

# Creating the Deep Space Environment for Testing the James Webb Space Telescope at NASA Johnson Space Center's Chamber A

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Chamber A is the largest thermal vacuum chamber at the Johnson Space Center and is one of the largest space environment chambers in the world. The chamber is 19.8 m (65 ft.) in diameter and 36.6 m (120 ft.) tall and is equipped with cryogenic liquid nitrogen panels (shrouds) and gaseous helium shrouds to create a simulated space environment. It was originally designed and built in the mid 1960's to test the Apollo Command and Service Module and several manned tests were conducted on that spacecraft, contributing to the success of the program. The chamber has been used since that time to test spacecraft active thermal control systems, Shuttle DTO, DOD, and ESA hardware in simulated Low Earth Orbit (LEO) conditions. NASA is now moving from LEO towards exploration of locations with environments approaching those of deep space. Therefore, Chamber A has undergone major modifications to enable it to simulate these deeper space environments. Environmental requirements were driven, and modifications were funded by the James Webb Space Telescope program, and this telescope, which will orbit Solar/Earth L2, will be the first test article to benefit from the chamber's new capabilities. To accommodate JWST, the Chamber A high vacuum system has been modernized, additional LN2 shrouds have been installed, the liquid nitrogen system has been modified to minimize dependency on electrical power and increase its reliability, a new helium shroud/refrigeration system has been installed to create a colder more stable and uniform heat sink, and the controls have been updated to increase the level of automation and improve operator interfaces. Testing of these major modifications was conducted in August of 2012 and this initial test was very successful, with all major systems exceeding their performance requirements. This paper will outline the changes in overall environmental requirements, discuss the technical design data that was used in the decisions leading to the extensive modifications, and describe the new capabilities of the chamber.

**Key Phrases / Topics:** Thermal testing, deep space simulation, thermo siphon, high vacuum, thermal shrouds

## Nomenclature / Acronyms

<i>ASA</i>	=	O-ring vacuum flange based on ANSI & ASME standard bolting and diameter sizing
<i>atm</i>	=	pressure in atmospheres
<i>BOT</i>	=	Boil off tank (phase separation)
DOD	=	Department of Defense
DTO	=	Detailed Test Objective
ESA	=	European Space Agency
GHe	=	Gaseous Helium
JSC	=	Johnson Space Center
JWST	=	James Webb Space Telescope
LN2	=	Liquid Nitrogen

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K	=	Kelvin
kW	=	Kilowatt
MI	=	Mass-In
MO	=	Mass-Out
NASA	=	National Aeronautics and Space Administration
p-h	=	pressure enthalpy
t-s	=	temperature entropy
TMP	=	turbo molecular pump
g	=	grams
UPS	=	Uninterruptable Power Supply

## I. Introduction

Chamber A was built during the height of the space race. At the time, this robust chamber was a great technological feat. The chamber used diffusion pumps and cryogenic panels to create a high vacuum. Large liquid nitrogen (LN<sub>2</sub>) shrouds and solar simulators provided the thermal extremes experienced en route to the moon. The chamber was human-rated to allow manned testing of the Apollo spacecraft in the thermal vacuum environment (figure 1).



Figure 1. Apollo Service and Command testing in Chamber A

## II. Major Requirements

Because the Apollo testing was short duration, high intensity, and schedule driven the system design concentrated on proven technology with an emphasis on availability and operability by a specific date. System efficiency, long duration reliability, and maintainability were not high priorities at the time. The testing of the optics on the James Webb Space Telescope imposed a paradigm shift on requirement priorities for the facility. The main requirements that needed to be addressed were contamination control, long duration reliability, colder environment, and vibration mitigation. Chamber A was examined holistically and NASA determined several of the legacy systems needed either modification or a complete change. Modifications included the removal of the solar simulation, installation of new LN<sub>2</sub> shrouds, a new helium shroud and refrigeration system, a new clean high vacuum system, and modern controls.

### A. Contamination

The contamination requirements warranted modification to the facility in several locations. One location was the floor structure. The spacecraft/test article floor was originally designed to rotate to allow solar heating on one side of a spacecraft in test. The floor had a seal that was pressurized with low vapor pressure oil. Since the rotation had not been used in 30 years and there was no requirement from JWST, the NASA team decided to remove the mechanism and close out the opening with a simple blind flange. This both removed the potential oil migration issue, and also eliminated a known air leak from the mechanism's drive shaft seal.

The chamber was built with 152 penetrations on its north side. These penetrations were capable of housing solar simulators. The bellows for the solar simulator connections were a source of leakage. The exterior structure for housing the solar lamps was removed and five new platforms were installed, accommodating new cryogenic

distribution valves and piping. All the solar bellows were removed and ASA flanges with new O-rings were installed to reduce the leakage.

One of the largest contamination mitigation projects involved the modification of the high vacuum system. The chamber was originally built with eighteen 35-inch diffusion pumps each connected to 48-inch angle valves. The diffusion pumps were backed by a parallel set of blowers and mechanical pumps. The diffusion pump oil and the hydraulic oil for the angle valves were concerns as potential contamination sources for the chamber. The system was replaced with twelve 48-inch cryogenic adsorption pumps and gate valves and six 14-inch turbo molecular pumps and gate valves on a 48-inch ASA adapter plate. The new turbo molecular pumps use the pre-existing backing system (blowers and mechanical pumps), but an LN<sub>2</sub> baffle was added to minimize any back streaming potential.

The modifications of the high vacuum system also facilitate several new modes of operation for the chamber. The turbo molecular pumps can begin pumping on the chamber volume at a higher pressure than the diffusion pumps allowing for a shorter time to achieve ultimate pressure, as well as faster response to find and mitigate chamber leaks prior to going to thermal conditions. The new high vacuum system also allows the chamber to achieve a lower pressure when heating shrouds for a chamber bakeout. When the chamber is a full cryogenic conditions and the JWST is performing optical tests, the cryogenic pumps will be off to reduce vibration; however when the testing is complete and the chamber shrouds are used to help drive the JWST warm, the cryogenic pumps will maintain the chamber at a low vacuum to assist thermal and contamination control.

## **B. Test Duration**

Two main areas were affected by the increase in test duration due to reliability and efficiency issues: the chamber leak rate and the LN<sub>2</sub> system.

The original chamber was designed with large helium cryogenic pumping panels used to achieve a high vacuum. These are very effective due to their large pumping capacity and can compensate for leakage rates that are unacceptable during long duration testing. For tests with durations of less than two weeks, it was not worth the manpower required to find and repair small leaks. For longer tests, however, gas collected over time poses a risk to the vacuum level, thermal strain, and contamination as this gas is released from the panels back into the chamber volume. All of the chamber penetrations were removed and new O-rings installed to lower the chamber leak rate. Also the main doors on the chamber have been updated to reduce leakage.

The original LN<sub>2</sub> process was a “forced flow” system. A series of pumps pressured the LN<sub>2</sub> and effectively kept the liquid sub-cooled as it picked up the heat in the chamber shrouds and distribution piping. It then transferred it to a low pressure boil-off tank (BOT) where the heat escaped in gas and the liquid returned to the pumps. The complex system was divided into thirty-three separate zones with supply, return, by-pass, and pressure safety systems for each zone. This required over 100 valves and safety devices. The pumps themselves were water pumps modified for cryogenic operation. The pumps were plagued by failing seals, which need to be changed after about 200 hours of operation. Balancing the flow to each control zone was also challenging due to the number of components and their rate of failure. For short-term tests simulating LEO, short mean time between failure and thermal non-uniformity were not an issue. For the long term testing of JWST, however, both were of major concern.

Changing the process to a thermo siphon system was challenging for a chamber that was designed to operate with single-phase sub-cooled liquid. A thermo siphon uses gravity and density change to create a fluid circuit. Liquid leaves an elevated phase separator and sub-cools as it picks up head pressure from the column height. It then picks up heat and lowers density to the point of being a low quality saturated fluid on its return the phase separator. At that point the vapor leaves the phase separator and the liquid returns to the chamber shrouds. Analysis showed this scheme to be feasible and in fact to be the best cost and operational solution when compared to the refurbishment of the original system. An additional feature of the natural flow/ thermo siphon system was that only minimal electrical power would be required for control, now that the large pumps were no longer required. Control cabinets, which feed the system instrumentation and valves positioners with power, were connected to an existing un-interruptible power system (UPS). This was a major benefit to the JWST because the chamber temperature can now be maintained at less than 100 K in the event of a primary power loss. This helps with both contamination issues and thermal stress concerns from rapid warming causing the release of certain condensables, like water, which would then be allowed to migrate within the chamber.

## **C. Colder Environment**

As noted previously, Chamber A was designed to simulate LEO conditions to test the Apollo Service and Command Module for its mission to the moon. The appropriate thermal environment was achieved with liquid nitrogen shrouds operating at around 92K and solar simulators providing the hot extremes. To simulate the JWST target orbit of Earth/Sun L2, the chamber was required to cool the optics to below 40K. The new requirement for

the chamber shrouds was less than 20K. “Filling in” the solar simulation areas with LN2 panels, and installing a new shroud using cryogenic helium gas accomplished this. The liquid nitrogen shrouds do the heavy work of cooling the chamber from 300K to less than 100K, while the new helium shrouds provide the environment to cool the JWST to below 40K with shroud temperatures at 15-20K.

The original chamber incorporated solar simulation on both the top dome (top-sun) and north wall (side sun), in areas of approximately 30-ft in diameter and 30-ft wide by 80-ft high. New shrouds were designed and installed in those regions.

The new helium shrouds required a new refrigeration system and new cryogenic distribution piping. The refrigerator was specified to provide 12.5 KW of refrigeration at 20 Kelvin and about 100 KW at 100 K. The refrigerator was managed in-house with a collaborative agreement with the cryogenics department at the Thomas Jefferson National Accelerator facility. The new cryogenic helium shrouds were sized to accommodate a fully deployed JWST Optical Telescope Element (OTE) and its associated optical Ground Support Equipment (GSE) at proper focal lengths. This required helium shroud dimensions of approximately 13.7 m (45-ft.) in diameter by 19.8 m (65-ft.) tall.

#### **D. Vibration Mitigation**

To test the JWST optics requires a quiet environment. The chamber is fortunately anchored in southeast Texas soil called “gumbo” (sand & clay mix) which does not transmit much vibration from the environment outside the facility as compared to facilities built on bedrock. The mechanical backing pumps that operate throughout the test have been put on vibration mitigation pads. The large helium compressors are mounted on their own foundations with large seismic masses. The cryogenic pumps are turned off during critical optical testing operations.

### **III. Project Time Line**

Chamber A was selected for JWST cryogenic vacuum testing in 2006 after NASA studied various options around the country. Design and concept of operation planning efforts ensued amongst JSC and JWST Program partners from 2006 to 2009. Major construction began in 2009 and completed in June of 2012.

### **IV. Technical Rationale**

#### **A. High Vacuum System**

The technical decision to remove the diffusion pumps and angle valves was directly based on a requirement from the JWST program and their concern about the potential of back streaming oil contamination. The decision to employ 12 Cryogenic pumps and 6 turbomolecular was determined through an analysis of required operation modes and pumping capacity. The new equipment also needed to adapt directly to the location of the original 18 diffusion pumps. Figure 2 shows the design concept for the equipment in its final location. Scale and size are hard to perceive from the figures, but each of the large gate valves for the cryopumps weighed over 10,000 lbs. and required specific rigging and scaffolding to lift and install. The arrangement in figure 2 spans six stories.

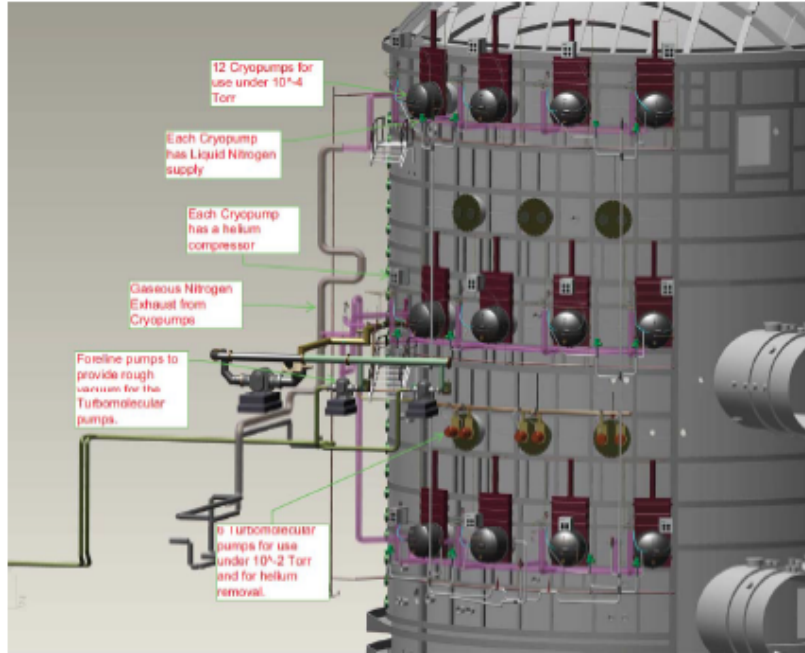


Figure 2. General Arrangement of High Vacuum Pumps on Chamber A

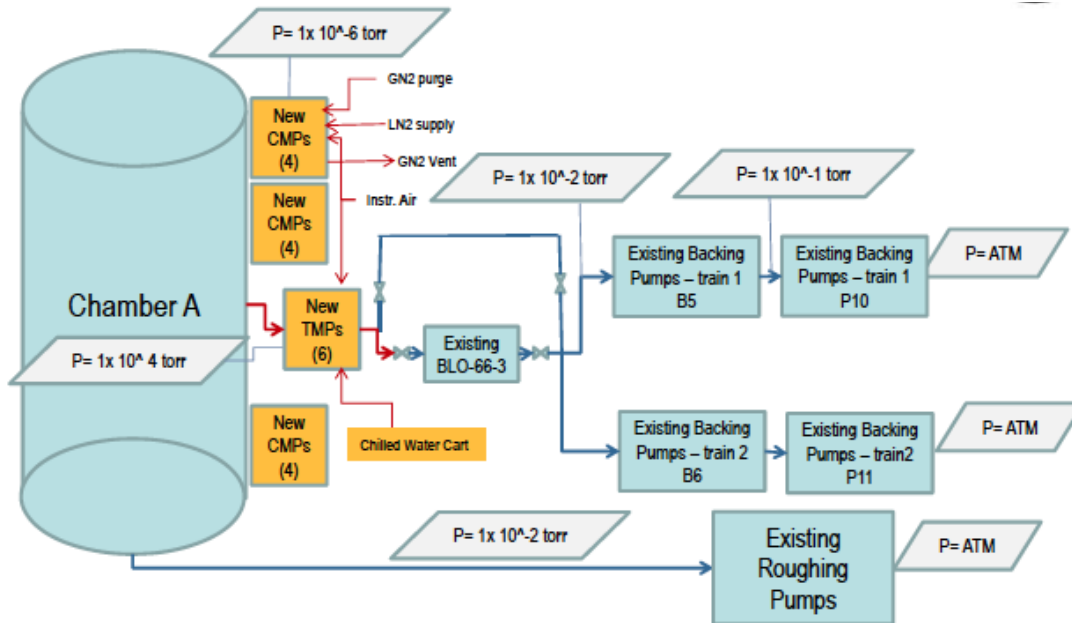


Figure 3. Functional Block Diagram of High Vacuum System

Figure 3 shows the system as a simplified block and performance diagram based on holding the chamber pressure at or below  $1 \times 10^{-4}$  Torr. This was required in order to make decisions and develop specifications for the new equipment and to verify it would integrate with pre-existing equipment used to back the original diffusion pumps.

The turbo molecular pumps (TMP) selected are designed for light gases, and specifically for helium. They are throughput pumps that operate at a broader pressure range than the cryopumps. The TMPs underperform the helium pumping capacity of the original diffusion pumps, but the rationale for 6 was based on the requirement to lower the helium background from  $5 \times 10^{-4}$  Torr to  $6 \times 10^{-6}$  Torr within 4 hours. Table 1 shows the summary of the analysis for 6 TMPs. Because there are different ways to calculate pumping speed, two models were chosen. One was a more common and conservative viscous-molecular flow model where conductance losses were considered within the

10M liter volume to the pumps, but an isothermal environment was assumed. The second model was made using thermal transpiration, composed of 3 thermal environments of 3.3M liters each: one 300 K (between the vacuum shell and LN2 panels), one 80 K (between LN2 panels and helium panels), and one 20 K (inside the helium shrouds). The conductance losses used were the same in both models. The results of the analysis are shown in table 1. As seen, six pumps were not adequate to remove the helium from the chamber in the viscous model, but less than four pumps were required to remove the helium in the calculations with thermal transpiration. Table 2. Shows the results of different pump numbers on the ultimate chamber pressure assuming a constant helium leak rate. The results from both lead to the decision to select six pumps since it proved closest to the conservative calculations and adding more did not greatly improve performance.

Number of Turbomolecular Pumps	Time calculating viscous flow	Time calculating thermal transpiration
	Hours	Hours
6	4.20	1.48/1.17
5	5.01	1.76
4	6.25	2.19

**Table 1.** Estimated Helium Removal Times from  $3 \times 10^{-4}$  to  $5 \times 10^{-6}$  Torr Partial Pressure of Helium

Number of Turbomolecular Pumps	Leak Rate $7.6 \times 10^{-7}$ Torr l/sec	Leak Rate $1.8 \times 10^{-2}$ Torr l/sec	Leak Rate 1 Torr l/sec
	Pressure Torr	Pressure Torr	Pressure Torr
6	$4.22 \times 10^{-11}$	$1 \times 10^{-6}$	$5.56 \times 10^{-5}$
12	$2.1 \times 10^{-11}$	$5 \times 10^{-7}$	$2.78 \times 10^{-5}$
60	$4.22 \times 10^{-12}$	$1 \times 10^{-7}$	$5.56 \times 10^{-6}$

**Table 2.** Helium Leakage Effects on Ultimate Chamber Pressure

The 12 Cryogenic pumps provide a significant pumping capacity. They exceed the effective chamber pumping speed of the original eighteen diffusion pumps which was 270K Torr-l/m of air as compared to the current 600K Torr-l/m). This modification alone provided the chamber with new capabilities, some of which were required for JWST testing. It is now possible to get the chamber to  $< 1 \times 10^{-3}$  Torr without any in chamber cryogenics, which allows for better chamber bakeout and molecular contamination baselining. Another operational improvement is the requirement to hold the chamber below  $1 \times 10^{-4}$  Torr when there is a loss of normal power. The helium shrouds within the chamber have a much greater pumping capacity (more than 2 orders of magnitude), but the refrigeration system that drives them is not currently on emergency power, so when there is a power loss the high vacuum system is required to hold the chamber pressure, with the cryopumps doing the majority of the air pumping. The new high vacuum system will also provide the ability to hold the chamber below  $1 \times 10^{-4}$  Torr while doing a controlled warm up of the cryogenic helium shrouds at the end of the test.

## B. Liquid Nitrogen System (LN<sub>2</sub>)

A high level thermodynamic study of the original LN<sub>2</sub> system and various other options was performed. The study looked at technical performance, capital cost for implementation, project schedule, efficiency of system operation, ease of maintenance, risk (technical / programmatic), and system advantages and disadvantages. The result indicated a significant advantage in using a natural flow (thermo-siphon) process design over the original forced flow system. Thermo-siphon, which uses fluid density changes and gravity to create flow, was chosen as the system to implement for Ch-A to support the James Web Space Telescope (JWST) testing. The advantages of a thermo siphon are stability (nature-driven process), reliability (no rotating parts), reduced maintenance (less control valves and safety devices); lower capital cost (fewer components), lower shroud temperature, lower LN<sub>2</sub> consumption and greater efficiency.

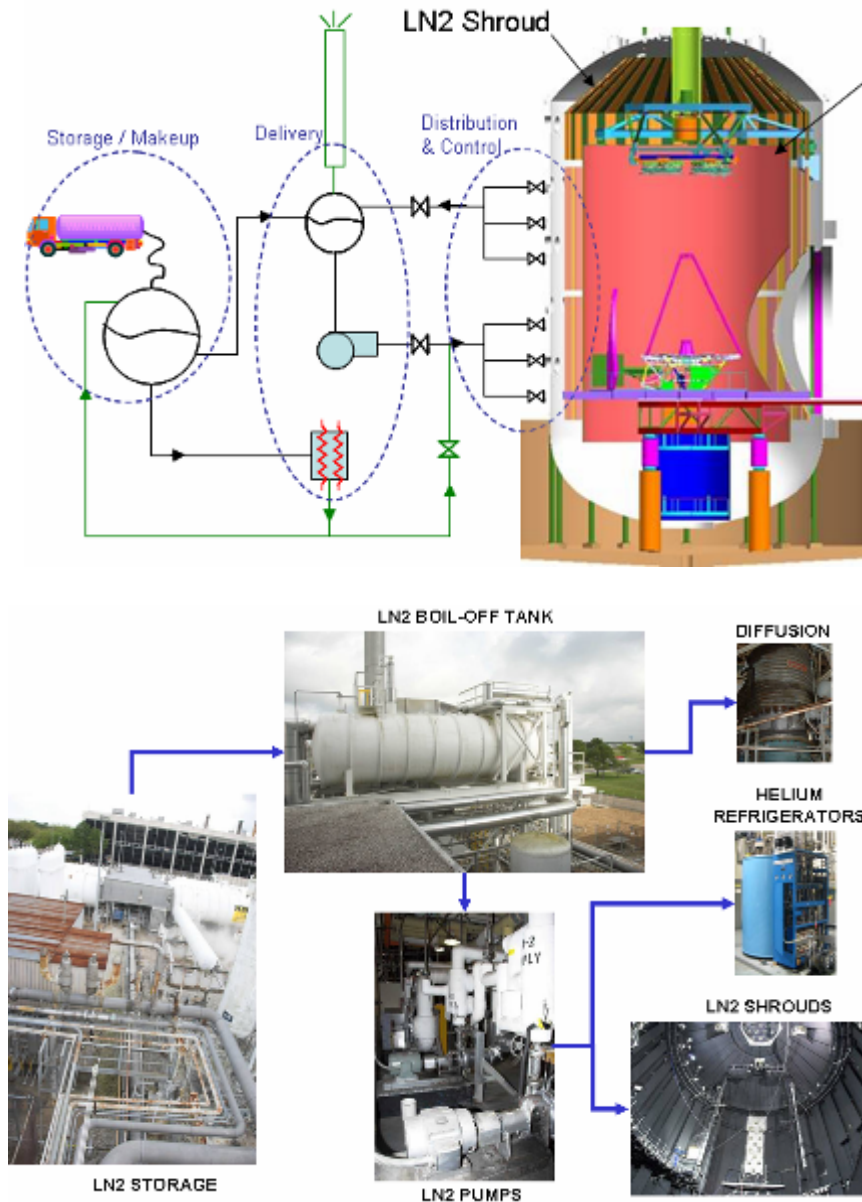
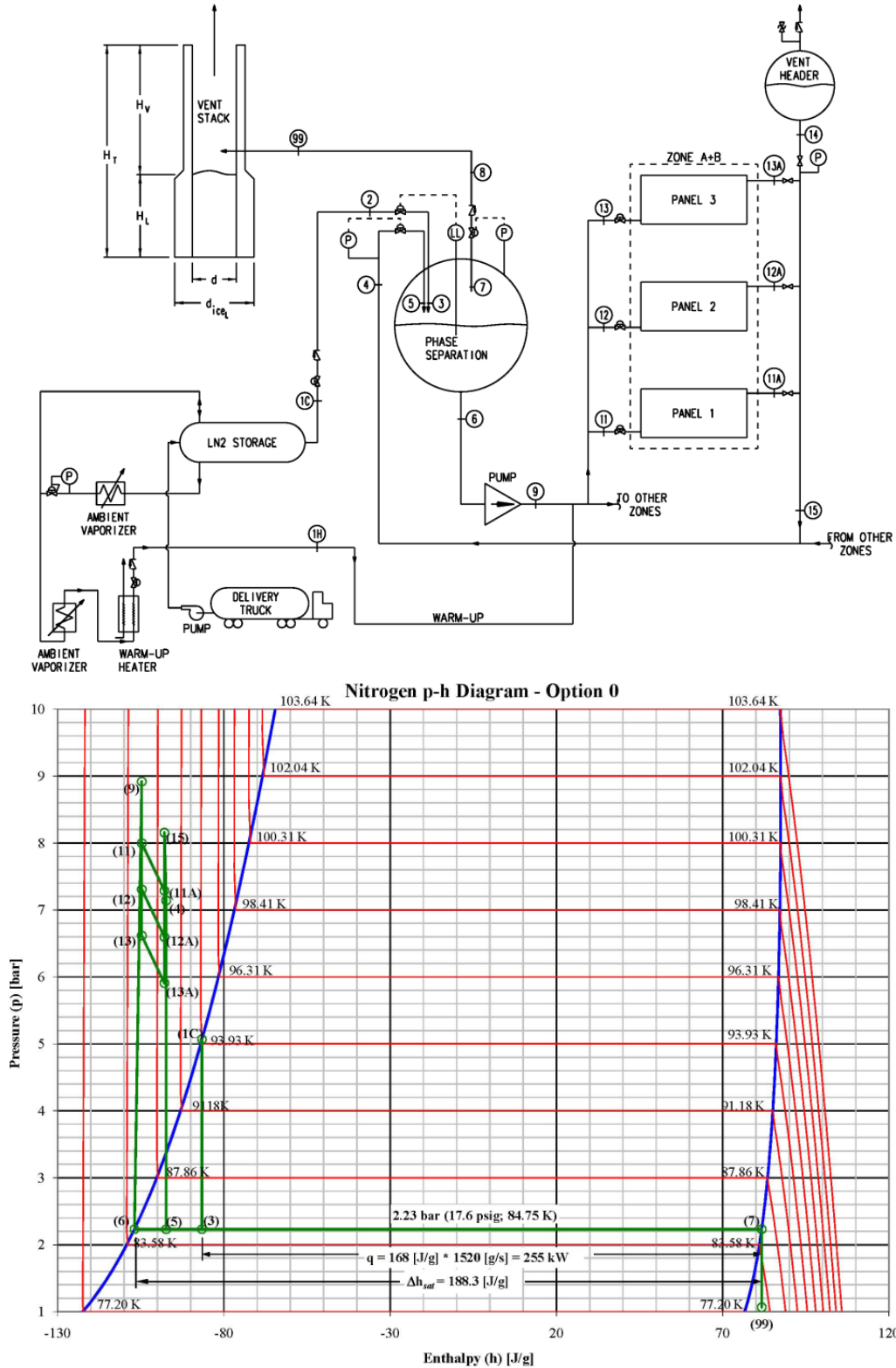


Figure 3. Original LN2 System Overview.

Figure 3 shows a simplified process flow and equipment overview of the original forced flow system. The main components of the original system are the six LN<sub>2</sub> storage tanks (with a storage capacity of 144,000 gallons); a 6000 gallon BOT, mechanical pumps, the shroud panels, and the vent stack. Sub-cooled Liquid nitrogen is circulated through the existing LN<sub>2</sub> shroud panels and returned to the BOT where the LN<sub>2</sub> is depressurized and thus the heat absorbed in the system is removed through liquid boil off. A thermodynamic analysis (figure 4 & 5) was performed on the system to define the loads in each component in the cycle and to understand the thermodynamic process path. The result of this analysis was considered as the baseline for comparison to other cycles being considered. Several options were considered and analyzed (which include modified pumped system with and without make-up pump, modified transfer lines and with various energy recovery cold boxes etc.), but only the original system and the thermo-siphon eventually chosen are discussed in this paper.

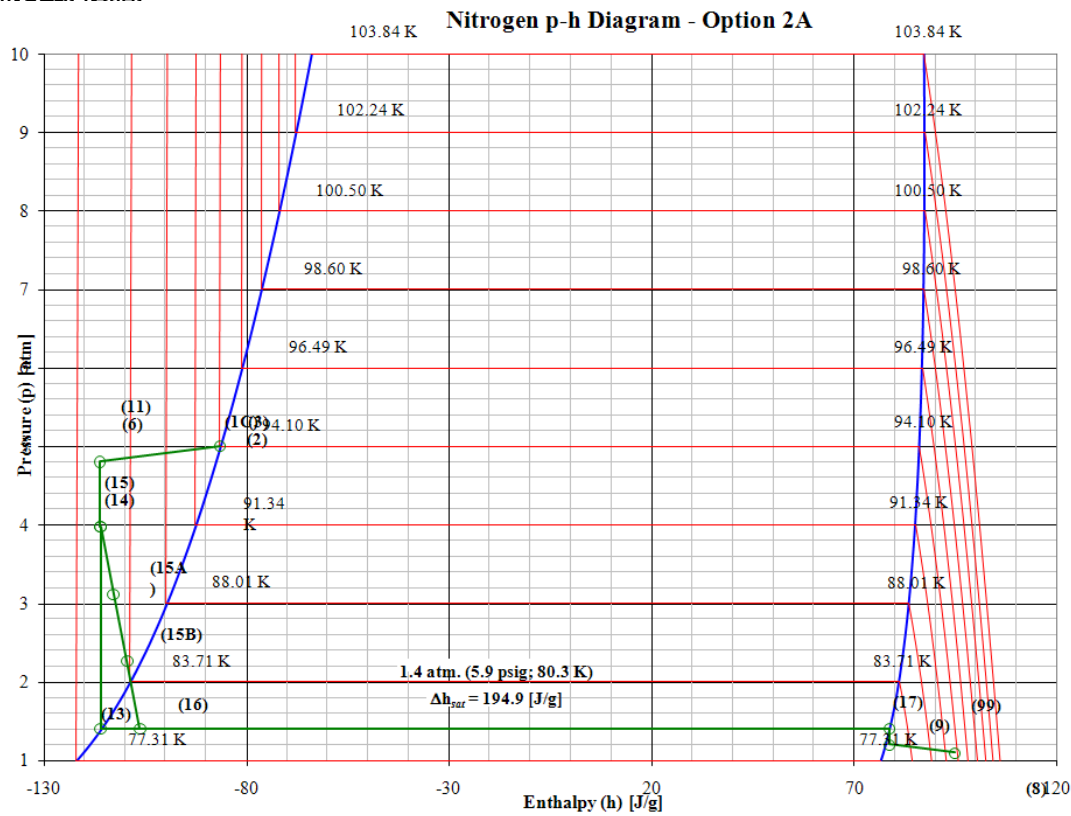
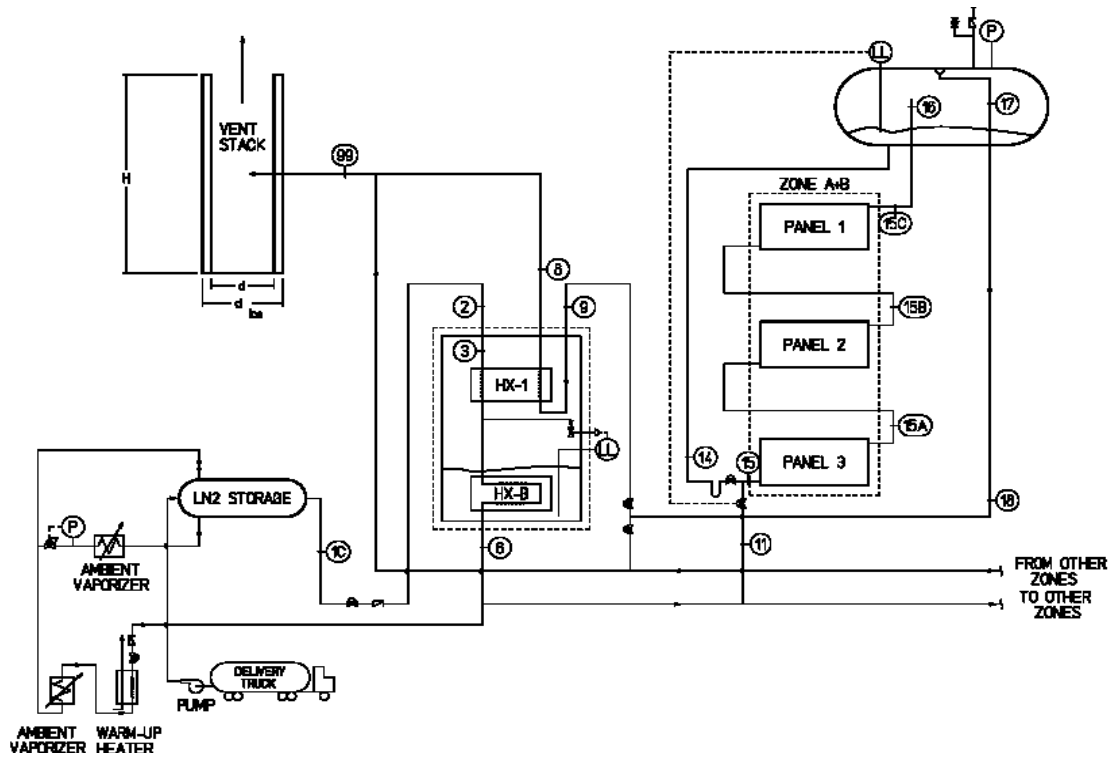


## B1. Thermodynamic Analysis of LN<sub>2</sub> Processes



**Figure 4.** – Process flow diagram and p-h diagram for Original Forced Flow





**Figure 5. Process flow diagram and p-h diagram for Thermo Siphon**

Figures 4 shows a simplified process diagram of the original process and a corresponding p-h plot. The process diagram was used to define points and get the fluid properties at each point to correctly plot the p-h diagram. Figure 5 is the same, but for the thermo siphon.

The original system (Figure 4) operated in the sub-cooled region with the operating pressure at the bottom of the chamber of nine atmospheres, which is a much higher pressure than is required to drive liquid to the top of the chamber. Heat rejection occurred at the BOT and resulted from a throttling pressure change and separation of the gaseous nitrogen from the LN<sub>2</sub>. The nitrogen mass vented as vapor was replaced by makeup LN<sub>2</sub> from the supply tanks. High pump pressures were used as the system was designed for the fluid to remain sub-cooled until it reached the BOT, allowing for flow distribution and balancing throughout the system and avoiding cavitation at the pumps. It should be noted that the shroud temperatures were slightly higher as a result of operating at this elevated pressure.

The new thermo siphon process (Figure 5) eliminates all rotation components and relies on natural circulation (i.e., the exploitation of gravity and fluid density change) to move the LN<sub>2</sub> through the chamber shrouds. Five identical 900-liter (240-gallon) phase separator tanks were installed are located on the top of chamber A inside building 32. The chamber is divided into quadrants; each quadrant is made of a number of shroud zones. An independent phase separator tank services each quadrant and the natural flow liquid is provided from the tank to the shroud zones that make the quadrant. The makeup LN<sub>2</sub> to replace the boil off is supplied through the refrigeration recovery cold box and through shroud zones to maintain the liquid level in the phase separator tanks. The refrigeration recovery cold box utilizes cold gas vented from the phase separators to sub-cool the pressurized LN<sub>2</sub> for makeup.

When designing systems using natural circulation (i.e. a thermo siphon) it is important to minimize horizontal lines, remove potential vapor traps within the process flow path and to maximize pressure difference between the supply and return lines. Although the ideal or perfect flow paths are difficult and expensive to achieve in the original system, the sheer size and height 36.5 m (120 ft.) of Ch-A, and by placing the phase separation tanks high enough on the top of the chamber, helped to achieve the adequate pressure difference to keep the process flow sub-cooled (single phase) through two thirds of the shroud panels height and thus makes it possible to ensure the required process flow distribution through the most torturous sections of the flow path.

		<b>Original Forced flow (Option-0)</b>	<b>Thermo Siphon (Option-2A)</b>
Chamber heat transfer	[kW]	176	176
Supply transfer lines	[kW]	15	9
Return transfer lines	[kW]	15	2
LN valves	[kW]	5	1
LN connections	[kW]	1	1
LN pump	[kW]	37	0
Phase separator	[kW]	2	1
LN helium plant	[kW]	5	10
Other loads (cryo-pumps etc.)	[kW]	0	5
Pressurization	[kW]	0	5
<b>Estimated loads</b>	<b>[kW]</b>	<b>256</b>	<b>210</b>
Supply pressure	[bar]	5.07	5.07
Supply temperature	[K]	94.1	94.1
LN supply enthalpy	[J/g]	-86.6	-86.6
Return pressure	[bar]	2.23	1.01
Return temperature	[K]	84.7	93.1
LN return enthalpy	[J/g]	81.7	94.5
Enthalpy difference	[J/g]	168.3	181.1
Required LN flow rate	[g/s]	1521	1159
LN supply density	[g/L]	722.7	722.7
<b>Required LN volume flow rate</b>	<b>[m<sup>3</sup>/day]</b>	<b>182</b>	<b>139</b>
<b>Savings compared to Option-0</b>	<b>[m<sup>3</sup>/day]</b>	<b>N/A</b>	<b>43</b>
	<b>[%]</b>	<b>N/A</b>	<b>24%</b>

**Table 3.** Liquid nitrogen consumption comparison

Table 3. was a direct comparison between the original forced flow system and the thermo-siphon in daily LN<sub>2</sub> consumption. Do to the risks of deliveries, and the desire to always improve performance and save energy this was a key factor in deciding to change the process.

#### D. Helium System

The new helium system consisted of two major projects:

1. The 12.5 KW @ 20K refrigerator and distribution to the chamber.
2. The 45ft x 65ft helium shroud and distribution within the chamber.

**D.1** The refrigeration plant was designed to provide the required refrigeration power while maintaining good efficiency over a wide temperature range. The anticipated load at 20K was between 8 kW and 12 kW. The major design requirements from the program were hard to define early in the project, but the driving requirements were the following:

1. Flexible performance at steady state
2. Tight thermal stability at steady state
3. Maximum power for cooldown/transient heat removal
4. Temperature control throughout full range

The refrigeration project was successfully managed at JSC using collaboration with the cryogenics department at Thomas Jefferson National Lab (JLabs), Jacobs Engineering, and NASA JSC civil service. JLabs successfully

designed the process and hardware specifications, while Jacobs executed the hardware procurements and implemented the system.

To meet the requirements of the program as well as use the lessons learned and best practices involved with owning and operating a cryogenic helium plant, the refrigerator cold box main features are:

- Two parallel TED45 turbines provide optimal refrigeration performance in the 100K range as well as in the 20K range.
- A large LN2 vessel, two parallel warm end heat exchangers and three load return valves at different temperature stages ensure an effective large cool down capacity.
- Two parallel 80K charcoal adsorbers and a subsequent bypass line are used to purify the circulating helium when the turbines are started and before the actual cool-down of the chamber.
- A cold gaseous nitrogen supply line reduces the LN2 consumption.

The Process Flow Diagram in figure 6 shows a simplified process arrangement. Warm high-pressure helium enters the Coldbox and is divided into two streams that are being cooled by the low-pressure He return flow and nitrogen vapor respectively. Re-connected into a single stream the high-pressure helium is then cooled to 80K in the nitrogen evaporator before it passes into one of two parallel adsorbers. After further cooling in subsequent return helium heat exchangers the supply helium is expanded in either one or two turbines, depending on the temperature range required and is then fed to the Space Chamber. The low-pressure helium return joins the process at 20K, 80K or 300K level depending on its temperature.

It is not unusual that the primary design conditions “Refrigeration Load” and “Load Return Temperature,” given vary in a considerable range. To be on the safe side a “worst case scenario,” via highest load and coldest temperature is defined to specify the demand for the refrigerator. Hence the system consisting of refrigerator, compressor(s) and load must possess sufficient flexibility to cope with all scenarios in an efficient way.

The process control of the cold box is based on the Ganni floating pressure cycle philosophy (simplified schematic figure 7) (see references 1 and 4 for detailed information on the Ganni Cycle. As the floating pressure control uses a constant pressure ratio and variable gas charge process, the compressor discharge pressure is adjusted to match the required load as indicated by the shield return temperature. Of course, the minimum compressor

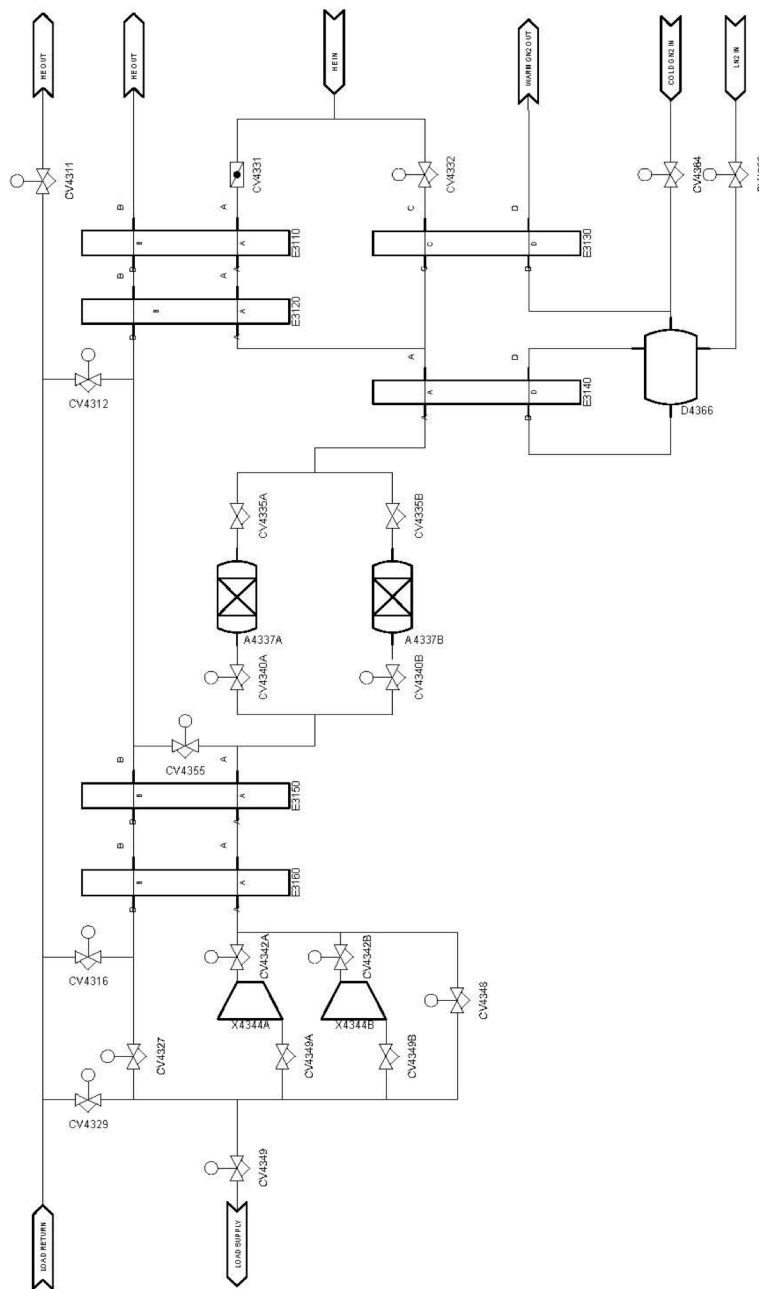


Figure 6: Cold Box Process Flow

discharge pressure is constrained by the pressure drop in the oil removal system while the maximum is set by the pressure rating of the compressor itself and components downstream of the compressor discharge). There are other compressor constraints, such as preventing the suction from becoming sub-atmospheric as this rotary screw compressor design uses a suction shaft seal. Turbine constraints such as maximum tip speed and bearing capacity are monitored by the local turbine control elements (i.e., inlet and brake valves) and are set to allow the widest possible operational envelope for the turbine. The Floating Pressure process typically utilizes two control elements that add or remove gas charge from the system; namely the 'mass-in' (MI) and 'mass-out' (MO) control valves, respectively. The compressor bypass valve operates only to prevent the sub-atmospheric suction condition. During steady (fixed temperature) operation, additional measures of capacity control, such as turbine bypass, are not implemented until the compressor suction pressure reaches its minimum allowed setting (say, 1.05 bar). During a cool down to a desired shield return temperature set point, the discharge pressure remains at its maximum limit, until the load return temperature reaches the given set-point (say, 20 K). Upon reaching the set point, the MI and MO adjust the discharge pressure to maintain the desired shield return temperature and at that point the refrigeration capacity matches the actual heat load.

After the system was designed and specifications were written for major components, a 12.5 kW @ 20 K cold box based on the process flow diagram in figure 6 was procured from Linde Process Plants., and a 1300 kW compressor was built by Salof industries. The components were then integrated into the system (figure 7) at JSC with controls developed in house to operate the system using the Ganni cycle.

**D.2** The helium shroud and internal piping was another major project. It does not have the process complexity of the refrigerator, but was unique in the fabrication, assembly, and installation. The shroud is the piece of hardware that provides the deep space thermal environment within the chamber. The chamber has a hinged 40ft diameter vehicle access door that provides the largest opening. The shroud being 45 ft. in diameter and almost 70 ft. tall was fabricated in three shops around the country, and then assembled within the facility in sections small enough fit.

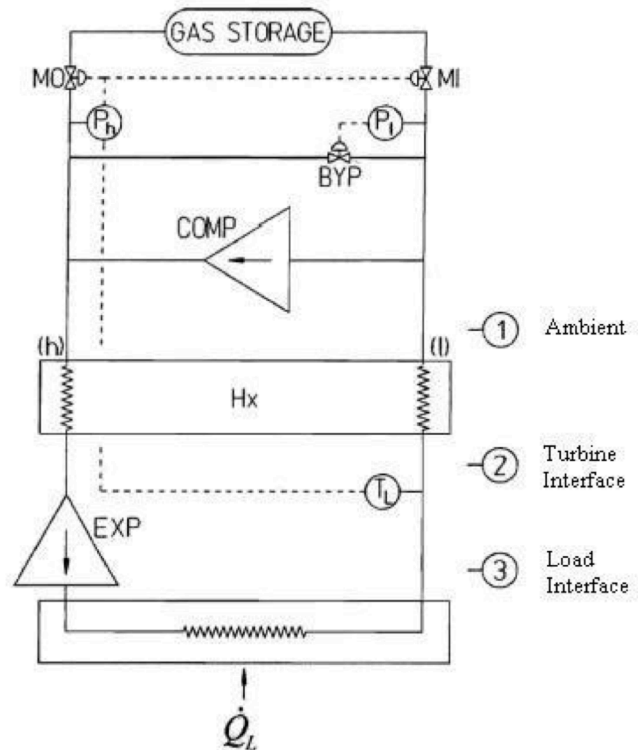


FIGURE 7: Floating pressure control schematic

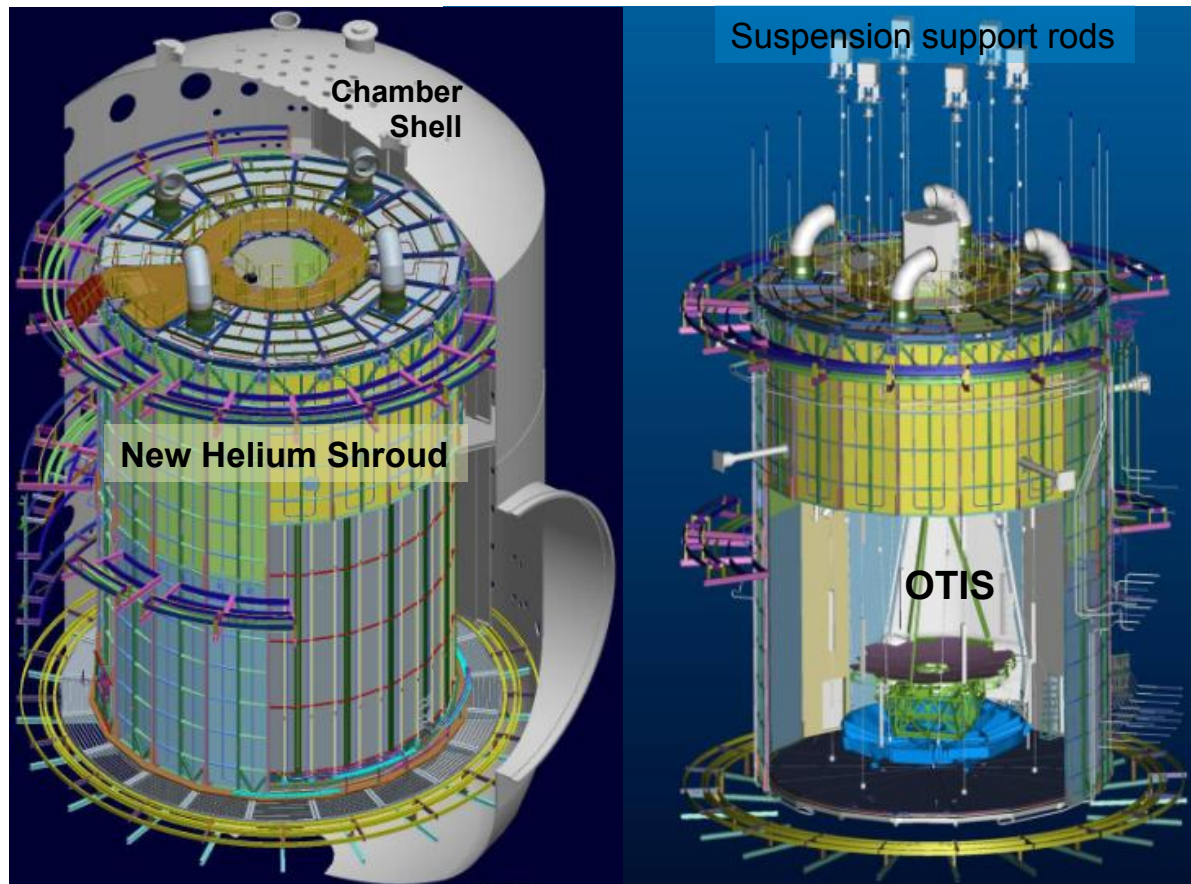


Figure 8. Helium Shroud

The shroud was uniquely designed not only for integration and assembly, but the ceiling and cylinder are suspended from the chamber top dome to minimize conductive heat loss. Lords™ “Z307” paint was used as the high emissivity coating due to its emissive properties at low temperatures and its durability to be handled and cleaned as compared to coatings with much higher emissivity. The cylinder was designed to have door sections that roll to allow full access of the chamber’s 40-ft vehicle door. The shroud ceiling is designed with air diffusers and the floor is designed as a balanced return air duct to allow for top-down airflow. This allows the interior of the helium shroud to maintain an ISO class 7 environment. The shroud is instrumented with over 200 silicon diodes to read temperatures from 350 K to 10 K.

## V. Functional Test and Initial Results

The major chamber and system modifications were completed in the early summer of 2012 with functional testing beginning in mid-July and running through August. The functional test was the first operation of the chamber to prove thermal vacuum capabilities since 2005. It would be the first time the new equipment would be operated on the chamber, and the first operation of the liquid nitrogen thermal siphon system. The high vacuum system had been operated and tested against its chamber isolation valves to verify general performance, and the helium system was tested in a closed loop using a test heater to verify and characterize its performance prior to the summer functional. The results of the functional test were pleasing. The chamber, which had over 200 penetrations removed and re-installed, had 18 angle valves cut and re-welded, and had the rotating floor removed and replaced still had some gross leaks as expected, but the new welds had no indication of leakage. The high vacuum system was able to achieve a chamber pressure of  $2 \times 10^{-4}$  Torr with an indicated leak rate of about 100 Torr-l/m. The high vacuum system successfully removed helium intentionally backfilled into the chamber, and the vacuum model using thermal transpiration provided the closest prediction to the actual time. The helium refrigerator went through performance commissioning prior to the chamber test and proved that it could safely exceed its design requirements. The refrigerator is capable of producing 16 kW of refrigeration with a return temperature of 20 K and 10 kW of

refrigeration with a return temperature of 15 K. During the chamber run, we were able to maintain the shroud at a temperature of around 13 K.

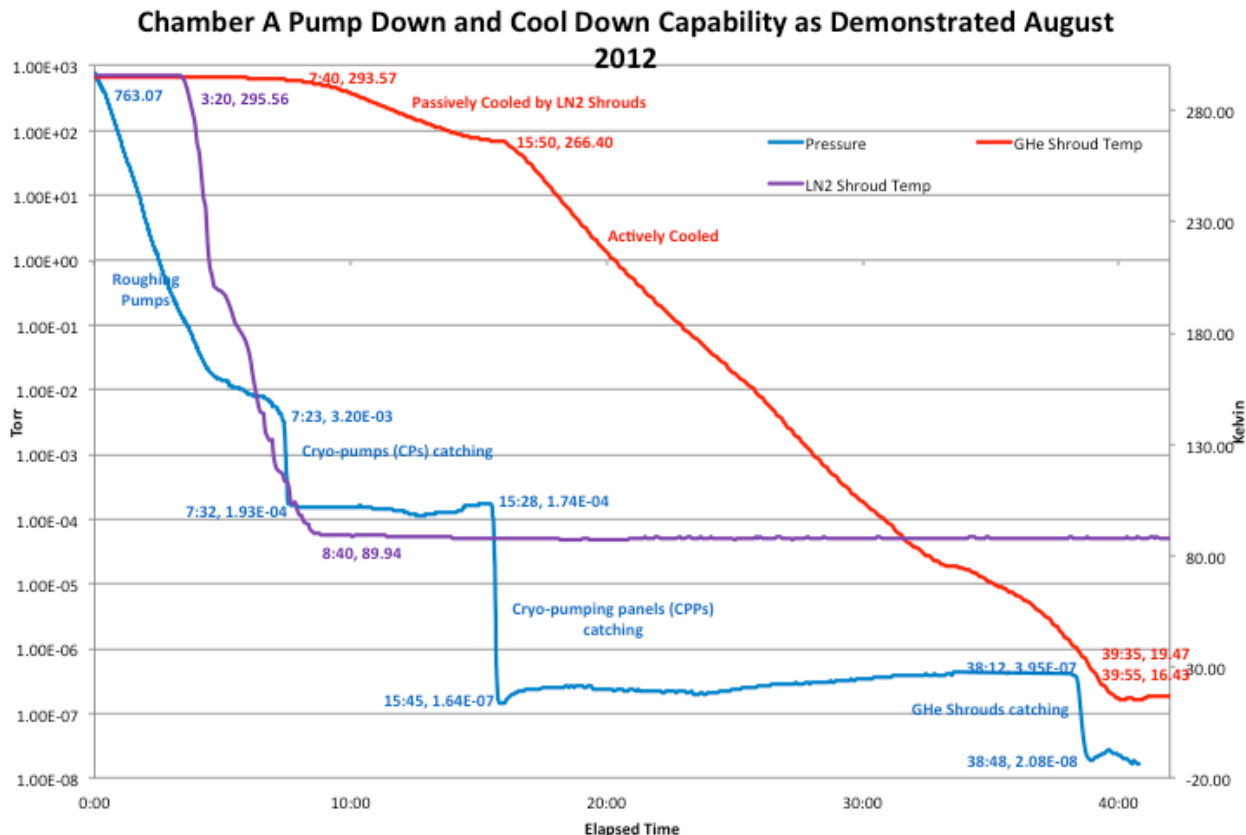


Figure 9. Initial Chamber Pumpdown and Cryogenic Operations

The results of the initial run are plotted in figure 9. The figure plots pressure and temperature vs. time. The chamber pressure (blue line) achieved  $2 \times 10^{-4}$  Torr when the cryogenic pumps were operated, continued down to below  $1 \times 10^{-6}$  Torr when the pre-existing internal cryo-pumping panels got to temperature, and eventually achieved a chamber pressure of  $2 \times 10^{-8}$  Torr when the new helium shrouds were brought below 20 K. The purple line represents the LN<sub>2</sub> shroud average temperature, and cooldown from the start of operations to a steady temperature below 90 K took less than 6 hours. Thermal stability of the LN<sub>2</sub> shrouds remained throughout the test and they also were proven to operate and remain steady during a power loss. The thermo siphon exceeded the original performance as predicted by design, showing a reduction of consumption of more than 50% compared to the original configuration. This differed greatly from the 23% in the first design analysis. This was because the design analysis made a comparison to the old operations and didn't account for the reduced heat loss on the LN<sub>2</sub> system provided by the addition of new panels and radiant barrier where the solar simulation use to enter the chamber and the shell was coated to have high emissivity. Table 4 shows the analyzed heat loads compared prior to the improvements and the re-analyzed performance with the reduction in heat load. In actual results, the system still outperformed the analysis. The best-measured daily consumption for the actual functional test was 77K liters (20.5K gallons). This is a reduction in consumption of 57% compared to original. This may be due to the chamber holding a lower vacuum and surfaces being cleaned to lower their emissivity, as well as use of conservative numbers on other system heat losses in the analysis.



Item / Source	unit	Original / Forced Flow	Proposed- Design / Thermo Siphon	New-Best Est / Thermo Siphon
Chamber Heat Transfer	kW	176	176	117
Supply Transfer Lines	kW	15	9	9
Return Transfer Lines	kW	15	2	2
LN2 Valves	kW	5	1	1
LN2 Connections	kW	1	1	1
LN2 Pump(s)	kW	37	0	0
Phase Separator	kW	2	1	1
LN2 to Helium Refrigerators	kW	5	10	10
Other LN2 (cryo Pumps, Baffles)	kW	0	5	5
System Pressurization	kW	0	5	4
<b>Estimated Loads</b>	<b>kW</b>	<b>256</b>	<b>210</b>	<b>150</b>
Supply Pressure	kPa	507	507	507
Supply Temperature	K	94	94	94
LN2 Supply Enthalpy	J/g	-86	-86	-86
Return Pressure	kPa	223	101	101
Return Temperature	K	85	93	93
LN2 Return Enthalpy	J/g	82	94	94
Delta h	J/g	168	180	180
Required LN2 Flow	g/s	1516	1168	832
	l/s	126	97	69
	l/d	181110	139580	99408
	<b>gal/day</b>	<b>47850</b>	<b>36877</b>	<b>26264</b>
Savings Compared to Original	gal/day	0	10972	21586
	%	0	23	45

Table 4. LN2 Consumption - Updated

The red line in figure 9 represents the average helium shroud temperature. The plot shows that the 25-ton shroud was cooled to below 20 Kelvin in just over 24 hours from the start of the refrigerators flowing through the shrouds. This exceeds a requirement for it to be cooled in less than 48 hours.

Many other chamber features not described in this paper were proven as well. One new upgrade provided for all of the systems were common graphic user controls to automate and/or provide remote operations and monitoring through the existing control and data system. Another major system tested was a modified emergency power system (new generator) and uninterruptible power system. It was tested by pulling all power from the test facility (3 main feeds). The UPS and EPS maintained power for 18 hours, and the chamber pressure recovered within 10 minutes of the power outage.

## VI. Conclusion

Chamber A and its primary thermal vacuum systems are ready to support testing. The chamber is still undergoing major upgrades to its ambient air handling systems and a new clean room is being installed in the main high bay. These are still major items to meet the stringent contamination requirements, but the new cryogenic systems and vacuum systems are capable of supporting testing. The LN2 system is expected to be more stable, reliable, and efficient operation. The system will also be easier to implement and maintain considering the number of active components that are being eliminated.

Another major feature from the LN2 system is that JSC currently pays \$0.23 (2012) per gallon for LN<sub>2</sub>. The thermodynamic change to natural flow with the improvements to the chamber saves ~27,000 gallons/day or a cost of \$6,210 per day in FY12 dollars or about \$558,900 for a 90 day test and it reduces the risk of delivery delays by three to four tankers that would need to be handled each day of test.

The helium refrigerator and shroud system exceeded its requirements with greater performance and operating ranges. With use of the bakeout heater, the system can be controlled to temperatures ranging from <15K to >330 K. The refrigerators output power to input power is highly efficient, saving electrical usage as well as hardware wear and tear.

The new controls and emergency power systems proved their worth and performed well, allowing the systems to be monitored and restarted quickly. With a full building outage there was no loss of the LN<sub>2</sub> system, and the high vacuum recovered quickly.

The refurbishment of Chamber A to test the JWST will provide NASA with an outstanding and efficient facility to test large spacecraft in a wide range of space environments.

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