

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

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Nomenclature / Acronyms

A = amplitude of oscillation

I. Abstract

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 remove 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

II. Introduction

Chamber A was built in the in the height of the space race. At the time, it was the very robust, and a great technological feat. The chamber used diffusion pumps and cryogenic panels to create a high vacuum. Large liquid nitrogen shrouds and solar simulators provided the thermal extremes seen on the way to the moon. The chamber was manned rated to allow humans to test the Apollo space craft in the thermal vacuum environment.

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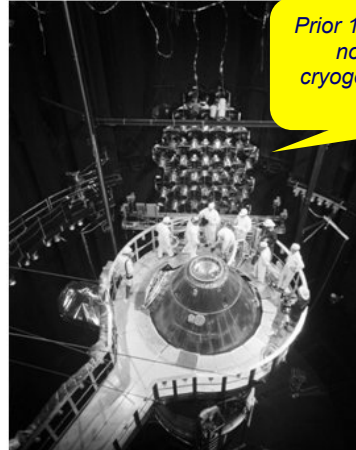
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**Boilerplate
Apollo S/C 008
in Chamber A
with side-sun
solar**



**Prior 150 side sun penetrations
now used by JWST for
cryogenic and instrumentation
feed-throughs**

**Crew ingress
for manned
Apollo CSM
testing in
Chamber A**

III. Major Requirements

Because the Apollo testing was short duration, high intensity, and schedule driven the systems were very robust with availability/ test readiness as a major requirement. This posed problems with efficiency, long duration reliability, and maintainability. The testing of the optics on the James Webb Space Telescope put a different set of requirements on the facility. The main requirements that needed to be addressed were contamination, long duration reliability, colder environment, and vibration mitigation. The chamber was looked at and several of the systems either needed modification or a complete change. The modifications included the removal of the solar simulation, installation of new LN2 shrouds, a new helium shroud and refrigeration system, new high vacuum system, and update controls.

A. Contamination

The contamination requirements required modification to the facility in several locations. One was the floor structure. The spacecraft/test article floor was originally designed to rotate to allow solar heating on one side of the spacecraft. The floor had a seal that was pressurized with low vapor pressure silicon oil. Since the rotation hadn't been used in 30 years and there was no requirement from JWST, it was decided to removed the mechanism and close out with a simple penetration. This both removed the silicon oil issue, and also improved the air leak rate from the mechanism.

The chamber was designed with 152 penetrations on the north side that 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 5 platforms were installed. All the solar bellows were removed and standard ASA? Flange plate were installed to reduced the leakage.

One of the largest contamination projects was the modification of the high vacuum system. The chamber was originally built with eighteen 35" diffusion pumps connected to 48" angle valves. The diffusion pumps were backed by a parallel set of blowers and mechanical pumps. The diffusion pump oil and the hydraulics for the angle valves were major contamination concerns. The system was replaced with twelve 48" gate valves and cryogenic adsorption pumps and six 14" gate valves and turbo molecular pumps. The turbo molecular pumps use the pre-existing backing system (blowers and mechanical pumps), but a liquid nitrogen baffle was added to minimize any backstreaming potential.

The modification of the high vacuum system also helped the chamber have several new modes of operation. The turbo molecular pumps can begin pumping on the chamber volume at a higher pressure than the diffusion pumps and allow for faster time to ultimate pressure and 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, but when the testing is complete and the chamber shrouds need to warm to help drive the JWST warm, the crogenic pumps maintain the chamber at a low vacuum to maintain thermal control and assist in contamination control.

B. Test Duration

Two main areas were affected by the increase in test duration: the chamber leak rate and the liquid nitrogen system. The chamber was designed with large helium cryogenic pumping panels to achieve a high vacuum. These are very effective, but can sometimes mask leaks due to the large pumping capacity. This again helped with test availability, because for a short duration test it was not worth the time to repair the leak(s) The other issue was the liquid nitrogen system. The original process was a “forced flow.” This means that a series of pumps pressured the liquid and effectively subcooled the liquid which picked up the heat and transferred it to a low pressure tank where the heat escaped as gas and the liquid returned to the pumps. The system was designed with three levels, four quadrants, and the floor. It was divided into 33 separate zones with supply, return, by-pass, and safety systems for each. This required over 100 valves and safety devices. Changing the process to a thermo siphon added 5 phase separator tanks, but reduced the total number of chamber valves to less than 20, and each phase separator has a relief valve and burst disk, so the total number of safety devices on the system is about a dozen. Changing to thermo siphon was a challenge because the chamber was designed to operate single phase / sub-cooled, but with proper analysis, it proved feasible and the best cost and operational solution. With out pumps, the only electricity required on the system is the controls. The control cabinets (which feed the system instrumentation and valves positioners with power) were put on our existing un-interruptable power system (UPS). This was a major benefit to the JWST because it meant we could maintain the chamber less than 100K in the event of a major power loss. This helps with both contaminaton issues and thermal stress concerns.

C. Colder Environment

As noted previously, chamber A was designed to create the LEO to test the Apollo Service and Command Module on its mission to the moon. The cold was accomplished with liquid nitrogen shrouds operating at around 92K, and solar simulators provided the hot extremes. With JWST going to Earth/Sun L2, the chamber was required to get the optics to below 40K. The new requirement for the chamber shrouds was less than 20K. This was accomplished by “filling in” the solar simulation areas with liquid nitrogen panels, and installing a new shroud using cryogenic helium gas. 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 around 15-20K.

The chamber had two main areas of solar simulation: One the top; This was an area of with a diameter of about 30 ft. The other was on the side; this was about 30ft wide by 80ft tall. New shrouds were designed and installed in those regions. PICTURES..

The new helium shrouds were Show pictures?

The helium shrouds required a new refrigeration system and new distribution piping to feed the shrouds with the cryogen. 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.

D. Vibration Mitigation

To test the optics require a quiet environment. The chamber is fortunately anchored gumbo and does not transmit much vibration from the environment outside the facility. The mechanical backing pumps that will need to operate throughout the test have been put on vibration mitigation pads. The large helium compressor are mounted on their own foundations with large seismic masses. The cryogenic pumps are turned off during critical optical testing.

IV. Project Time Line

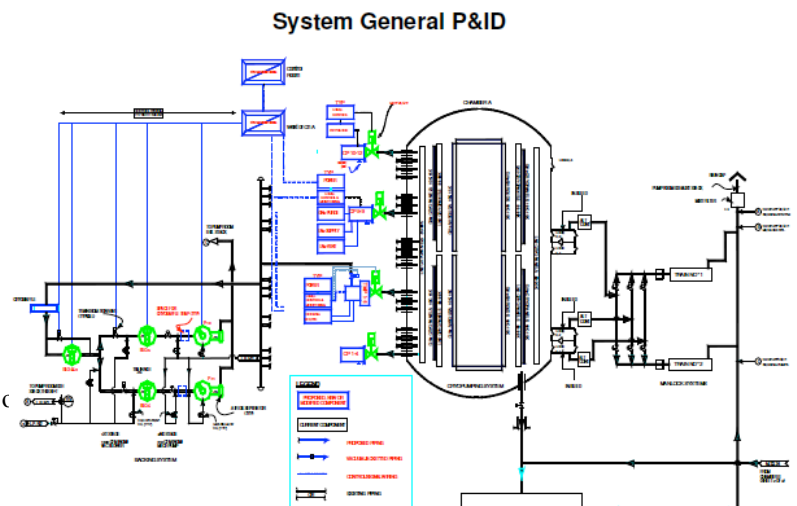
Chamber A was selected in 2006 after NASA studing various options. COF for major construction was funded between 2009 to 2012. Project completed in June 2012.

V. Technical Rational

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. The decision on the go with 12 Cryogenic pumps and 6 turbomolecular was decided through an

American Institute of



analysis of the required operations and needed performance.

The turbo molecular pumps 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 do not come close to the helium capacity of diffusion pumps, but the rationale for 6 was based on the requirement to remove a helium background of 5×10^{-4} Torr to 6×10^{-6} Torr within 4 hours. Show figure? Explains “sweet spot.”

The 12 Cryogenic pumps provide a significant pumping capacity.

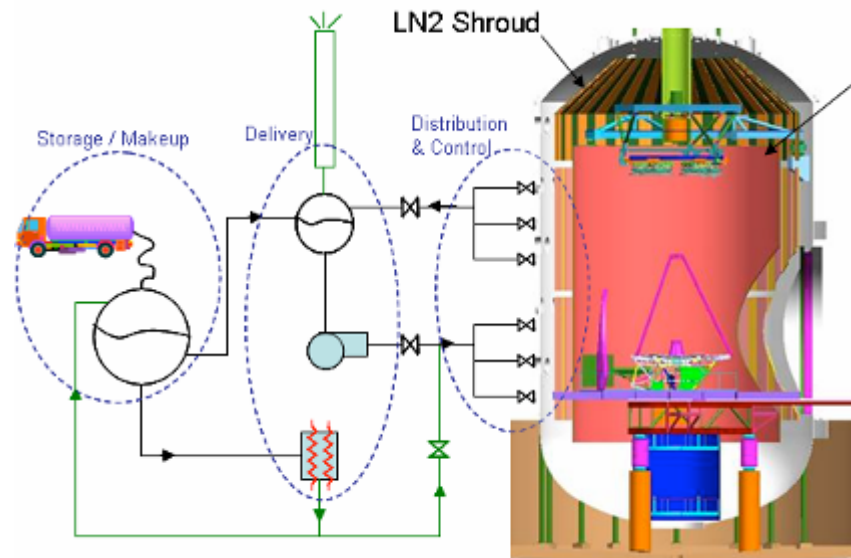
B.

C. Liquid Nitrogen System

Figure out how to summarize in 1 page.

Liquid Nitrogen (LN_2) is used throughout the Building 32 facility in NASA Johnson Space Center in support of space simulation testing. Its primary use for Chamber A (Ch-A) is to cool the nitrogen shrouds providing an 80 K environment background simulating the cold of space in low Earth orbit. The original LN_2 system was a forced flow system which uses pumps to circulate LN_2 through the shrouds and other ancillary equipment (Figure 1). The return flow is routed to a low pressure recovery tank (also known as the boil-off tank, or BOT), where the nitrogen vapor is separated from the liquid and vented to atmosphere while the liquid is returned to the pumps.

A high level thermodynamic study of the existing 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. The thermo-siphon system 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_2 consumption and greater efficiency.



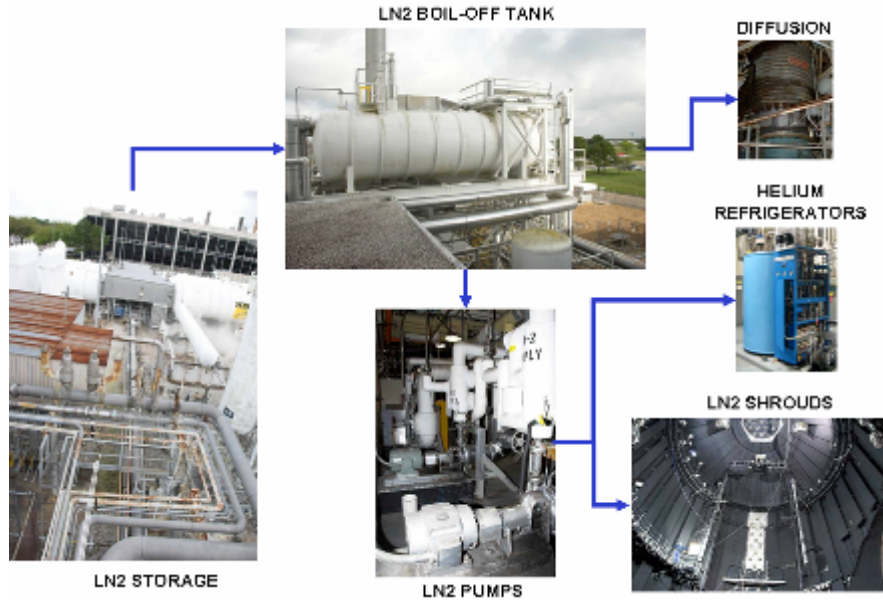


Figure 1. Existing LN2 System Overview.

C1. LN2 Thermodynamic Analysis

C1.1 System thermodynamic analysis of the original system, Option-0:

The main components of the original system are the six LN₂ storage tanks (with a storage capacity of 144,000 gallons), a 6000 gallon BOT, mechanical pumps, the shroud panels, and the vent stack. The flow diagram is shown in Figure 2. Sub-cooled Liquid nitrogen is circulated through the existing LN₂ shroud panels and returned to the BOT where the LN₂ is depressurized and thus the heat absorbed in the system is removed through liquid boil off. A thermodynamic analysis 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 decided upon are discussed in this paper. Option-0 is the current process and option-2A is the thermo siphon process which was ultimately selected as the design approach.

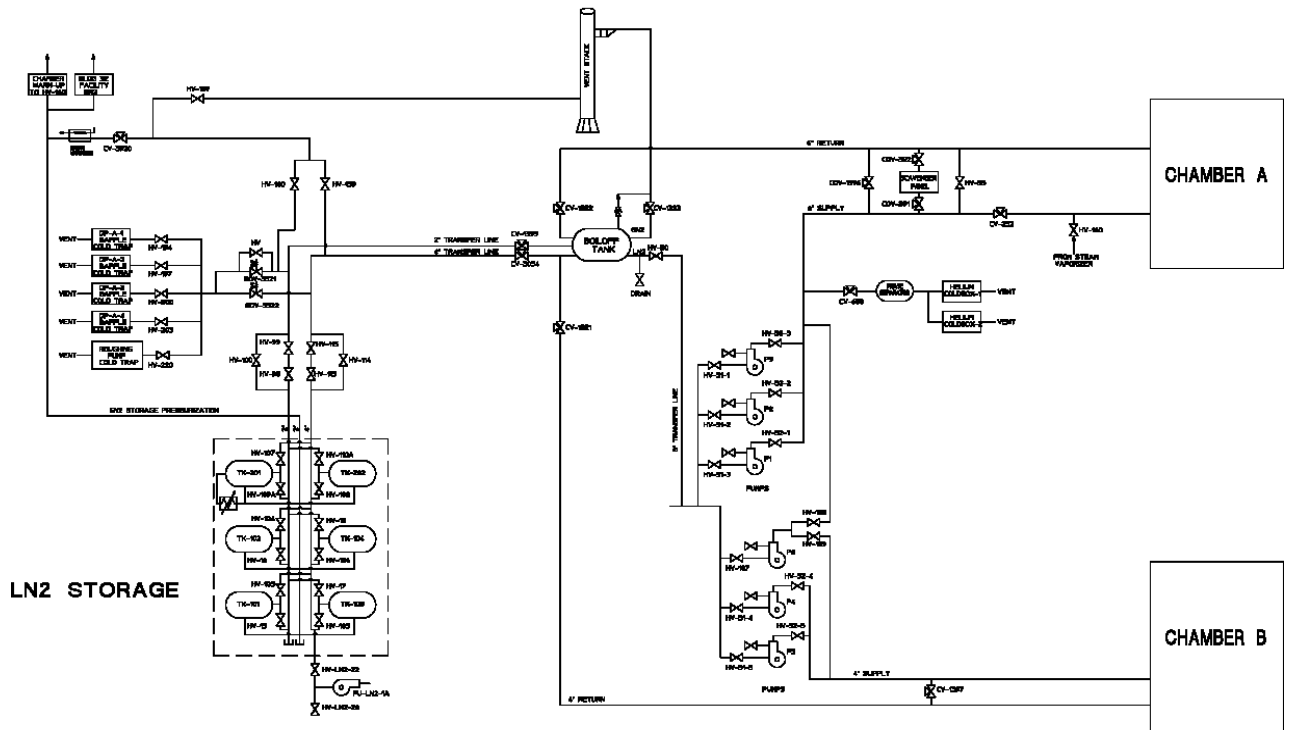


Figure 2. Current system flow diagram, Option-0

The analysis of the original system was based on LN₂ consumption data from test runs occurring over the past 40 years, and the experience and insight from those people that have been operating the system. The Ch-A steady state LN₂ consumption (without the solar simulation system operating) has been very consistent. The analysis also verified independently using known sub-system nominal heat loads and alternative thermal analysis methods (i.e. heat transfer to and from the components, the vent stack and the energy balance methods).

The present system heat load estimation is summarized in Table 2 (Opt-0). The total heat load estimates in Table- 2 match the total quantity of liquid nitrogen required to run Ch-A using the current operational method under steady state conditions. The simplified version of the present forced flow system is shown in Figure 3 and is used to define the thermodynamic state points of the cycle on the pressure-enthalpy (p-h) diagram in Figure 4. The resulting pressure-enthalpy diagram in Figure 4 shows the thermodynamic path that the cycle follows. The system operated in the sub-cooled region and the BOT separated the N₂ vapor from liquid (resulting from the throttling; pressure change) without liquid carryover to the vent stack when operating correctly. The N₂ vapor vented is replaced by makeup LN₂ in the process. The operating pressure at the bottom of the chamber was around 9 atm, which is a higher pressure than is required to drive liquid to the top elevation of the chamber. This was required to avoid some operational issues. The main issue was that the system was designed for the fluid to remain as sub-cooled liquid until returning to the BOT (for flow distribution and balancing). The second issue was cavitation at the pumps. Both were solved by operating at higher system pressures, but it should be noted that the shroud temperatures were slightly higher than they would have been had the system pressure been lower (see Figure 8).

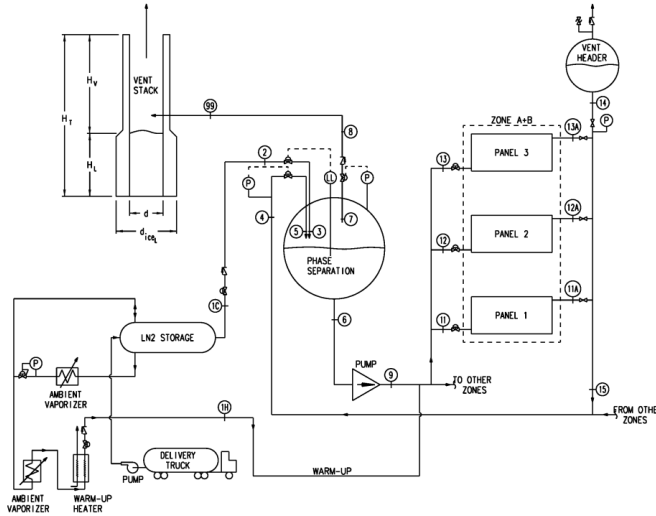


Figure3. Current system simplified flow diagram, Option 0

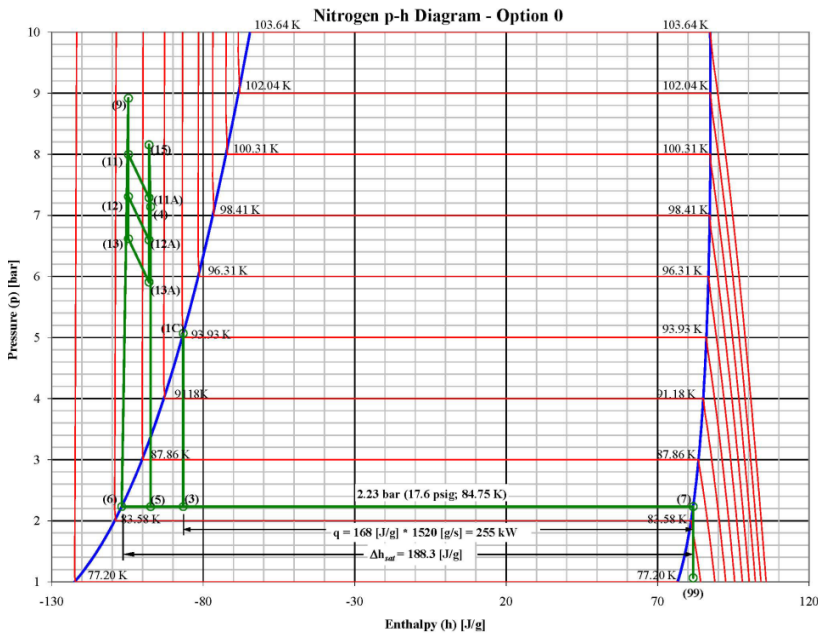


Figure 4. Nitrogen p-h Diagram, Option 0 (Forced Flow)

C1.2 Thermodynamic Analysis of the thermo siphon option, Option 2A:

A simplified schematic flow diagram of the thermo siphon system is presented in Figure 5. This system eliminates all rotating components and relies on natural circulation (i.e., the exploitation of gravity and fluid density change) to move the LN₂ through the chamber shrouds. It uses five identical phase separator tanks, 240 gallons each, all to be 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. Each quadrant is serviced by an independent phase separator tank and the natural flow liquid is provided from the tank to the shroud zones that make the quadrant. The makeup LN₂ 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 system utilizes a refrigeration recovery cold box to reduce the liquid nitrogen consumption during normal operations and to provide the sub-cooled LN₂ for makeup. A thermal analysis similar to the one developed for the forced flow system was

performed to estimate the heat loads and the consumption rates of the LN₂. The results are summarized in Table 2, which shows Option-2A will have a 27% reduction in LN₂ consumption as compared to Option-0.

The heat load on the shrouds can be reduced further if improved radiation shielding (e.g. multi-layer insulation) is added between the warm wall of the chamber and the nitrogen shield panels or shrouds. Results by analysis of improving radiation shielding are also shown in Table 2.

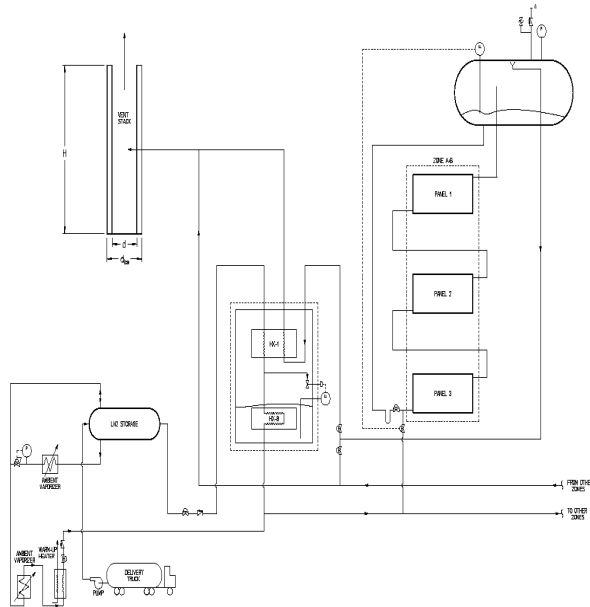


Figure5. Schematic flow diagram of the thermo siphon system, Option 2A

Thermal and hydraulic analysis of the thermo siphon design

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 existing system, the shear 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.

A thermal-hydraulic analysis was performed for the natural circulation option to validate the conversion of the current forced flow system to a thermo siphon design. Ch-A is divided into different zones based on the existing physical design. Table 3 shows the heat load for each shroud zone around the chamber. In the thermal-hydraulic model, a certain flow quality is assumed at the end of the return leg to the phase separator. The mass flow can then be calculated using an energy balance, then the pressure drop in the thermo siphon loop can be directly calculated. The available pressure drop (created by the supply liquid to return fluid density at the phase separator) must be greater than the required pressure drop resulting from the flow in the loop for the natural circulation to start. The actual LN₂ flow circulated will naturally adjust to where the available pressure drop and actual pressure drop are equal.

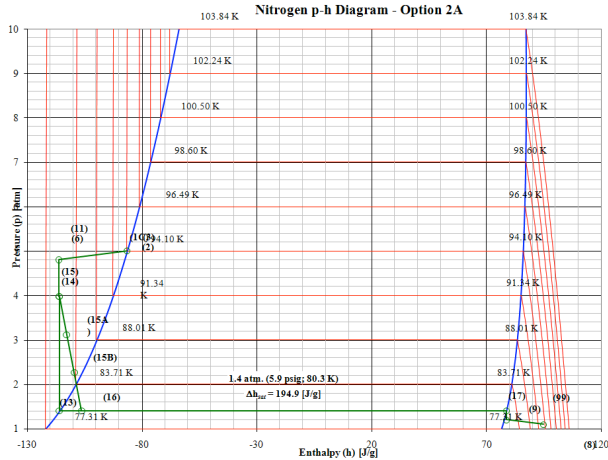


Figure 6. Nitrogen p-h Diagram, Option 2A

Two-Phase Study

Figure 7 shows the required pressure drop and the available pressure drop for various assumed qualities in the flow loop for Quad-1. Table 3 summarizes the results of the pressure drop analysis for two cases. The first case is for an assumed quality of 5%, and the second case is for an assumed quality of 10%. These two cases illustrate the effect of quality on the percent available pressure drop used for the flow circulation. In 5% quality case for Zone A, 39.1% of the available pressure drop is used for flow circulation (i.e. there is 60.9% pressure drop margin) and only 13.7% (i.e. 86.3% pressure drop margin) for the 10% quality case. The available pressure drop margin increases with the quality. This is important for an understanding of the thermo siphon system operation. Every zone will operate as an independent thermo siphon system, each with its own flow quality at the end of the return leg that depends on the heat load that zone experiences and balances with the hydraulic pressure drop resulting from the total flow in that zone. According to the analysis, the minimum flow quality of each zone is estimated to be between 3% to 6%. This is shown in Table 4 for an assumed quality, with the associated available pressure drop, the required pressure drop and the resulting recirculation flow.

The available pressure drop and required pressure drop are plotted against the flow quality for the zones in quadrant 1. In this case, the circuit will operate with an exit quality where the two curves intersect (i.e., ~3.5% quality).

		Opt-0	Opt-4A	Opt-0 W/ MLI Opt-0.1	Opt-4A W/MLI Opt-4A.1
Chamber heat transfer	kW	176.0	176.0	117.3	117.3
Supply Transfer lines	kW	14.5	9.0	14.5	9.0
Return Transfer lines	kW	14.5	2.0	14.5	2.0
Ln2_Valves	kW	5.0	1.0	5.0	1.0
Ln2_connections	kW	1.0	1.0	1.0	1.0
Ln2_Pump	kW	36.6	0.0	36.6	0.0
Ln2_Heplant	kW	5.0	10.0	5.0	10.0
Phase Separator	kW	2	1	2	1
Estimated loads	kW	254.6	200.0	195.9	141.3
Supply P	atm	5	5	5	5
Supply T	K	94	94	94	94
Ln2_Supply Enthalpy	J/g	-85.7	-85.7	-85.7	-85.7
Return P	atm	2.2	1	2.2	1
Return T	K	84.75	93	84.75	93
Ln2_Return Enthalpy	J/g	82.3	94.2	82.3	94.2
Dh	J/g	168	179.9	168	179.9
Required Ln2 Flow rate	g/s	1516	1112	1166	786
	gpm	33.2	24.4	25.6	17.2
	gpd	47,850	35,100	36,824	24,804
Savings compared to Opt-0	gpd	-	12,749	11,025	23,045
	%	-	26.6	23.0	48.2
Option-0.1 (New Sielding effect reduces the chamber heat load by 1/3)					

Table2. Liquid nitrogen consumption comparison

Quadrants	QUAD-1		QUAD-2		QUAD-3		QUAD-4		Main Door
Zones	A	B	H-K	F-G	LF	E-ML	C	D	J
Total Load/QUAD (kW)	34.8		56.3		33.4		42.7		11
Load/Zone (kW)	17.4	17.4	19.1	37.2	11	22.4	18.3	24.4	11
Min. Return Quality	4%	4%	4%	6%	3%	4%	5%		3%
Recir. Flow /zone (g/s)	2211	2211	2426	3437	1863	2846	4340		1863
Make Up Flow/QUAD (g/s)	177		286		170		217		56
Total dp Drop (psi)	2.8	2.8	3.5	5.9	0.9	2.7	7.2		1.3
Total Dp Available (psi)	5.3	5.3	6.3	8.0	3.7	5.5	8.1		3.7
Dp Margin (psi)	2.5	2.5	2.8	2.1	2.8	2.8	0.9		2.4
Dp-Required/Avail (%)	53	53	56	74	24	49	89		36
Dp-Margin/Avail (%)	47	47	44	26	76	51	11		64

Table 4. Summary results of Ch-A thermo siphon analysis

Figure 8 shows the maximum operating temperature in the LN₂ shields as a function of the flow quality for the case of the existing system (forced flow of sub cooled liquid; quality is 0) and for the case of the thermo siphon system. There is a net decrease in the shield operating temperature for the case of the thermo siphon system. This is due to the fact that the maximum operating pressure in the shields has been reduced from the present 9 atm to about 4 atm.

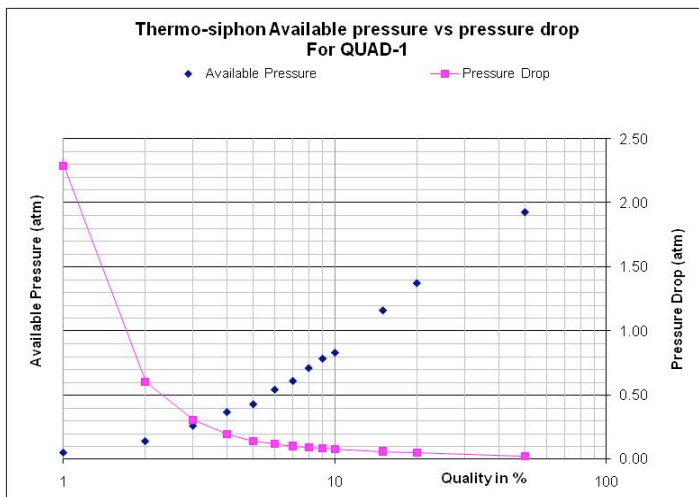


Figure7. Driving and required pressure drops vs. fluid quality

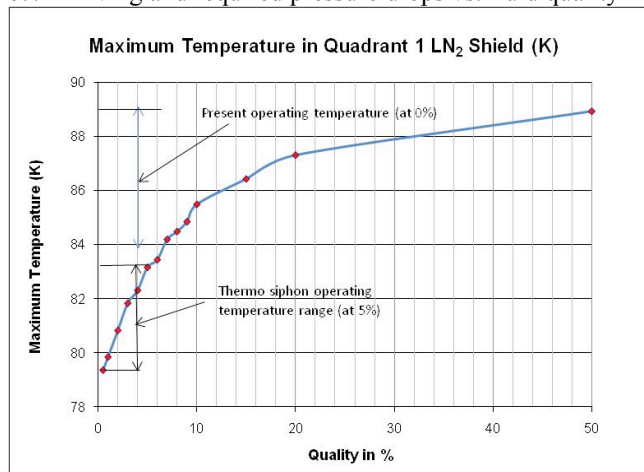


Figure8. Comparison of Steady State Operating Temperatures

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 with good efficiency over a wide temperature range. The anticipated load at 20K was between 8 kW and 12 kW. This the major design requirements from the program were hard to define at the time of project, but the driving requirements were the following:

1. Flexible performance at steady state
2. Tight thermal stability at steady state

Many other requirements were desired, and ended up being satisfied. These were:

1. Maximum power for cooldown/transient heat removal
2. Temperature control throughout full range

The refrigeration project was successfully managed at JSC using a 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 procurments and implemented the system.

To meet the requirements of the program as well as use the lessons learned and best practices of 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 before the actual cool-down of the chamber when the turbines are started.
- A cold gaseous nitrogen supply line reduces the LN2 consumption.

The Process Flow Diagram in **FIGURE 1** shows a simplified process arrangement. Warm high pressure helium enters the Coldbox and is divided into two streams that are being cooled down by the low pressure return flow and the nitrogen vapor respectively. Connected to one stream again the high pressure helium is cooled down to 80K in the nitrogen evaporator before it passes one of the two parallel adsorbers. Being further cooled down in the subsequent heat exchangers the helium is expanded in one or two turbines, depending on the temperature range and 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 details of the JSC refrigerator have been presented, with the key process of the steady state operating on the Ganni Floating Pressure Cycle. This process is well described in [find the dang papers] is a useful control strategy to provide this flexibility and energy saving potential. The implementation of the floating pressure theory to the existing 3.5kW system at NASA, JSC and the resulting gains are presented in [find and list paper, don’t rewrite].

The process control of the cold box is based on the Ganni floating pressure cycle philosophy (simplified schematic: **FIGURE 2**). As the floating pressure process is 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 discharge pressure is constrained by the design of the oil removal system and the maximum by the system design pressure (i.e., the pressure rating of the compressor and components downstream of the compressor discharge). Additionally, there may be other compressor constraints, such as preventing the suction from becoming sub-atmospheric (e.g., for rotary screw compressor designs using a suction shaft seal). Turbine constraints such as maximum tip speed and bearing capacity are normally handled by the local

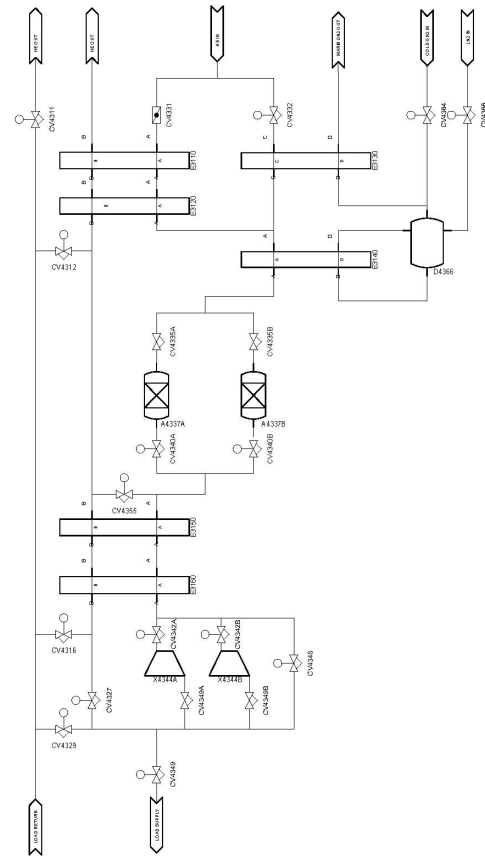


FIGURE 1: Process Flow Diagram

turbine control elements (i.e., inlet and brake valves). These are set so as to allow the widest possible operational envelope for the turbine. The Floating Pressure process typically utilizes two control elements to 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 a sub-atmospheric suction condition. As such it is normally closed, except under greatly reduced loads (i.e., less than approximately 50% of the maximum load) or in cases of manual intervention (e.g., such as required in a single turbine operation at 100 K for maximum capacity due to a turbine pressure ratio limitation). 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 so that the refrigeration capacity matches the actual heat load.

Liquid nitrogen (LN) is used for pre-cooling the high pressure helium stream down to 80 K. The LN pre-cooler implements nitrogen phase-separation using a thermo-siphon and directs the total high pressure helium flow through the latent nitrogen heat exchanger section. The LN supply maintains a pre-determined liquid level set-point in the phase-separator vessel (i.e., the ‘LN pot’). The usage of the LN is regulated by the high-pressure helium bypass between the large 300-80K helium-helium heat exchanger and the smaller 300-80K helium-nitrogen vapor heat exchanger. This valve uses the warm-end helium-helium stream temperature difference as the primary process variable to affect minimum LN usage. Cascade control is implemented on this valve to prevent the warm-end helium-nitrogen vapor stream temperature difference from becoming too extreme (say, a 240 K nitrogen vent temperature).

The system is designed to meet the needs of flexible load (both in meeting the actual load and the required operational temperature for the experiment) with good efficiencies. However, it is important for the supplier of cryogenic plants to receive as much information as possible in the early phases of a project in order to design the process and particularly the expansion turbines to achieve optimal results in the most relevant load cases. In addition the floating pressure philosophy is expected to provide improved temperature stability and the reliability as proven in other systems operating under this principle, and these are of critical importance to this system.

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 had to be fabricated at shops around the country, assembled within the facility to sections small enough fit, with final assembly integrated with the installation.

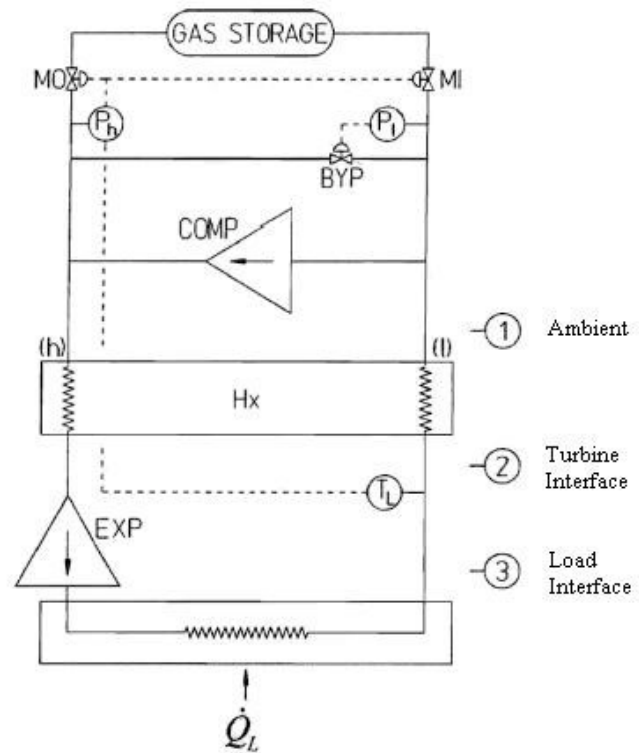
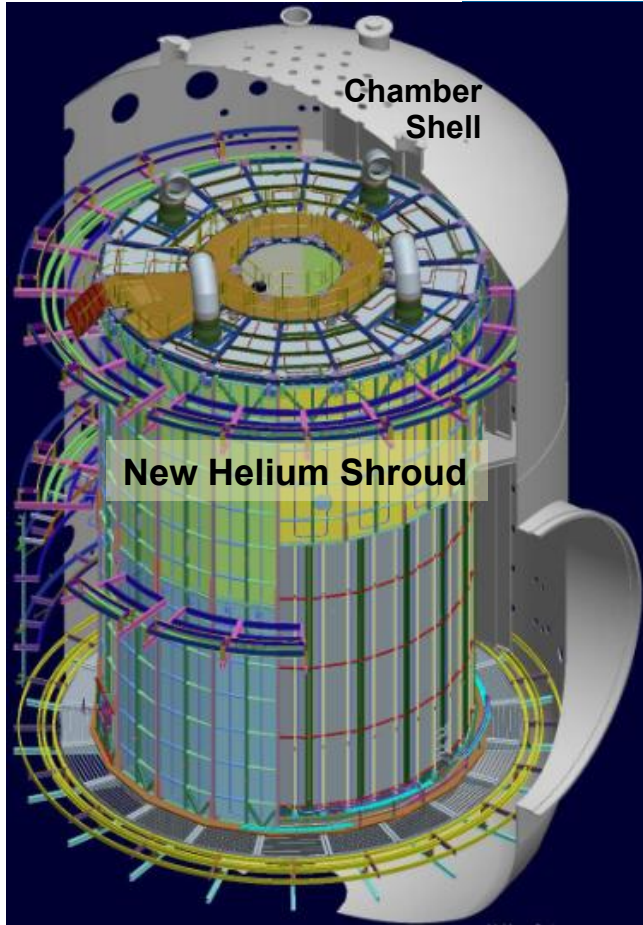
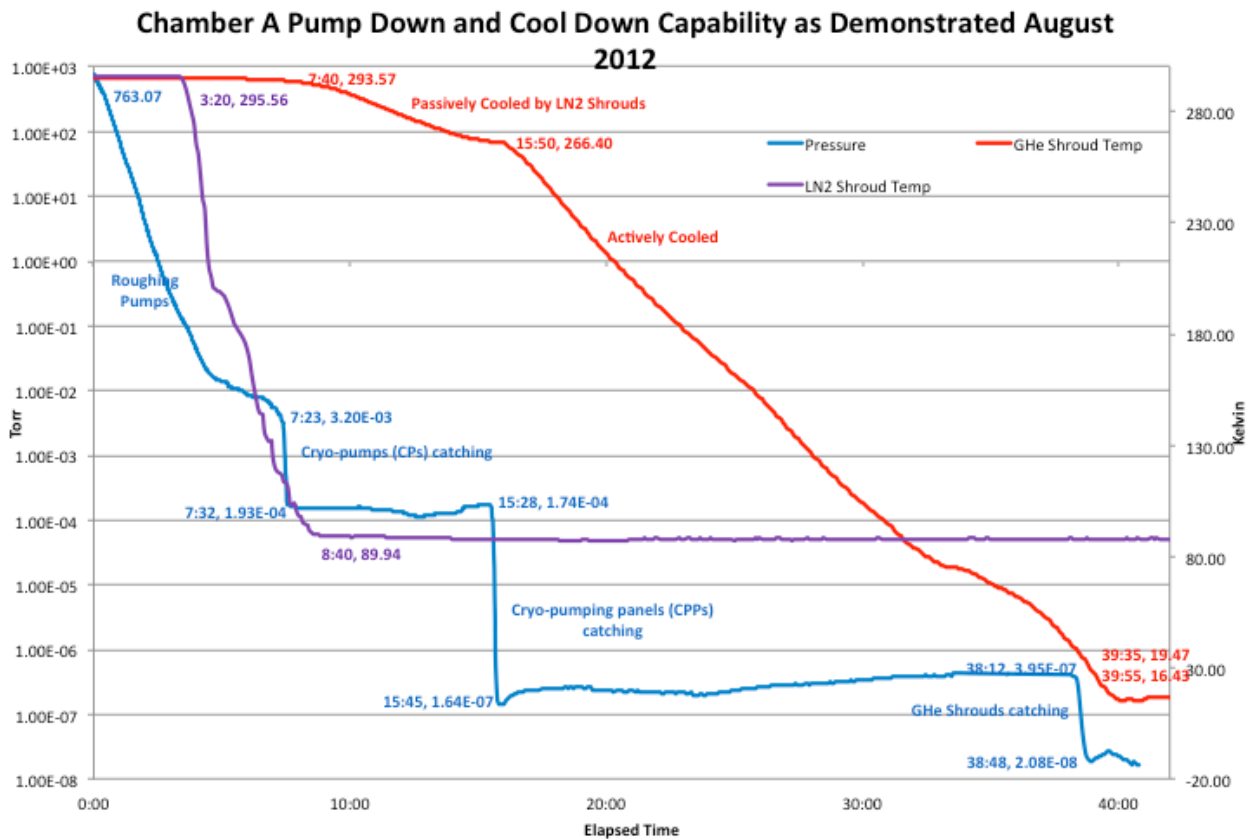


FIGURE 2: Floating pressure control schematic

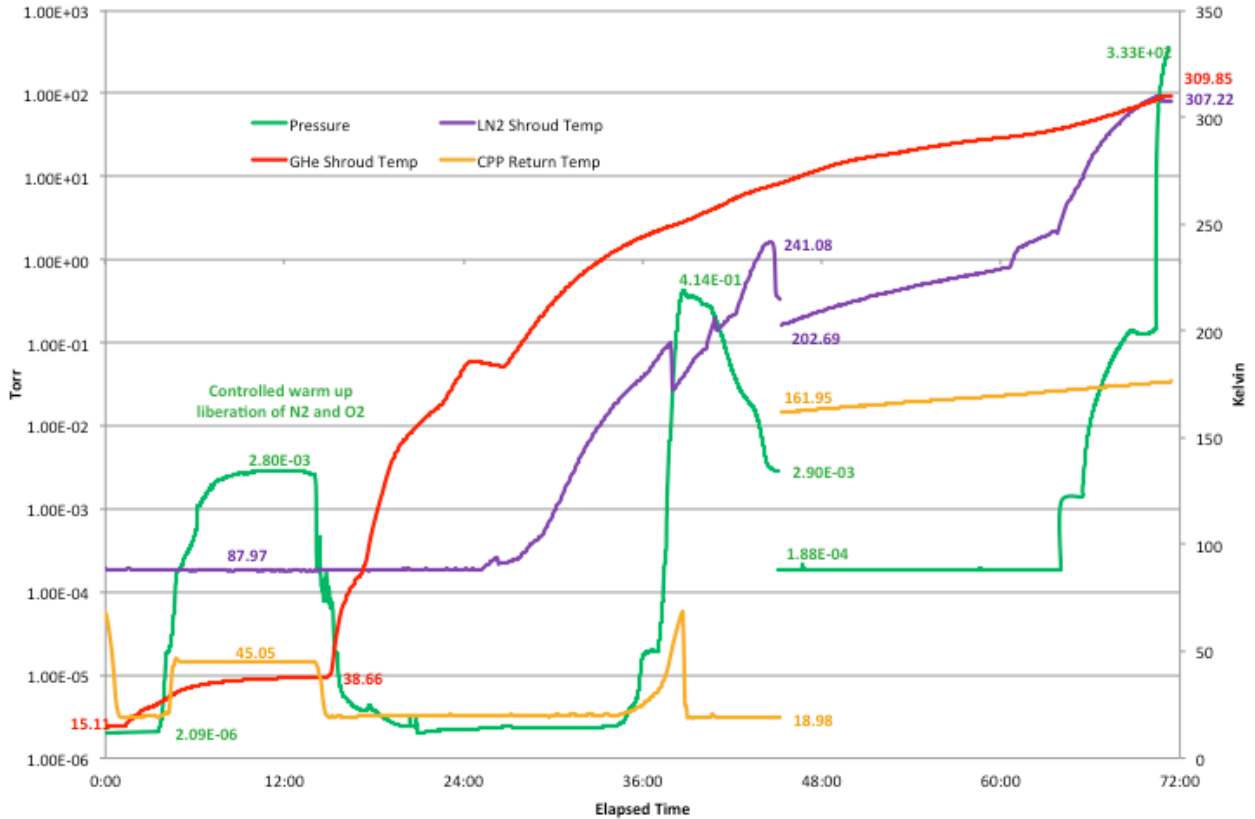


VI. Function Test and Initial Results

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 a first run of the systems and chamber to see if the major systems were performing, an initial chamber leak test, and the first operations of the liquid nitrogen thermal siphon system. The high vacuum system was able to be operated and tested against its valves to verify general performance, and the helium system was tested in a closed loop to test 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 the 18 angel valves cuts and re-welded, had the rotating floor removed and replaced had some gross leaks as expected, but the cuts on and welds on the chamber had no indication of leakage. The high vacuum system worked to get the chamber in the 2×10^{-4} Torr range with a leak rate of about 100 T-l/minute(?). The high vacuum system successfully removed helium purposefully backfilled in the chamber. The helium refrigerator went through performance commissioning prior to the chamber test. During that time we proved the refrigerator 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 keep the shroud at a temperature of around 13 K.



Chamber A Warmup and Repress Capability as Demonstrated August 2012



VII. 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 highbay. 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 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 \$0.44? (2012) per gallon for LN₂ with an increase of 10% per year thereafter for the foreseeable future. The thermodynamic change to natural flow saves ~24,000 gallons/day or a cost of \$10,560 per day in FY12 dollars or about \$950,000 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. There is 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 refrigeration power to input power is highly efficient, saving electrical usage and hardware wear and tear.

The new controls and the emergency power systems worked great. With a full building outage there was no loss of the LN₂ 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.

Acknowledgments

This work is a co-operation of NASA JSC, Jacobs Engineering, Hamilton Sundstrand, Jefferson Lab, Linde Cryogenics, Division of Linde Process Plants, Inc. and Linde Kryotechnik AG. We thank all of the many people who are contributing to the success of this project.

References

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1. Ganni, V., “Optimal Design and Operation of Helium Refrigeration Systems”, *to be published in PAC09 Proc.*, Vancouver, British Columbia, Canada, May4-8, 2009. .
2. Ganni, V., Knudsen, P., “Optimal Design and Operation of Helium Refrigeration Systems Using the Ganni Cycle”, *to be published in CEC-ICMC Proc.*, Tucson, AZ, June 2009.
3. Homan, J., et al., “Floating Pressure Conversion and Equipment Upgrades of Two 3.5kW 20-K Helium Refrigerators”, *to be published in CEC-ICMC Proc.*, Tucson, AZ, June 2009.
4. JACOBS., “Statement of Work and Technical Specification for a 12.5 kW Helium Refrigeration Cold Box (CBX3) System”
5. V. Ganni, et al. “Design, Fabrication, Commissioning and Testing of a 250 g/sec, 2-K Helium Cold Compressor System”, Invited presentation at CEC/ICMC Conference, July 16-20, 2001 at Madison, WI.

Periodicals

¹Vatistas, G. H., Lin, S., and Kwok, C. K., “Reverse Flow Radius in Vortex Chambers,” *AIAA Journal*, Vol. 24, No. 11, 1986, pp. 1872, 1873.

²Dornheim, M. A., “Planetary Flight Surge Faces Budget Realities,” *Aviation Week and Space Technology*, Vol. 145, No. 24, 9 Dec. 1996, pp. 44-46.

³Terster, W., “NASA Considers Switch to Delta 2,” *Space News*, Vol. 8, No. 2, 13-19 Jan. 1997, pp., 1, 18.

All of the preceding information is required. The journal issue number (“No. 11” in Ref. 1) is preferred, but the month (Nov.) can be substituted if the issue number is not available. Use the complete date for daily and weekly publications. Transactions follow the same style as other journals; if punctuation is necessary, use a colon to separate the transactions title from the journal title.

Books

⁴Peyret, R., and Taylor, T. D., *Computational Methods in Fluid Flow*, 2nd ed., Springer-Verlag, New York, 1983, Chaps. 7, 14.

⁵Oates, G. C. (ed.), *Aerothermodynamics of Gas Turbine and Rocket Propulsion*, AIAA Education Series, AIAA, New York, 1984, pp. 19, 136.

⁶Volpe, R., “Techniques for Collision Prevention, Impact Stability, and Force Control by Space Manipulators,” *Teleoperation and Robotics in Space*, edited by S. B. Skaar and C. F. Ruoff, Progress in Astronautics and Aeronautics, AIAA, Washington, DC, 1994, pp. 175-212.

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Proceedings

⁷Thompson, C. M., “Spacecraft Thermal Control, Design, and Operation,” *AIAA Guidance, Navigation, and Control Conference*, CP849, Vol. 1, AIAA, Washington, DC, 1989, pp. 103-115

⁸Chi, Y., (ed.), *Fluid Mechanics Proceedings*, SP-255, NASA, 1993.

⁹Morris, J. D. “Convective Heat Transfer in Radially Rotating Ducts,” *Proceedings of the Annual Heat Transfer Conference*, edited by B. Corbell, Vol. 1, Inst. Of Mechanical Engineering, New York, 1992, pp. 227-234.

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Reports, Theses, and Individual Papers

¹⁰Chapman, G. T., and Tobak, M., "Nonlinear Problems in Flight Dynamics," NASA TM-85940, 1984.

¹¹Steger, J. L., Jr., Nietubicz, C. J., and Heavey, J. E., "A General Curvilinear Grid Generation Program for Projectile Configurations," U.S. Army Ballistic Research Lab., Rept. ARBRL-MR03142, Aberdeen Proving Ground, MD, Oct. 1981.

¹²Tseng, K., "Nonlinear Green's Function Method for Transonic Potential Flow," Ph.D. Dissertation, Aeronautics and Astronautics Dept., Boston Univ., Cambridge, MA, 1983.

Government agency reports do not require locations. For reports such as NASA TM-85940, neither insert nor delete dashes; leave them as provided by the author. Place of publication *should* be given, although it is not mandatory, for military and company reports. Always include a city and state for universities. Papers need only the name of the sponsor; neither the sponsor's location nor the conference name and location are required. *Do not confuse proceedings references with conference papers.*

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¹³Richard, J. C., and Fralick, G. C., "Use of Drag Probe in Supersonic Flow," *AIAA Meeting Papers on Disc* [CD-ROM], Vol. 1, No. 2, AIAA, Reston, VA, 1996.

¹⁴Atkins, C. P., and Scantelbury, J. D., "The Activity Coefficient of Sodium Chloride in a Simulated Pore Solution Environment," *Journal of Corrosion Science and Engineering* [online journal], Vol. 1, No. 1, Paper 2, URL: <http://www.cp.umist.ac.uk/JCSE/vol1/vol1.html> [cited 13 April 1998].

¹⁵Vickers, A., "10-110 mm/hr Hypodermic Gravity Design A," *Rainfall Simulation Database* [online database], URL: <http://www.geog.le.ac.uk/bgrg/lab.htm> [cited 15 March 1998].

Always include the citation date for online references. Break Web site addresses after punctuation, and do not hyphenate at line breaks.

Computer Software

¹⁶TAPP, Thermochemical and Physical Properties, Software Package, Ver. 1.0, E. S. Microware, Hamilton, OH, 1992.

Include a version number and the company name and location of software packages.

Patents

Patents appear infrequently. Be sure to include the patent number and date.

¹⁷Scherrer, R., Overholster, D., and Watson, K., Lockheed Corp., Burbank, CA, U.S. Patent Application for a "Vehicle," Docket No. P-01-1532, filed 11 Feb. 1979.

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