to use LN2 as a surrogate fluid for LO2 during the densification testing. This substitution was justified when considering the thermodynamic properties of LN2 (liquid temperature range, heat capacity, vapor pressure, and density) relative to those for LO2. A schematic representation of the densification test setup is shown as Figure 1. Figure 2 shows an aerial photograph of the test site, which provides an indication of the scale of the integrated tests as well as the overall placement of the system major elements which includes the following:

- Two LN2 storage tanks with a total fluid capacity of 20K gallons
- A cryogenic fluid Loading Skid consisting of two parallel modulating flow control valves used to regulate the flow of cryo fluid during tanking operations
- The 2nd Gen. LO2 Densification Unit, incorporating the LH2 injection process which is capable of producing 118°R LO2, at 32 lbm/sec flow rate
- A fully instrumented 12K gallon test tank, which served as the simulated vehicle tank
- A 10K gallon LH2 trailer which supplied the LH2 to the 2nd Generation LO2 Densifier
- An open-top rectangular dump bath used for the disposal of LN2 after test completion

Other system elements included system interconnect plumbing and valves (2-inch and 3-inch), venturi flow meters for flow rate measurement, a cross-country LH2 transfer line between the LH2 trailer and the densification unit, a hydrogen vent stack to divert the vaporized hydrogen away from the test area, temperature and pressure instrumentation, and several video cameras to monitor operations from the control room, which was located remotely from the test site.

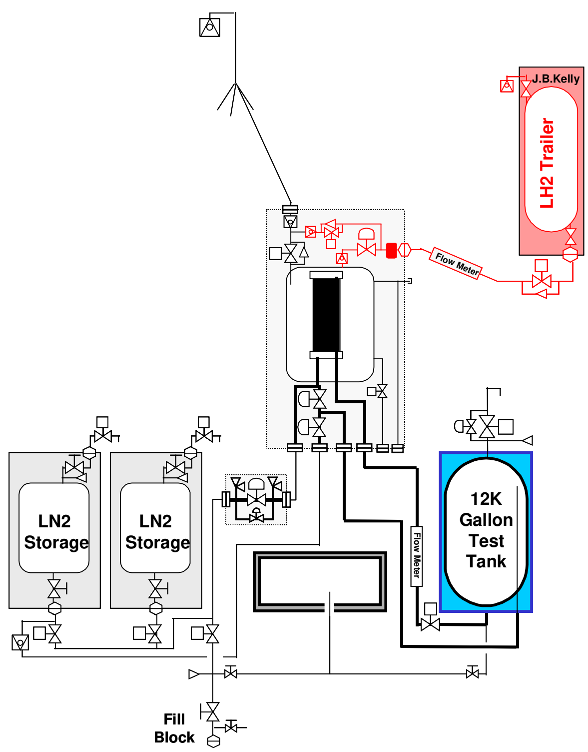

Figure 3. LO2 Densification Test Schematic

Figure 4. Large Scale Densification Test Bed

LN2/LO2 Portable Loading Skid

To remotely control the flow rate of cryo fluid through the densifier, a portable loading skid (Figure 5) was designed and built by Cryo Technologies (Allentown PA). The loading skid was built per ASME code and was made using 1.5-inch & 3-inch CRES piping. The skid support structure was fabricated from carbon steel and painted with 2-part epoxy paint. Other features include: 3-inch and & 1.5-inch Cryolab variable position pneumatically actuated valves, standard 150 lb class flanges, a GN2 purged NEMA-4 electrical and pneumatic box, and 4" thick LO2 compatible glass-foam insulation with Pitcoat surface sealer.

Figure 5 Loading Skid

12k Gallon Test Tank Description

The 12,000-gallon tank used in the test program is shown in Figure 6. The stainless steel tank is liquid oxygen compatible and was manufactured during the Rockwell X-33 program as part of the Integrated Propulsion Technology Demonstrator (IPTD) project. The tank is 10 feet diameter with an overall length of 24 feet. The end domes are ellipsoidal in shape and the tank is supported using a girth ring and hangers that are attached to the tank 12-ft x 12-ft support structure. Each end of the tank consists of a 36-inch diameter flanged opening to which the interconnect plumbing is attached. The key interfaces with the integrated system include the fill and drain connection on the tank bottom flange, the recirculation return connection and the tank vent line and manifold. Internal to the tank is attached an instrumentation rake that consists of 11 silicon diode sensors to measure liquid temperature and 3 silicon diode sensors to measure ullage temperature. The rake extends down the middle of the tank with a sensor approximately every 28 inches axially and at varying radial distances from the center axis. The tank is insulated with foam insulation, which is bonded to the outside tank wall.

Figure 6. 12K Gallon Test Tank

Integrated Test Results

Test Description and Performance Summary

Several large-scale densification tests were conducted on the system described. Due to the scale of the test site, the tests were designed to maximize the technical benefits by meeting multiple objectives where possible. The tests that were conducted included the following:

1. System checkout and performance baseline loading NBP LN2 into the tank.
2. 2nd Generation Densifier checkout defining operational characteristics & performance of the heat exchanger.
3. Densified propellant loading tests demonstrating real time operation of the Densifier and in-tank thermodynamics.
4. Densified propellant thermal stability & system warm up.

The tests demonstrated that the Boeing LH2 injection process can be successfully used to produce 120R sub-cooled cryogenic fluid real-time during loading operations without the use of expensive and high maintenance rotating machinery. The specific test observations and results are described below.

2nd Gen LO2 Heat Exchanger Operations and Performance

The key criteria for judging the performance of the densifier during operation are 1) the ability to control the subcooled LN2 bath temperature during LH2 injection and 2) the ability of the densifier to supply conditioned cryo fluid to the outlet at the desired temperature. Figure 7 shows a plot of the densifier LN2 bath temperature during chilldown using the LH2 injection method. The results show that the bath chilldown rate is controllable and can be maintained between 116°R – 118°R by throttling the flow control valve using the temperature measurements within the dewar. Several tests found that the process was repeatable and that the LH2 injection flow rate could be stopped and restarted without difficulty.

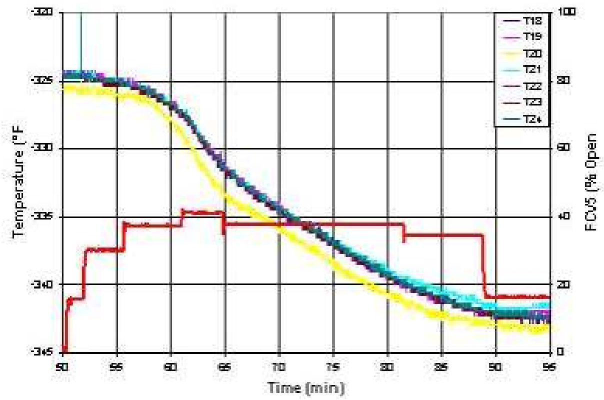

Figure 7. LO2 Densifier Bath Temperature

It was also found that the heat exchanger bath average temperature and outlet temp was maintained within 1°R during flow through the densifier (Figure 8), which validated the analytical models that predicted the heat exchanger performance. This provides a sizing design tool, which can be used to design the next generation LO2 densifier.

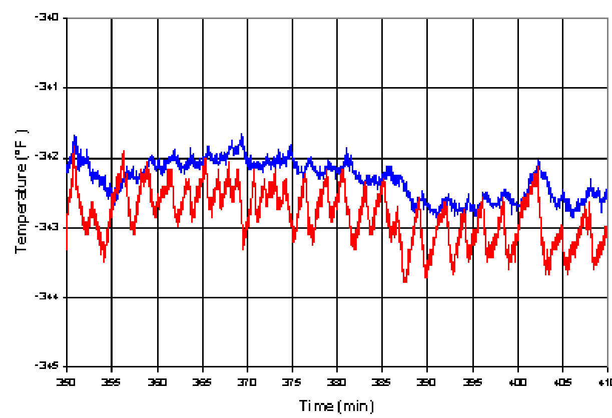

Figure 8. Densifier Bath & HX Exit Temp

Densified Loading Thermal Stratification

One of the Launch Commit Criteria (LCC) for a booster rocket is the on-board propellant loaded mass, which must be reliably and consistently measured and known to guarantee the mission success. The loaded propellant mass for a conventional booster using free-boiling propellant is usually calculated by starting with the saturation density which is a function of the tank ullage pressure. Other factors are then taken into account such as bubble volume, tank volume stretch, liquid level tolerances, and so on to calculate the propellant mass on board. Using densified propellant adds another dimension to determining the bulk propellant mass because the subcooled propellant density is no longer a function of pressure, but of temperature as well. It is recognized that the thermal gradient of the fluid within the tank will vary as a function of the total heat load to the propellant, with the coldest liquid residing at the tank bottom and the warmest liquid floating on the surface. The goal is to predict and consistently achieve the desired thermal stratification such that the proper propellant mass is loaded for launch.

The temperature rake inside the 12K gallon tank enabled Boeing to determine the thermal stratification within the tank during fill operations. Figure 9 shows a plot of the temperatures during loading, which resulted in a average bulk temperature of 123.6R after fill, which is 20 degrees colder than free-boiling LN2. The stratified warm layer at the top of the liquid surface was evident during the fill process and was similar to that observed in the LO2 subscale tests densification tests that were performed in 1998.

After the 12K gallon tank was filled with subcooled LN2, the recirculation pump was activated and closed-loop recirculation operations were successfully demonstrated. During this process, the warm saturated layer at the top of the surface was recycled back to the densifier where it was subcooled to 120R before being pumped back to the bottom of the test tank. The procedures that were used in this process were completely validated and are directly applicable for the development of a full-scale system.

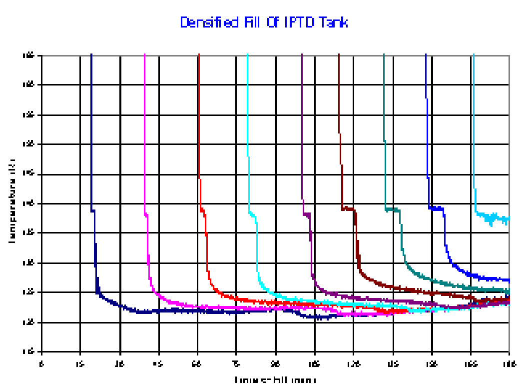

Figure 9. Temps During Chill and Fill Operation

For some vehicles, it may be desirable to load the tank directly with densified propellant without recirculation in order to simply the loading system. Based on the thermal gradient established for densified chill and fill of 12K gallon tank , the bulk density gain after tanking was determined (Figure 10). Results show that and average bulk density gain of 5.04% was achieved, corresponding to an average bulk temp of 123.6R If the same bulk average temperature were achieved using LO2, the equivalent density gain would be 8.8% after chill & fill.

There are other methods for determining the increase in bulk density after tank fill other than temperature averaging. One method is direct density measurement using a ΔP transducer. This method involves solving directly for the fluid density using the hydrostatic pressure measurement and the height of the liquid column. This method was used during both the subscale and large scale densification programs with some success, however, the accuracy of this system can only be as good at the accuracy of the pressure transducer measuring the hydrostatic pressure. This method is promising but additional development effort will be required in order for it to used as a reliable density measurement system.

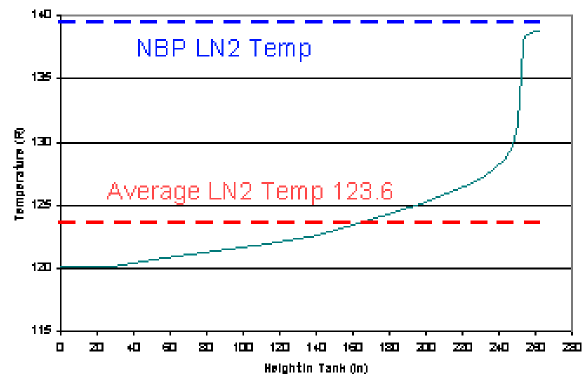

Figure 10. Test Tank Temperature Gradient

<u>Tank Lockup Performance</u>

One concern of the investigators was the pressure rise that would occur during tank lockup after the vent valve had been closed, therefore, one objective of this test program was to address this issue. During the lockup test it was observed that the ullage pressure increased immediately after closing the vent valve. This was also observed during the subscale LO2 densification test program and may be caused by the boil-off/evaporation of the saturated layer, which is then suppressed due to the rising ullage pressure. Figure 11 shows the ullage self-pressurization rate measured during the lockup test. The nominal lockup pressurization rate was approximately 0.23 psi/min and was completely safe and manageable.

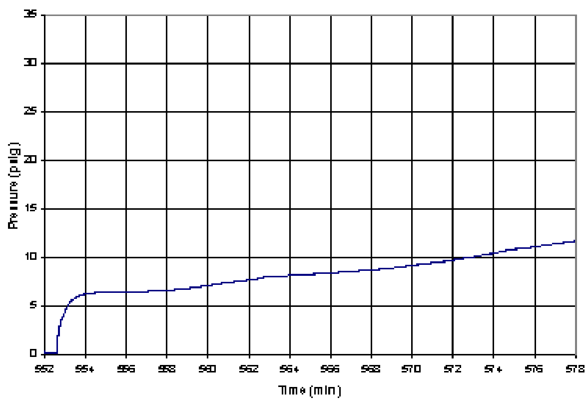

Figure 11. Lockup Pressure Rise Rates.

During the tank lockup test, the rise in liquid temperature was measured and found to be ~1 R/hr (Figure 12). From this data an average tank heat load of 58 btu/hr-ft2 was established, which is comparable to the Shuttle ET LO2 tank heat load of 78 btu/hr-ft2.

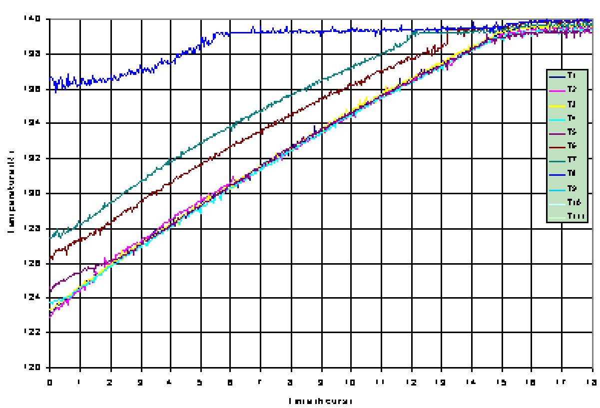

Figure 12. Tank Lockup Temperature Rise.

Stop Flow and Recovery

Stop flow is a frequent occurrence of loading operations and as such was investigated during this test program. Stop and restart of the transfer pump was performed a number of times and was found to be completely recoverable, with no adverse problems to the pump. Placing the pump downstream of the densifier helped mitigate problems that could occur due to heat load to the line by maintaining the inlet temperature of pump below saturation.

Emergency Venting Results

One opinion that is commonly propagated is that rapid venting of a tank filled with densified propellant will result in a negative tank pressure that may result in a catastrophic tank collapse. Boeing engineers were always of opinion that this would never occur due to the saturated layer that forms on the top of a cryogenic liquid. During tank venting, this saturated layer would boil off and maintain the ullage pressure slightly above ambient pressure. To prove this point, several rapid venting tests were performed. The results of these tests (Figure 13) show that the ullage pressure does not decay below atmospheric pressure during rapid venting and that venting subcooled cryogens are just as safe as normal boiling point propellants.

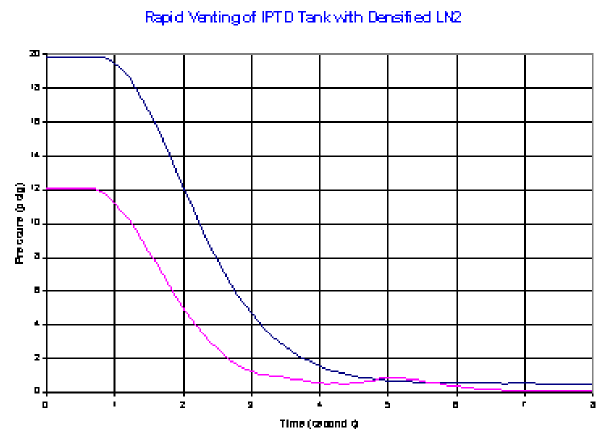

Figure 13. Ullage Pressure During Rapid Venting

Conclusions/Summary

Overall, the densification test program was a success and it demonstrated that LO2 densification can be performed without the use of compressors or large power requirements. In addition to densification concept demonstration, integrated loading tests with densified liquid nitrogen further advanced the propellant densification technology readiness level. All of the key objectives of the test program were met, which were to:

- Demonstrate operations of the 2nd Generation Densifier using the Boeing LH2 injection process for real time production of 120R cryogenic fluid.
- Demonstrate propellant loading operations with densified fluid using a 12K gallon test tank as a simulated vehicle tank
- Establish the thermal gradient or stratification in the test tank during and after loading with subcooled propellant
- Define chill and fill operations and procedures for densified propellant
- Demonstrate off-nominal operations (vent, stop/restart, tank lockup)

- Determine the LO2 Densifier Heat Exchanger performance characteristics.

In addition, the advantages of the using the LH2 injection process for LO2 densification were demonstrated by the relatively short time it took to chill the LN2 bath to the densification process temperature. The innovative densifier design can be directly scaled for use in a full scale system, and is significantly cheaper that the alternative densification system which uses cold vapor compressors. The Boeing LO2 densifier also is more compact and is inherently more reliable because it does not require rotating machinery or power to operate.

Additional testing with the densification unit is proposed for the future to further refine the temperature control accuracy and to gain additional operational data. The densification concept validated is considered to be a strong candidate in future densification system trades for the next generation reusable launch vehicle due to the relatively high technology level (TRL 5) demonstrated at Boeing.

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Nomenclature

ET	External Tank
RSS	Reusable Space Systems
RLV	Reusable Launch Vehicle
NBP	Normal Boiling Point
SSTO	Single Stage to Orbit
LO2	Liquid Oxygen
LH2	Liquid Hydrogen
LN2	Liquid Nitrogen
GN2	Gaseous Nitrogen
GHe	Gaseous Helium
°R	Degrees Rankine
GLOW	Gross Liftoff Weight
psi	Pounds per square inch
psia	Pounds per square inch, absolute
MSFC	Marshall Space Flight Center
NASA	National Aeronautics & Space Administration
NASP	National Aero-Space Plane
LeRC	Lewis Research Center
GRC	Glenn Research Center
BTU	British Thermal Unit
sec	second
lbm	Pound mass
lbf	Pound force
TP	Triple point
CY	Calendar year
LCC	Launch commit criteria

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