Long Duration Storage of Liquid Hydrogen via Two-Stage Active Cooling Hardware Characterization and Test Planning

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The zero boil-off storage of liquid hydrogen using active cooling (cryocoolers) with a two-stage cooling approach is being investigated by NASA. In interest of advancing the technology to enable extended duration storage for the agency's future long duration missions, NASA's Technology Demonstration Mission Program has funded this five-year effort which includes the design, build and testing of a test article to demonstrate the concept. This paper includes discussions of the multiple Cryogenic Fluid Management technologies that were studied under NASA's Cryogenic Propellant Storage and Transfer project, design of the test article to be demonstrated, then the planned test objectives which include characterization testing of the active cooling system, demonstration of the control system, preliminary testing with liquid nitrogen, and a complete demonstration of zero boil-off storage of liquid hydrogen. The full demonstration will be conducted in the East Test Area at NASA Marshall Space Flight Center and is currently scheduled to begin on October 1st, 2024.

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I. Nomenclature

cm	=	Centimeter
GHe	=	Gaseous Helium
GH_2	=	Gaseous Hydrogen
K	=	Kelvin
Kg	=	Kilogram
kW	=	Kilowatt
LCH_4	=	Liquid Methane
LH_2	=	Liquid Hydrogen
LN_2	=	Liquid Nitrogen
LNG	=	Liquid Natural Gas
LO_X	=	Liquid Oxygen
PSIA	=	Pounds per Square Inch, Absolute
s	=	Seconds
W	=	Watts

II. Introduction

NASA is emphasizing the development of reusable, refuellable cryogenic systems in pursuit of returning astronauts to the lunar surface, and then eventually on to Mars. The high energy densities associated with propellants stored at cryogenic conditions enable the use of high performing propulsion systems for in-space transport and ascent/decent elements which carry astronauts to/from the lunar and Martian surfaces. The utilization of in-situ resources (ISRU) is a possibility with cryogenics, where propellant gas is to be produced, liquefied, and stored on the lunar or Martian surface and available when needed for vehicle refueling. The extended storage times associated with NASA's future missions impose significant challenges for the use of cryogenic propellants. When subjected to environmental heat loads, cryogens have a propensity to boil-off resulting in excessive propellant tank pressures which must then be controlled by venting, or by heat removal via active cooling (cryocoolers). Propellant tank venting is undesirable for long duration missions as it results in propellant loss which over an extended period of time can be significant. Active cooling is undesirable for short duration missions as cryocoolers are a significant amount of dry mass to be carried throughout the mission. For any cryogenic vehicle and mission, a mass and power trade must be conducted to determine if active cooling is feasible, or if additional propellant mass should be carried to accommodate the losses associated with boil-off and venting.

The current State of the Art (SOA) for the storage of Liquid Hydrogen (LH_2) on orbit is on the order of hours. Recognizing that future missions require LH_2 storage for months, or even years, the agency is now making significant investments in the advancement of Cryogenic Fluid Management (CFM) technologies. To maintain cryogenic liquid propellant for such an extended period of time, "near zero" propellant loss, or Zero Boil-Off (ZBO), must be achieved. This may be accomplished with the implementation of "near zero" leakage components, a high performing suite of passive CFM technologies to minimize the environmental heat loads, and active cooling via cryocoolers to intercept and remove heat from the propellant storage tanks. To achieve ZBO conditions for LH_2 storage, cryocoolers operating at 20K are required since they operate close to the saturation temperature at expected storage pressures. Likewise, 90K cryocoolers are used to achieve ZBO for soft cryogens such as Liquid Oxygen (LO_X), Liquid Methane (LCH_4), or Liquid Natural Gas (LNG). Since cryocoolers are a source of dry mass and require electrical power, it is desirable to minimize the refrigeration required to achieve ZBO by including an optimized suite of passive CFM technologies. Lower refrigeration requirements lead to reduced mass and power associated with active cooling. ZBO conditions for LH_2 storage can be achieved with 20K cryocoolers alone, however the 20K units have a significantly larger Specific Mass (kg/W) and Specific Power (W/W) than their 90K counterparts meaning larger mass and greater electrical power required per watt of refrigeration. This activity focuses on the design, build, and testing of a ground test article to investigate a two-stage active cooling approach which can potentially lead to mass and power savings when active cooling is implemented for long duration LH_2 storage. Since the Specific Mass and Specific Power associated with the 20K cryocoolers is high relative to 90K cryocoolers, the objective is to intercept and reject as much heat as possible with a 90K cryocooler, then using the 20K cryocooler for tank heat removal and pressure control. Previous studies have shown via analysis, that this two-stage approach trades well against a single-stage approach (see Fig. 1 and 2) in terms of mass and power savings.

A NASA team is leveraging previous efforts conducted under the Cryogenic Propellant Storage and Transfer (CPST) project to develop a two-stage active cooling ground test article. Many of the technologies included have been demonstrated, but never assembled and tested as a fully integrated system. The test article is comprised of an ASME rated aluminum propellant tank, approximately 360 gallons internal volume. The propellant tank is outfitted with a Tube-On-Tank (TOT) heat exchanger which is to be integrated with a 20K cryocooler. This configuration makes use of the tank surface area to remove heat from the propellant tank liquid and ullage space. The tank will then be insulated with Quest Thermal Group's Integrated Multi-Layer Insulation (IMLI) specifically designed for load bearing capability. A custom designed Tube-On-Shield (TOS) Broad Area Cooling (BAC) heat exchanger is installed over the IMLI inner blanket and integrated with a cryocooler operating at 90K or less. This allows for the heat load thru the tank acreage to be intercepted within the IMLI blankets before reaching the propellant tank outer surface, hence easing the burden on the 20K cryocooler. An outer blanket of IMLI is then to be installed over the TOS BAC heat exchanger. The tank is to be supported by six low conductivity, titanium support struts which will be thermally strapped to the TOS BAC heat exchanger discharge loop, "The Halo". Since the heat loads via conduction through the structure are most often significant, this approach will enable further heat interception with the 90K or less cryocooler. A two-stage industrial cryocooler was sized and procured for this application. **Going forward, the TOS BAC intermediate cooling at 90K or less, and the TOT final cooling at 20K will be referred to as the 1st and 2nd Stages, respectively.**

The development of this test article was reported in detail in [1]. This paper will briefly revisit the design and development, but will focus primarily on the planned testing which includes characterization of the two-stage cryogenerator to evaluate performance at test conditions, demonstration of the control system, initial testing with Liquid Nitrogen (LN2), and then an updated test plan for the LH_2 ZBO demonstration.

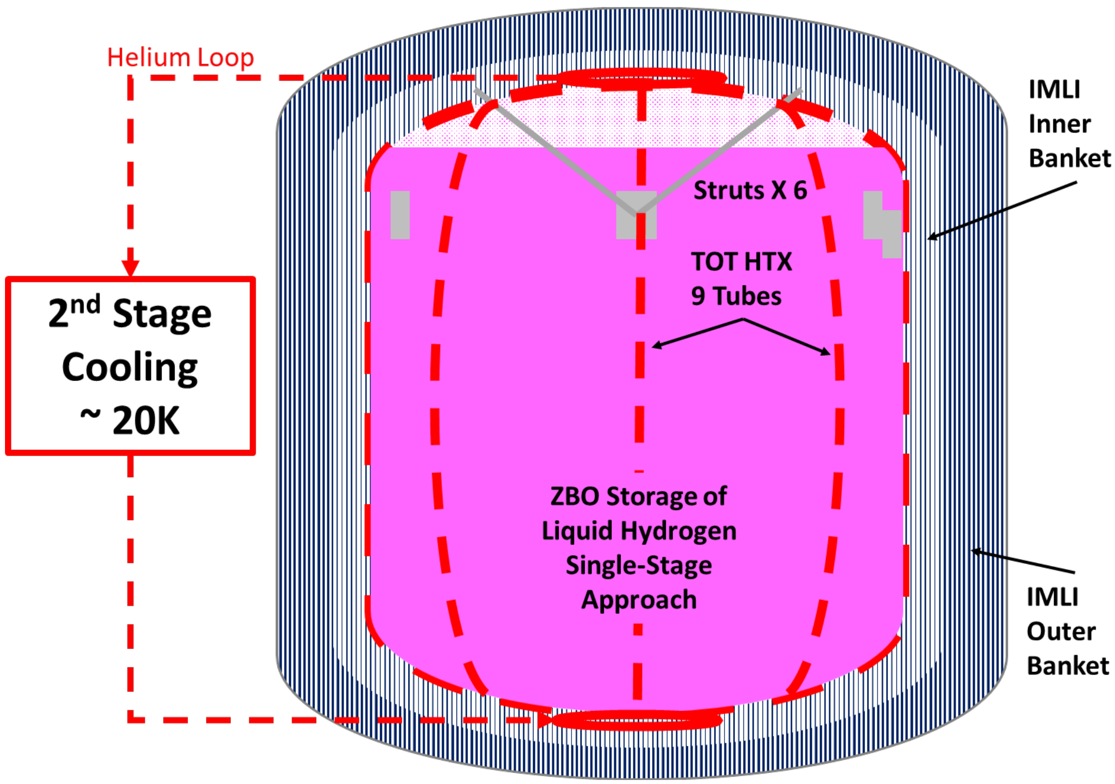

Fig. 1 Single-Stage Cooling Approach – Baseline

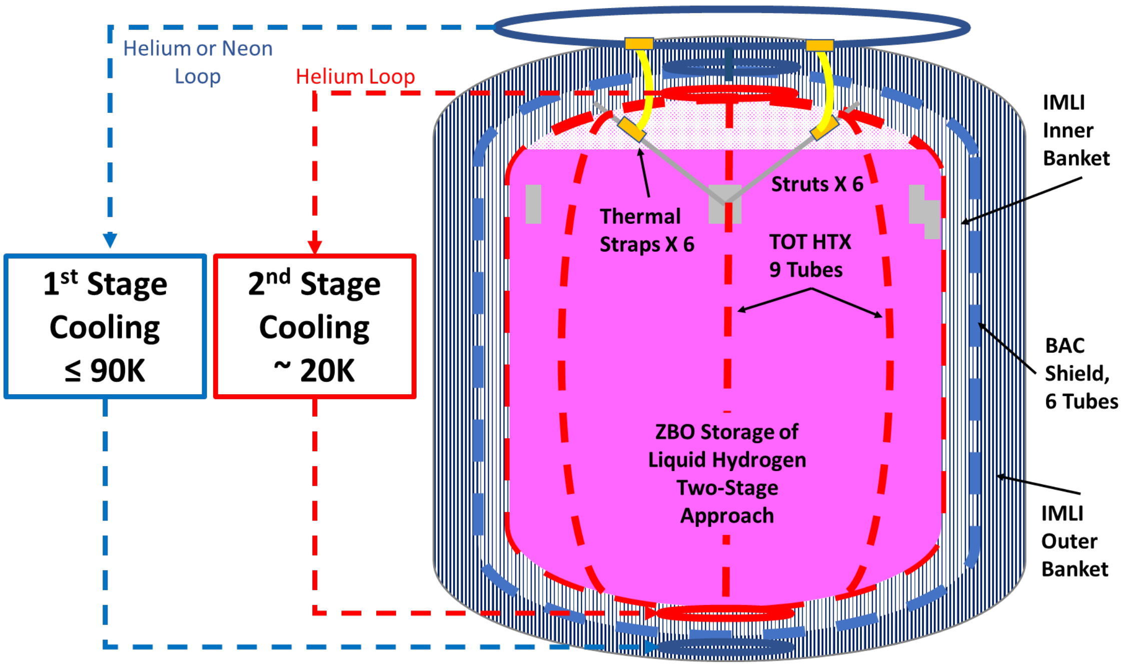

Fig. 2 Two-Stage Cooling Approach to be Demonstrated

III. Background

Most of the technologies included in the two-stage cooling test article have been demonstrated previously during the CPST project, but not yet assembled and tested as a fully integrated system. Among these demonstrations were three cryogenic test series: the Zero Boil-Off (ZBO) series, the Reduced Boil-Off (RBO) series, and the Vibro-Acoustic Test Article (VATA) series. The intention of CPST was to mature cryogenic technologies and establish a foundation for a technology demonstration mission but was later reformulated to a ground technology demonstration due to budget constraints. The current activity is the culmination of these efforts.

The ZBO test series was performed at Glenn Research Center (GRC) using the Small Multi-Purpose Research Facility (SMiRF), which can create a "simulated space" thermal vacuum environment. This test series was designed to demonstrate the effectiveness of using a BAC tube network, also known as a TOT heat exchanger, to achieve ZBO of propellant and maintain constant tank pressure for long durations. LN_2 was used as a propellant simulant due to the safety concerns and cost restrictions of testing with LO_X. The tank itself was constructed with stainless steel and features ten tubes (five supply and five return) attached vertically to the tank wall using a combination of welding and epoxy [2]. The cooling source for these tubes was a 15W/77K Reverse Turbo-Brayton (RTB) cycle cryocooler using neon as the working fluid. The tank was insulated with two traditional Multi-Layer Insulation (tMLI) blankets for a total of 75 reflector layers. The test series ultimately proved to be successful with the cryocooler running continuously for seven tests over the course of a 19-day period, during which the tank was not vented. An 88% reduction in stratification compared to other unvented and unmixed cryogenic tanks was also observed over the course of this test series [2].

The RBO test series was also performed at GRC using SMiRF to create a simulated space thermal vacuum environment. The primary purpose of this test was to demonstrate a flight-like active thermal control system called a TOS BAC shield heat exchanger in addition to passive thermal control systems, such as tMLI and Spray-On Foam Insulation (SOFI) for a LH_2 tank [3]. The BAC shield consists of a thin aluminum sheet, which surrounds the tank and is attached to coolant tubes similar to ZBO's TOT cooling system. A BAC shield nestled between two MLI (Multi-Layer Insulation) blankets in this fashion allows for heat to be intercepted before it encounters the tank, lessening the load on the cryocooler. The coolant running through these tubes was supplied by a 20W/90K RTB cycle cryocooler, which also cooled the support struts and plumbing via thermal straps. As previously mentioned, the BAC shield was mounted between two tMLI blankets and supported by low conductance polymer standoffs. The inner MLI blanket between the BAC shield and the SOFI consisted of a low-density (8-layer/cm) 30-layer blanket, and the outer MLI was a standard density (20-layer/cm) 30-layer blanket, as well as 15 layers of MLI on the tank struts and plumbing.

Two primary tests were performed with this system, a "Cooler Off" test to assess the baseline performance using only passive thermal control, and a "Cooler On" test to demonstrate the active cooling ability. LH_2 was used as the fluid in the tank for these tests, and neon was the working fluid in the cryocooler for the “Cooler On” test. When comparing the results of these two tests, a boil-off reduction of 48% was seen, as well reductions in heat leak through the tank penetrations and inner MLI [4].

Lastly, the VATA series of tests were designed to test the structural integrity of the MLI/BAC shield assembly when subjected to simulated launch loads [5]. The tank, outer MLI, and BAC shield used for this test series were physically similar to the apparatus used in the RBO testing, however LN_2 was used as the cryogenic test fluid due to safety concerns with LH_2. Additionally, two different types of MLI were tested for the inner MLI; a tMLI blanket, similar to the one used on RBO, as well as a Load Bearing MLI (LBMLI), which was capable of supporting the weight of the BAC shield without the use of standoffs. These tests were performed at Marshall Space Flight Center (MSFC) using an Acoustic Chamber to simulate launch loads, as well as the Exploration Systems Test Facility (ESTF) for thermal testing. Testing was performed in groups of three tests for each configuration of MLI. First, a thermal test was performed to determine the baseline thermal performance, followed by the acoustic test, and finally another thermal test to observe any variations that may have occurred due to the acoustic test. These tests were successful, with no degradation in thermal performance as a result of the acoustic testing and increased thermal performance of the LBMLI compared to tMLI [5].

An ASME rated aluminum propellant tank with approximately 360 gallons internal volume was built and is similar in design to the ZBO, RBO, and VATA test articles to enable the use of some common hardware. Like ZBO, the propellant tank will be outfitted with a TOT BAC heat exchanger which is to be integrated with a 20K cryocooler (2^{nd} Stage). This configuration makes use of the tank surface area to remove heat from the propellant tank liquid and ullage space. The tank will be insulated with ten layers of Quest Thermal Group’s IMLI underneath a custom designed TOS BAC shield integrated with a 90K or less cryocooler (1^{st} Stage). This allows for the heat load through the tank acreage to be intercepted within the IMLI blankets before reaching the propellant tank outer surface, hence easing the burden on the 2^{nd} Stage. A 16-layer outer IMLI blanket is then to be installed over the TOS BAC heat exchanger. The tank is to be supported by six low conductive titanium support struts thermally strapped to the TOS BAC heat exchanger discharge loop via high purity copper thermal straps to enable structural heat interception with 1^{st} Stage (see Figs. 1 and 2).

A two-stage industrial cryocooler (cryogenerator) was sized and procured for this application. The aforementioned test programs were conducted with the TOS BAC Shield temperature at 80K and 90K showing benefit at the lower temperatures. In this demonstration, the effects of varying the TOS BAC Shield temperature will be examined for the purpose of additional power savings and characterizing high vacuum insulation performance at lower temperatures.

IV. Test Article Design

A. Propellant Tank

The team procured a propellant tank outfitted with a TOT heat exchanger specifically for this test article. It is a “non-flight” ASME rated tank constructed of Al 5083 and the TOT heat exchanger made from Al 1100 which has an extremely high thermal conductivity at LH_2 temperatures. There are a total of nine tubes, each having a flow diameter of 0.18 inches. However, the tubing is D-shaped, thick-walled tubing which is desirable to minimize the risk associated with welding and maximize the contact area between the tube and the tank surface. The tube-on-tank heat exchanger has a supply/return manifold on both the forward and aft ends to enable the refrigeration loops to be configured for flow in either direction. An image of the two-stage cooling propellant tank is shown below in Fig. 3 and 4.

Fig. 3: Two-Stage Cooling Propellant Tank Model Courtesy PHPK

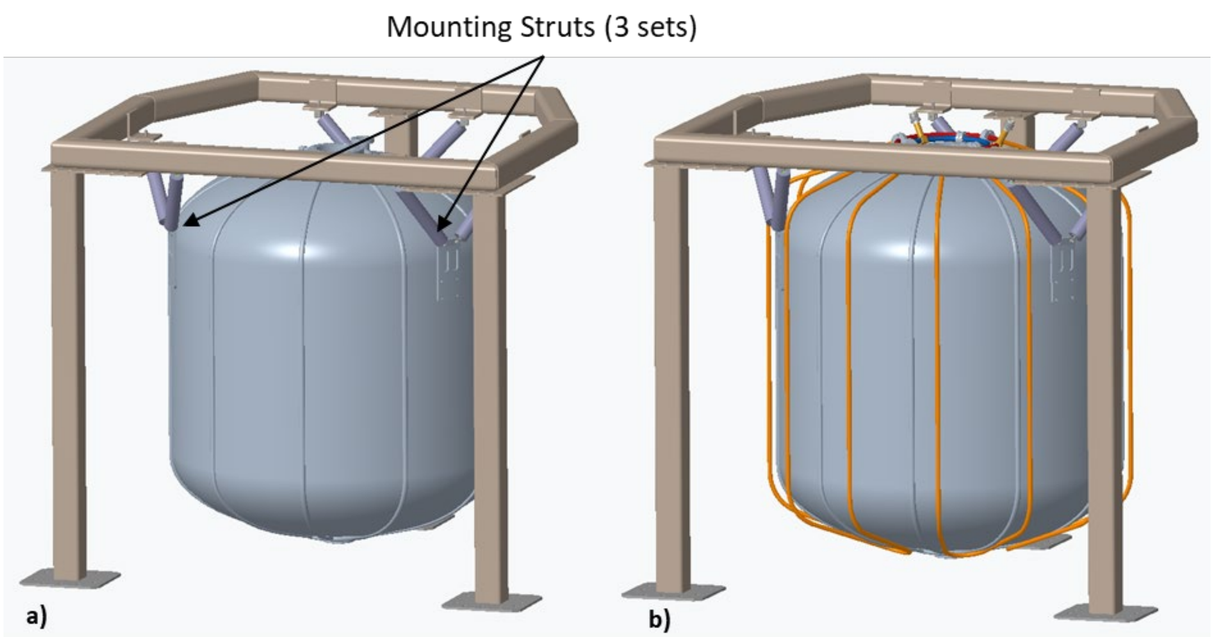

Fig. 4: Two-Stage Cooling Propellant Tank in Support Structure: a) BAC Shield Not Shown, b) TOS BAC Shield Coolant Loops Shown, Legs and Removable Feet Not Shown

B. Insulation System and Tube-On-Shield Broad Area Cooling

The eventual use of the flight cryocoolers imposes constraints on the insulation system design. To enable a "zero boil-off" demonstration with the 20K flight cryocooler, not only did the allowable pressure drop and helium flow capacity drive the sizing of the TOT heat exchanger, but there are limitations on heat lift which drives the design of the insulation system as well. A heat load budget was created assuming 20W as the cryocooler cooling limit. Allowing for parasitic heat loads associated with cryocooler integration and including some conservative margin, the result is an 11W limit for the total propellant tank heat load, of which 3W is through the tank acreage while the remaining is associated with support structure, penetrations, and instrumentation. To achieve this low heat flux (~0.52 W/m2), a high performing insulation system must be implemented.

NASA contracted Quest Thermal Group via the Small Business Innovation Research (SBIR) program for the design, build and installation of the test article insulation system which includes both IMLI inner and outer insulation blankets, the thin foil TOS BAC heat exchanger, and their Wrapped Multi-Layer Insulation (WMLI) system to be applied to the struts, refrigeration lines, as well as penetrations for filling, draining, pressurizing, and venting the test article. The inner blanket will have the load bearing capability needed to support the weigh associated with the thin foil TOS BAC heat exchanger and the outer blanket. Based on the final analysis, the inner and outer blanket configurations are to be 10 and 16 reflective layers, respectively.

C. Cryogenerator

The first phase of testing is planned to be conducted with a two-stage industrial cryocooler, or cryogenerator, with the 1st stage and 2nd stages operating at 80K and 20K, respectively. This team recently procured such a unit with two separate heat exchangers and gas flow loops that would meet the requirements with extra margin to spare for future test programs: the Stirling Cryogenics SPC-1T (see Fig. 5 and Reference 8). Initially, this system will simulate the operation of the Reverse Turbo-Brayton Cycle cryocoolers which are currently being developed for flight applications and planned to be used on a follow-on test series.

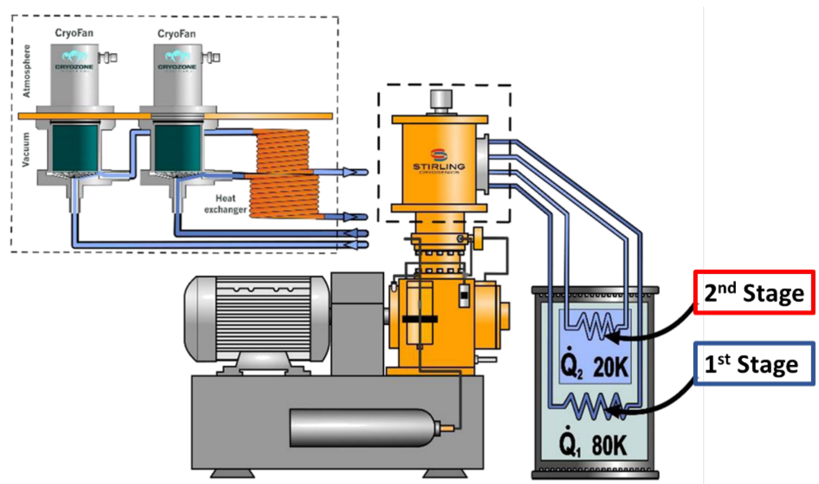

Fig. 5: Two-Stage Cryogenerator, Courtesy Stirling Cryogenics

D. Interface Adapter Design – "The Can"

The design for an Interface Adapter (or "The Can") is shown in Fig. 6. and will be the interface between the Two-Stage Cryogenerator and the Thermal-Vacuum Chamber where the two-stage cooling demonstration is scheduled to occur. Internal to "The Can" are two separate but identical flow loops, one for each stage of cooling. Each loop will contain four RTDs, both a turbine-type and Coriolis flowmeter, a pressure transducer, and line surface heaters. "The Can" and the aforementioned components will be used to conduct characterization testing for the Two-Stage Cryogenerator. During this characterization testing, the heaters will be used to apply an artificial heat load at our planned test conditions, and evaluate how the system responds. When the two-stage cooling demonstration occurs, the heaters will be used to apply an artificial heat load for temperature control. For instance, the 1st Stage will control the TOS BAC shield temperature to a predetermined setpoint (55K to 80K), for at least two different setpoints during the demonstration, then the 2nd Stage will be controlled to ~ 21K which is the temperature of LH_2 saturated at 18 PSIA.

The Interface Adapter will be able to slide away from the internal components for easy access, and all pressure taps and electrical feedthroughs will be on the end cap which is fixed to the cryogenerator. The Interface Adapter is currently part of the chamber vacuum boundary, but it has been proposed to design a gate valve scheme which would allow closing off the chamber without breaking the pressure boundary in the loops; with this design, the cryogenerator and Interface Adapter could be isolated, enabling maintenance without the need to repressurize the main chamber. During characterization testing in the lab, the interface to the chamber pipe will be capped, and the loops will be closed off with a thick-walled tube chosen to simulate the pressure drop of the full system. A turbomolecular vacuum pump will be installed to evacuate the Interface Adapter.

The loops will be filled with Ultra High Purity (UHP) helium from bottles, after a purging and drying process. The cryogenerator includes a filling and venting system, and a connection which will allow a K-bottle to be attached that will provide protection against overpressurization when the unit is shut down. Each loop will have a relief valve for safety, and an electric heater to set the output lift to desired levels (the cryocooler stages are not powered independently and have excess cooling capacity).

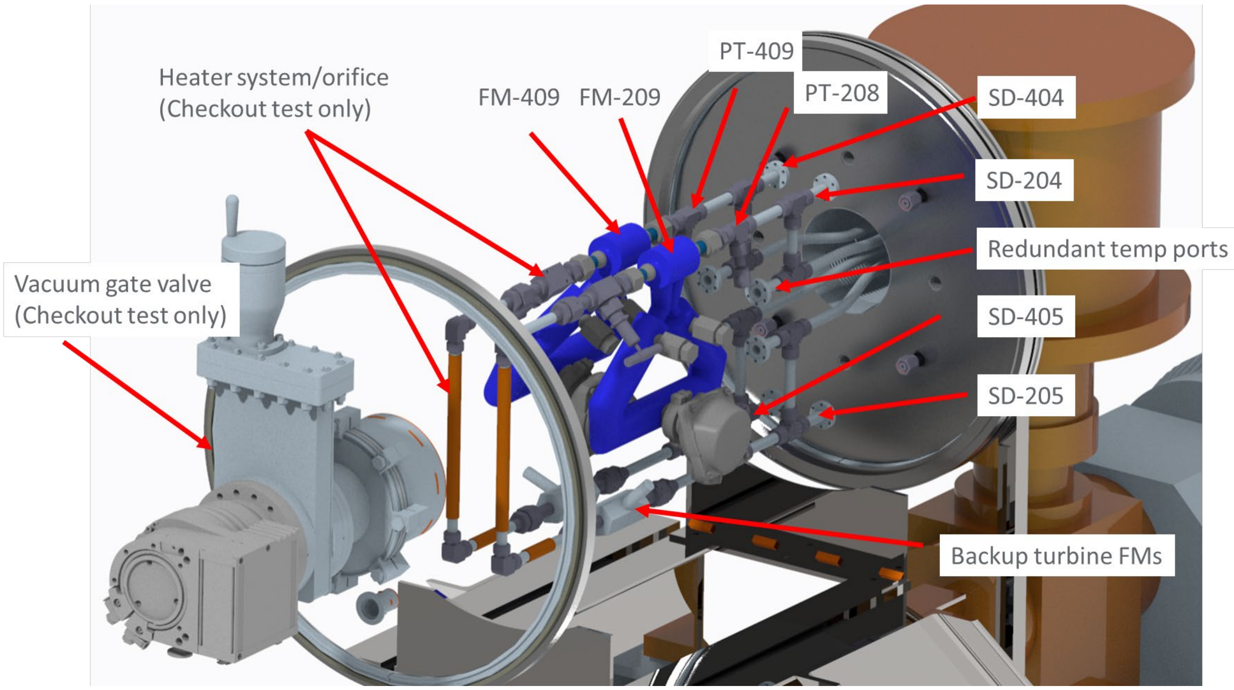

Fig. 6: Cryogenerator with Interface Adapter ("The Can") Installed

V. Demonstration Plan

A. Controls and Bench Test Design

Inherent in the design of the two-stage cooling demonstration are multiple input and output parameters to control with parallel Proportional-Integral-Derivative (PID) loops. These parameters will affect each other in ways which must be analyzed and accounted for in the software. In general, we are looking to achieve a narrow band in the final output variable to claim successful ZBO has been reached, as indicated by saturation temperature and constant pressure in the tank with all valves closed, while conducting a meaningful simulation of flight-like cryocooler operation.

In terms of operations, the heat load on the 2nd Stage is so low that it could pose a challenge to accurately control the heat load to precision required. This heat load can be changed during testing with tank wall heaters to artificially increase heat load if needed, at the expense of good simulation.

Depending on the mission, many factors can complicate the operation of an active propellant cooling system. Some examples are rapid ullage collapse during engine burn, rapid pressure increase (hot gas feedback from engine burn if autogenous pressurization is used), rapid change in heat flux in cooling circuit resulting in unstable PID loops, complications if helium pressurant is used, solar heating (unequal distribution over surface, roll rate), and varying operations between short burns and long burns. Special challenges for nuclear thermal propulsion can include varying neutron heat load, especially if propellant tanks are used as partial shielding.

A test stand is a shared environment, with schedule pressures and facility limitations. Failure that results in a scrubbed attempt at a test of a Ground Test Objective (GTO) can result in a multiple day delay. We have a fixed amount of time in the test area to get as much testing in as possible, so it is in the project's interest to reduce the risk of not getting all the required data within the budget.

A mission to Mars will require ZBO storage for a duration order of magnitudes longer than we will be able to demonstrate with time allotted at the test area, so we will need to demonstrate a very tight control band to be confident in an extended mission duration. Also, flight like cryocoolers do not operate exactly like the Two-Stage Cryogenerator – we will use control of loop heaters and cryofans to simulate RTB cryocooler speed changes. Properly defining "steady-state" to decide when tests are complete is key to avoid unnecessary delay while still getting meaningful data. We use past experience as a guide to set these conditions.

A PID loop is one of the simplest feedback loop control methods in common use. It only utilizes three parameters that do not rely on knowing the physics of the underlying system, because the parameters can be tuned by trial and error; however, physical modeling of the system can inform the starting values for the parameters.

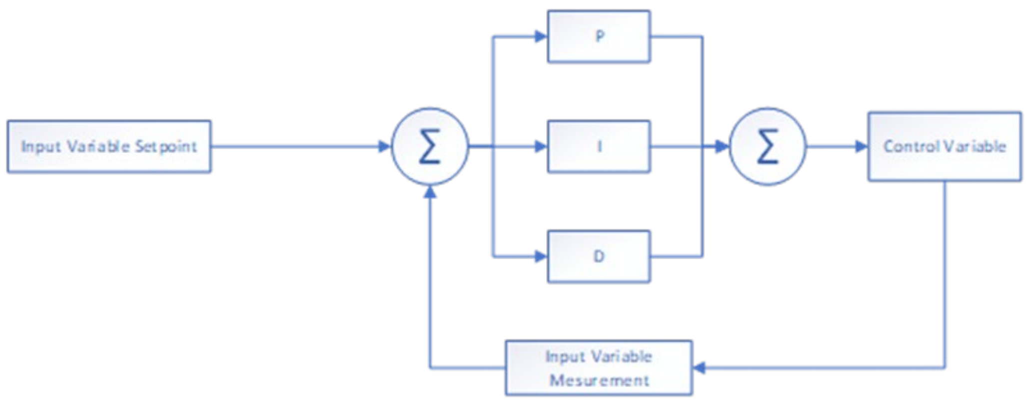

Fig. 7 PID Loop Schematic

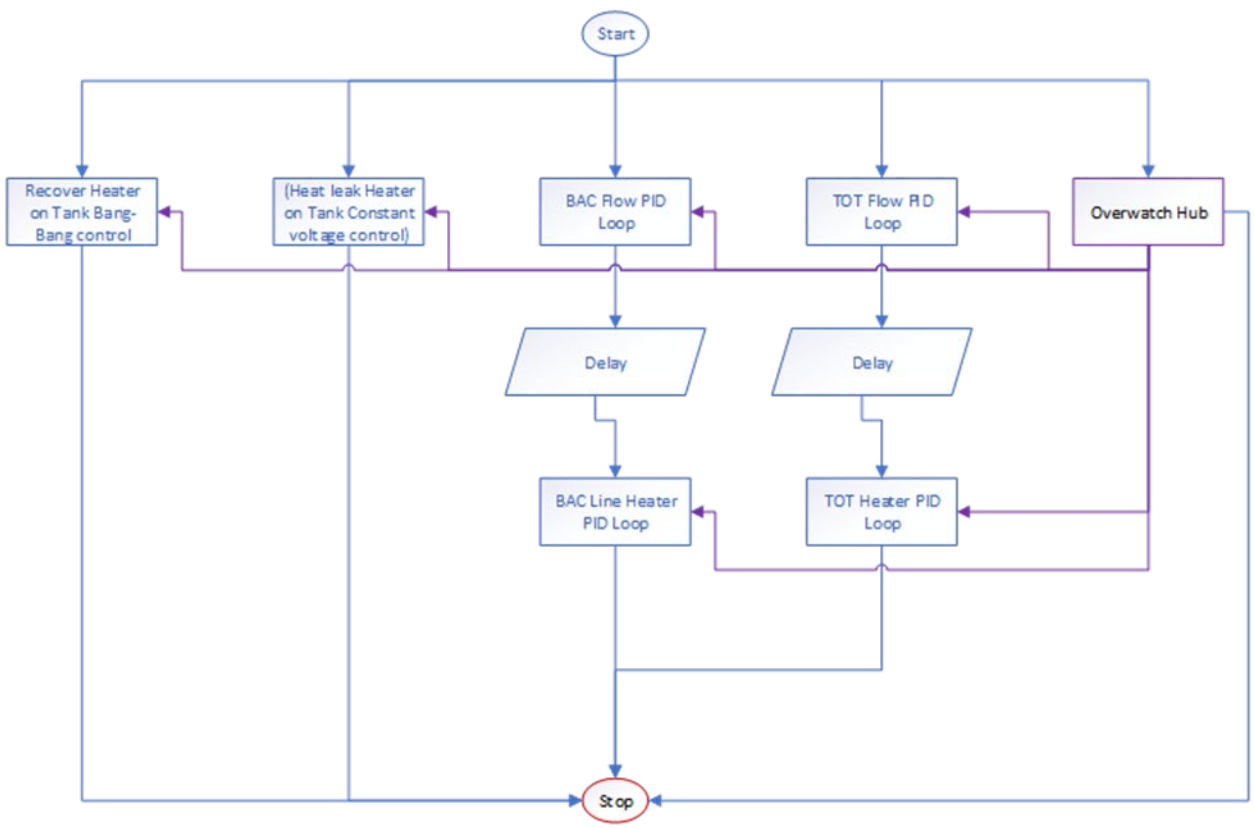

Fig. 8 Overall Control Flow

The system will be controlled with PID loops. With the exception of the Cryogenerator's PID, the 1st and 2nd Stage have their own independent PID loops. Each PID will be tuned will all other conditions held in steady-state. Ziegler-Nichols method will be used to tune them with manual adjustments performed afterwards.

Trim Heater PID will make fast but small adjustments on the Trim Heater output. This will be tuned to ensure the temperature stays within the tight tolerance. The Variable Heater PID will control five, larger, resistance heaters and will be tuned an order of magnitude slower and will maintain the bulk load on the system. The Flow PID will control the Cryofan on the Cyrogenerator.

A system of single input/single output PIDs is a method used to simplify a complex system, while giving the user better control over any one single input/single output PID (or one multiple input/multiple output PID). However, interactions between loops can increase the likelihood of runaway oscillations. If necessary, an "overwatch hub" can be created which will sense that condition and actively damp it out based on physical modeling predictions.

The assumption that is being made to justify using parallel loops for the TOT and TOS BAC is that the two loops are sufficiently isolated by the IMLI that feedback between the loops will be below other feedback noise and can be neglected. Similarly, we assume that the fan speed and line heaters (TOT and TOS BAC) can be in parallel because the time constant between the two can be configured to a few orders of magnitude difference. If the difference in time constant alone is not sufficient, we may need to add a filter to one or both of the loops, or use an Overwatch application to help keep the loop from oscillating out of control. Lab testing before the actual test will be conducted to verify assumptions and demonstrate effective control.

Key Hardware

Tank GH2 Pressure: This project defines success criteria for ZBO as a system-level requirement and other GTO success criteria; as such this is the ultimate control parameter and the uncertainty in this measurement needs to be known. The definition is to maintain pressure within 1% of the target pressure, when temperatures are at steady state and vent is closed.

Secondary Derived Measurement calculations require the tank GH_2 Temperature, Bulk Ullage Temperature which can be an average of Si-Diode rake measurements above liquid level, Bulk Fluid Temperature which can be an average of Si-Diode rake measurements below liquid level, and Tank Wall Temperature at appropriate locations.

TOT Inlet Temp: This measurement is used both as the PID Loop Temperature control variable and to calculate heat removal from the tank. A similar value is calculated for the BAC.

TOT Outlet Temp: This measurement is used to calculate heat removal from the tank. A similar value is calculated for the BAC.

Cryogenerator Inlet and Outlet Temperatures are Cernox probes mounted close to the flowmeters, and so are used in calculating mass flow from the turbine flowmeter output.

Loop Flow Rates: Coriolis flowmeters read loop helium gas mass flow directly. Emerson model CM025M (+/- 1%). Turbine flowmeters read volumetric flow, so pressure and temperature near sensor are required to calculate mass flow. FTI model FTO-5AIR1-GHC-5 (+/- 0.6% in calibrated range) is used as a backup/check to Coriolis meters.

Tank Wall Heater, Recovery Heater Current and Voltage: These measurements are redlines.

Tank Wall Heater, Leak Heater Current and Voltage: These measurements are redlines. A BK 9104 PSU will supply the tank wall heaters (30 W each, ~480 ohm) with a total capacity of 90 W (heat leak) and/or 180 W (recovery). Phosphor bronze wiring will be used to minimize conducted heat through the insulation.

Loop Heaters: Loop heaters are used to maintain constant temperature conditions at the test article heat exchanger inlets (compensating for excess cryogenerator lift). A BK 1687B PSU will supply the 50 W heaters (~15.7 ohm), and a Rigol PSU will be used for the 15 W (~52 ohm) trim heaters. Bi-polar circuits driven by DAQ TTL signals will be used to switch the heater relays. Current shunts provide accurate power measurement; actual heater resistances will be recorded before assembly, and voltage set points will be verified with certified voltmeters prior to testing. A surface temperature RTD measurement will provide overtemperature protection to the heaters themselves. Heaters are Kapton film flat type wrapped around stainless tubing, fixed using thermally conductive epoxy and Kapton tape overwrap, with 22 AWG leads.

Diode rake: Twenty-four sensors, Si-445 silicon diodes with 4-wire connections (+/- 250 mK at 20K). Si-445 diode used in rake also provides fill level information in overcurrent mode. Heat leak into insulated tank volume is through ninety-six 32 AWG phosphor bronze wires. Rake construction is of G-10 composite tube with 36 AWG phosphor bronze wiring and is expected to have negligible effect on heat transfer. The electrical hermetic feedthrough is custom built by Douglas for LH_2 conditions.

TS300 SD signal conditioner cards: Uncertainty is (+/- 0.1% on current supply, +/- 0.3 mV on input) and can be operated in high current mode for level sensing (intermittent operation)

Pressure transducers: MKS 627 heated Baratron (+/- 0.12% of reading) are mounted outside "The Can", and will induce a heat leak through the 1/8" stainless sense lines.

Tank wall, BAC shield and inner MLI temperatures are DT-670A-SD surface mounted sensors with epoxy.

Broad Area Cooling Shield is an aluminum foil shield with stainless steel tubing. Quest Thermal Group has been contracted to design and construct the TOS BAC shield.

Overwatch Program

The overwatch program is a software solution which protects the system from positive feedback oscillations beyond the ability of hard coded self-tuning algorithms to handle. It can recognize early signs of runaway and determine the best override action based on physical modeling, measured parameters, and theoretical predictions of system interactions. Such a program could even incorporate Artificial Intelligence (AI) learning code to refine its actions based on experience. We believe that an overwatch program will not be necessary for this testing, but will implement one if it becomes so. Development of this kind of code could improve reliability of flight systems over long periods of time. For example, it could utilize the energy balance equation and ideal gas law (or empirical equations of state) to predict where the tank pressure is likely to be in the next given amount of time, and determine if more aggressive PID values are needed to keep the pressure within the defined set limits to prevent tank damage or loss of propellant by venting.

Component Testing

Component Level: Verify that compressor turns on and ramps up and down, 20K cryofan turns on and ramps up and down, 80K cryofan turns on and ramps up and down, cryofans turn off, compressor turns off.

System Level: Verify PLC is capable of holding 20K loop at set temperature without Ethernet control (internal PID loop), and that cooling water system is sufficient to avoid high temperature alarm at full power.

Risk Reduction: Test all built in stop functions.

Two-Stage Cryogenerator Characterization Testing

Once satisfied that all cryogenerator hardware and software works as it should, begin testing of the integrated cryogenerator and interface adapter ("The Can"). Each loop is completed inside "The Can", with no connection to the test tank, using a short length of tubing with a wall thickness selected to emulate the flow resistance of the TOT and TOS BAC circuits.

Component level tests: verify operation of loop instrumentation and loop heaters, calibrate the DAQ control of power supplies, and calibrate the temperature and pressure sensors.

PLC and PID loop tests: verify control and data acquisition operate correctly, and tune the PID loops at nominal and extreme operating points.

Redline reaction tests: Induce conditions to force redline actions and verify correct operation.

Map as-built parameters such as pressure drops and heat leaks, to improve model predictions.

Create lift and mass flow maps at selected operating points predicted by modeling, with at least ten data points per curve.

Perform perturbation analysis to verify predicted sensitivities to external conditions and variable changes, for example, the effect of cooling water temperature variations on lift.

Verify PID loop response to excursions by inducing conditions likely to lead to runaway oscillations. If necessary, modify code or add an overwatch.

First testing will be with only one set of PID loops activated. The Heater PIDs will be put into automatic and the Flow PIDs will be put into manual to maintain a constant flow. As many as three different flow rates may be included for each test set. In Heater PID mode, two PID loops will be used to control the heater, thus controlling the tank temperature.

In the first test, the setpoint for the Variable Heater will be 50% and the Process Variable will be the Trim Heater's output. By using this method, we hope to ensure that the Trim Heater never reaches its limits of 0 or 100%. As it increases, the Variable Heater will as well, but much slower to take on the load so it can eventually decrease back to 50% where it has the most mobility. This method will require more precise tuning as it is at higher risk of critical oscillation but has the potential for the best results.

If the first test fails, the next test will be using the temperature as a process variable for both the Trim Heater and the Variable Heater. If tuned improperly, this still has the risk of critical oscillation but the tolerances are much higher. This method includes an additional risk of the trim heater reaching a limit and abrupt changes needed on the variable heater which is likely to put the system out of tolerances.

The next tests will have the Flow PIDs in automatic and the Heater PIDs will be put into manual to maintain a constant heat load. The Flow PIDs consist of Cryofans in the Two Stage Cryogenerator, one per loop as well as a single PID in the Cryogenerator itself. The Cryogenerator PID will maintain the Cryogenerators output temperature while the Cryofans will be modulated to maintain the tank's inlet temperature. If needed, an additional test of keeping the Cryofans constant and feeding the Cryogenerator PID the tank's inlet temperature directly will be ran.

B. "Shakedown" Tests with LN_2

Upon completion of the test article assembly, the team plans to conduct an initial phase of testing to gather preliminary assessments of insulation performance and the effects of thermal strapping on the passive heat load. The test article will be installed in MSFC's ESTF which is a vacuum chamber approximately nine feet in diameter and twenty feet in length. Equipped with a roughing pump, two turbo-pumps and three cryo-pumps, the vacuum chamber can reach 10^{-6} Torr to simulate a space environment. Without a thermal shield internally, the test will be limited to ambient temperature which is consistently 293K. It is equipped with fill, drain, pressurization and vent lines as well instrumentation interfaces for data acquisition. For safety reasons, ESTF is limited to the use of LN_2 only as a surrogate for cryogenic propellants, however use of this facility is minimal cost to the project making it ideal for initial characterization testing of this kind and small/medium scale testing of low Technology Readiness Level (TRL) technologies.


Fig. 9: ESTF 9'X20' Vacuum Chamber


Fig. 10: ESTF 9'X20' Vacuum Chamber with ZBO

The test article will be placed in the vacuum chamber and placed on three "puck type" load cells. All temperature instrumentation will be connected which includes 24 Si-Diodes along an internal vertical rake, 65 Si-Diodes on the tank exterior surface, 36 Si-Diodes within the internal IMLI 10-layer blanket, 9 Si-Diodes on the TOS BAC heat exchanger, and 36 E-Type thermocouples withing the 16-layer outer IMLI blanket. The pressurization, fill and drain lines will be connected.

After successful checkouts of the instrumentation and data acquisition system, the vacuum chamber will be pumped down to 10^{-6} Torr. The test article will be filled to approximately 95% with LN_2 as noted by the vertical rake Si-Diodes and load cells. The test article will then be allowed to "cold soak" while recording all temperature transients until thermal steady-state is reached, anticipated to be approximately one week. Once a final replenishment is complete, the LN_2 will boil-off at a steady rate for 1 week. Boil-off rates will be measured via load cells and vent flowmeters. The boil-off rates and tank ullage and vent temperatures will be used to determine latent and sensible heat loads, respectively.

A second test will be conducted to evaluate the effects of the thermal straps on the passive heat loads. Once the first test series concludes, the tank will be drained, allowed to warm, then the vacuum chamber brought back up to atmospheric pressure to allow for safe entry. The team will then install the highly conducive thermal strapping between the six low conductive titanium struts and the TOT BAC discharge loop referred to as "The Halo". The thermal straps will be covered in MLI to minimize their effects on lead loads. The aforementioned boil-off test will then be repeated. Post processing of data will give an indication as to how significant the presence of the thermal straps were on the passive case.

C. ZBO Demonstration of LH_2 Storage via Two-Stage Active Cooling

Once the "shakedown" testing with LN_2 concludes and the team is satisfied that all instrumentation is operable and there is no evidence of leakage, the test article, interface adapter, and two-stage cryogenerator will all be transported MSFC's East Test Area and integrated into Test Stand 300 which includes a large-scale thermal-vacuum chamber (see Fig. 11).


Fig. 11 Test Stand 300 at MSFC's East Test Area

The thermal-vacuum chamber to be used for the two-stage cooling demonstration is a cylindrical chamber, twenty feet in diameter and thirty-five feet tall. It is equipped with a thermal shroud around the perimeter of the chamber as well as in both the floor and ceiling. Chilled with LN_2, the thermal shroud can get to temperatures as low as 80K. If higher temperatures are desired, a secondary thermal shroud made of anodized aluminum and outfitted with heaters is typically custom made to surround the test article. The anodized aluminum is cooled by the surrounding LN_2 cold walls and the heaters are controlled to a predetermined setpoint to achieve the desired temperature. For this specific test series, the surrounding temperature will be controlled to 220K. Internal to the vacuum chamber is a one-thousand channel data acquisition system and internal high-definition cameras. Vacuum levels as low as 10^{-8} Torr can be achieved via two fifty-two-inch diffusion pumps and three mechanical pumps with blowers. Cryogens such as LN_2, LH_2, LCH_4 and LNG can be accommodated as well as autogenous and non-condensable (GHe) pressurization capabilities. The vacuum chamber is outfitted with a vent system which includes a variable position valve and control system for back pressure control to some predetermined setpoint while measuring the vent outflow via turbine-type flowmeters.

The two-stage cooling test article will be placed in the vacuum chamber for the LH_2 ZBO demonstration (see Fig. 12).

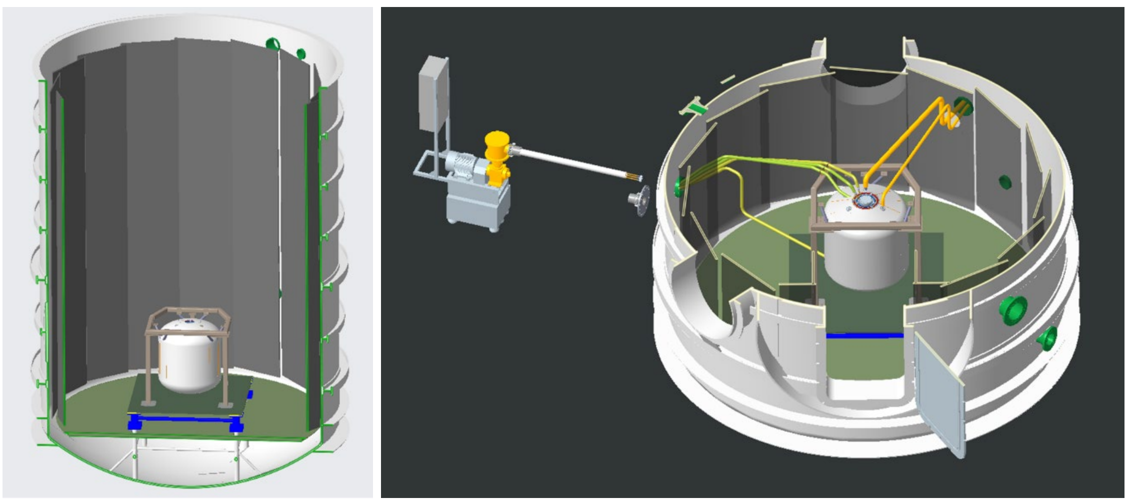

Fig. 12: Two-Stage Cooling Test Article in 20' Thermal-Vac Chamber at MSFC TS300

The Ground Test Objectives (GTOs) for the LH_2 ZBO storage demonstration are listed below:

- **GTO 1:** Conduct "cold shock" test with LN_2 at hard vacuum
- **GTO 2:** Fill Tank to 95% liquid level with LH_2
- **GTO 3:** Achieve thermal steady-state conditions, and measure heat load at 220K environmental temperature
- **GTO 4**: Demonstrate ZBO using a single stage approach, 20K loop only, 220K
- **GTO 5:** Demonstrate ZBO using a two-stage cooling approach, 20K and 80K loops, 220K
- **GTO 6:** Demonstrate ZBO using a two-stage cooling approach, 20K and <80K, 220K
- **GTO 7:** Demonstrate ZBO using a two-stage cooling approach, 20K and <<80K, 220K
- **GTO 8:** Demonstrate GTO 7 at lower liquid level, time permitting

Once the test article is integrated into the thermal-vacuum chamber at MSFC, the first objective will be to conduct a LN_2 "cold shock", GTO 1. After the test article is leak checked at ambient conditions with GHe, the vacuum chamber will be pumped down to hard vacuum, approximately 10^{-6} Torr, then the test article will be filled to 95% liquid level which will be achieved by monitoring the internal Si-Diode rake and the load cells. The vacuum chamber pressure will be monitored closely to assure there is no loss of vacuum due to external leakage from the test article, plumbing, or from the vacuum chamber itself. The team will verify the operation of all instrumentation and address any issues before draining, allowing to warm, then bringing the vacuum chamber back up to ambient conditions in preparation for the next GTO.

GTO 2 simply addresses the initial filling of the test article with LH_2. While monitoring the vacuum chamber pressure for any indications of leakage, the tank will be filled with LH_2 to 95% liquid level which once again will be achieved by monitoring the internal Si-Diode rake and the load cells. Once again, all instrumentation and load cell operation will be verified during this fill.

Once GTO 2 is completed, the test team will proceed to GTO 3 where the LN_2 thermal walls in the vacuum chamber will be activated, and the anodized aluminum shroud on the test article will be set to 220K. The test article will then be allowed to "cold soak" while the tank is vented. During this time, the team will monitor IMLI internal temperature, tank pressure and boil-off rates. Thermal steady-state is considered achieved once the IMLI internal temperature rate of change is less than 0.5K/6 hours and when boil-off rates are steady. At this point, the tank will be replenished back to 95% full and the vent system will be set to automated back pressure control where a variable position valve in the vent line will control the tank pressure to 18 PSIA. The boil-off rates will then be monitored via load cells and turbine-type flowmeters internal to the vent line. It is anticipated that it will take approximately one week to achieve thermal steady-state, then steady-state boil-off and internal tank temperatures will be recorded over a one-week period to obtain a steady-state heat load.

GTO 4 will be the baseline LH_2 ZBO demonstration with the 2nd Stage of the cooling system working alone. With the thermal shroud being maintained at 220K, the test team will set the back pressure control to 18.5 PSIA. The Two-Stage Cryogenerator will then be started and controls set to desired levels based on models and characterization testing. The PID temperature control on the 2nd Stage will then be engaged to maintain tank pressure to 18 PSIA, then disengaged. Then, the PID flow control on the 2nd Stage will be engaged to maintain tank pressure to 18 PSIA, then disengaged. The PID temperature control to maintain desired temperature at TOT heat exchanger inlet manifold and allowed to stabilize. Then the PID flow control to maintain tank pressure at 18 PSIA will be set and allowed to stabilize. Once again, the test team will monitor the IMLI temperatures to assure the test article is thermally at steady-state conditions. The tank pressure should then be 18 PSIA and the TOT heat exchanger inlet temperature, mass flowrate and heater power should be at the correct levels to achieve ZBO. This is a demonstration of the baseline active cooling approach with the 2nd Stage cooling (20K, TOT heat exchanger) active only. One full week of data will be acquired that this condition.

Once GTO 4 concludes, the Two-Stage Cryogenerator will then be shutdown, the LN_2 cold walls deactivated and the test article drained, warmed, and the vacuum chamber brough back up to atmospheric conditions for safe entry. At this time, the test team will enter the vacuum chamber to install the thermal strapping which is intended to intercept and remove heat from the support structure to the 1st Stage during the two-stage cooling demonstration of ZBO LH_2 storage, GTOs 5 thru 9. The thermal straps were intentionally not included in the baseline cases, GTO 3 and 4, due to the additional heat loads associated with them when the 1st Stage is inactive.

Now to proceed with GTO 5, the vacuum chamber will once again be pumped down, the LN_2 cold walls activated, the thermal shroud heaters set to 220K, and the tank filled to 95% liquid level. The test team will use the same approach as in GTO 3 for the test article to "cold soak" and eventually achieve thermal steady-state conditions. The vent back pressure control will once again be set to 18.5 PSIA. The Two-Stage Cryogenerator will then be started and controls set to desired levels based on models and characterization testing. The 1st and 2nd Stage loop heaters will be set to the expected power levels for maintaining the desired TOS BAC and TOT heat exchangers inlet temperatures, respectively. Flowrates will then be set to their predicted values via the 1st and 2nd Stage cryofan speed. The PID temperature control on the 1st Stage will be engaged to maintain loop temperature and allowed to stabilize, then disengaged. Then, the PID flow control will be engaged to maintain loop flow and allowed to stabilize, then disengaged. Both PID temperate controls for both stages will be engaged and allowed to stabilize. Then, both PID mass flowrates are engaged to maintain tank pressure at 18 PSIA and allowed to stabilize. IMLI temperatures will once again be monitored to determine when steady-state conditions are reached. The tank pressure should stabilize at 18 PSIA and the TOT and TOS BAC heat exchanger inlet temperatures, mass flowrates, and heater powers should be at the correct levels for ZBO demonstrations.

GTO 5 is the first of the two-stage cooling demonstration with the 1st Stage and TOS BAC heat exchanger temperatures set to 80K. GTO 6 and 7 are repeats of GTO 5, but at lower 1st Stage temperatures, 70K and possibly as low as 55K. Lower temperatures on the 1st Stage are of interest for two reasons: 1) analysis shows improved electrical power savings at the lower temperatures, and 2) IMLI performance data does not exist with boundary temperatures between 20K and 70K, or between 20K and 55K. Acquiring performance data in these temperature ranges is new and will be beneficial in evaluating insulation performance for future applications.

VI. Conclusions

Analysis to date and previous test programs indicate that the implementation of the two-stage cooling approach can potentially lead to significant mass and power savings when active cooling is used to enable the long duration storage of LH_2. The NASA team is leveraging lessons learned from the CPST program to design and build a test article which will demonstrate the two-stage cooling approach using the fully integrated suite of required technologies which includes a propellant tank equipped with a TOT heat exchanger, an IMLI inner insulation blanket, a TOS BAC shield thermally strapped to the support struts, and an IMLI outer insulation blanket. The TOS BAC shield will be connected to the 1st-stage cooling loop of an industrial cryogenerator and will be operating at temperatures of 80K and below, while the 2nd-stage loop will be connected to the TOT heat exchanger and operating at approximately 21K. The team plans to conduct a detailed test series which includes demonstrating ZBO utilizing a single-stage cooling approach (baseline with 20K unit only), and the two-stage cooling approach at different BAC shield temperatures. When the effort concludes, this approach and integrated suite of CFM technologies will advance to TRL 6 for surface applications. However, due to the gravitational sensitivity associated with the TOT heat exchanger in a micro-g environment, the application will remain at TRL 5 until a flight demonstration can be achieved. Testing is currently planned for late 2024.

VII. Future Work

Potential use of engineering model "flight like" cryocooler is being discussed, but will be the focus of a future effort. NASA has development efforts underway via Small Business Innovation Research (SBIR) contracts for the design, fabrication, and testing of two "flight like" engineering model cryocoolers, both based on a the RTB cycle. For LH_2 storage applications, one unit (20W/20K) is designed to remove up to 20W when operating at 20K. Then for soft cryogens such as LO_X, LCH_4, and LNG, a second unit (150W/90K) is in development which can remove up to 150W when operating at 90K. The 150W/90K unit is also applicable to LH_2 storage if only RBO is required, or if two-stage cooling is implemented to achieve ZBO. Both units will be delivered to NASA where further risk reduction testing will be conducted including the planned demonstration utilizing this test article.

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