COMMISSIONING OF THE LIQUID NITROGEN THERMO SIPHON SYSTEM FOR NASA-JSC CHAMBER A

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Abstract. NASA's Space Environment Simulation Laboratory's (SESL) Chamber A, located at the Johnson Space Center in Houston Texas has recently implemented major enhancements of its cryogenic and vacuum systems. The new liquid nitrogen (LN) thermo-siphon system was successfully commissioned in August of 2012. Chamber A, which has 20 K helium cryo-panels (or "shrouds") which are shielded by 80 K nitrogen shrouds, is capable of simulating a deep space environment necessary to perform ground testing of NASA's James Webb Space Telescope (JWST). Chamber A's previous system used forced flow LN cooling with centrifugal pumps, requiring 220,000 liters of LN to cool-down and consuming 180,000 liters per day of LN in steady operation. The LN system did not have the reliability required to meet the long duration test of the JWST, and the cost estimate provided in the initial approach to NASA-JSC by the sub-contractor for refurbishment of the system to meet the reliability goals was prohibitive. At NASA-JSC's request, the JLab Cryogenics Group provided alternative options in 2007, including a thermo-siphon, or natural flow system. This system, eliminated the need for pumps and used one tenth of the original control valves, relief valves, and burst disks. After the thermo-siphon approach was selected, JLab provided technical assistance in the process design, mechanical design, component specification development and commissioning oversight, while the installation and commissioning operations of the system was overseen by the Jacobs Technology/ESC group at JSC. The preliminary commissioning data indicate lower shroud temperatures, 68,000 liters to cool-down and less than 91,000 liters per day consumed in steady operation. All of the performance capabilities have exceeded the design goals. This paper will outline the comparison between the original system and the predicted results of the selected design option, and the commissioning results of thermo-siphon system.

Keywords: Nitrogen, cycles, refrigeration, natural flow, gravity flow, thermo siphon
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INTRODUCTION

NASA JSC's Chamber A was designed and built to test the Apollo Service and Command Module through its thermal extremes on its round-trip to the moon. Liquid nitrogen (LN) shrouds supplied by a forced flow (pumped) process simulated the cold temperature experienced by the space vehicle. The chamber has also been used for many other tests where the LN environment could provide a Low Earth Orbit (LEO) thermal conditioning for fairly short duration testing (less than two weeks). In 2006, the chamber was selected to test the James Webb Space Telescope (JWST), described in reference [1]. At that time it was determined that the original forced flow system was un-reliable for the testing durations require by the JWST program. At the request of NASA JSC, a review of the system was performed by the cryogenics department of Jefferson Lab after the project cost to use the original process and refurbish and upgrade the original equipment proved to be prohibitive. Several options were proposed, and the thermo siphon was clearly the best choice from a total cost and performance basis. The design and technical reasoning was detailed in a previously presented paper [2]. In summary, the thermo siphon design reduced the number of valves and safety devices by more than 80%, reduced LN consumption, and did not require electrical power other than controls, which were easily put on an un-interruptible power supply (UPS).

Project Planning

The low reliability, complexity, lack of stability and refurbishment cost of the originally proposed project were the major concerns that prompted NASA JSC to request the JLab technical advice for the LN system. Due to the large expenses of testing, the cool-down and warm-up time periods for the chamber panels and test articles needed to be as short as possible and the system needed to be extremely reliable.

From previous demonstrated experience [3], the JLab cryogenics group knew that the thermo syphon process could provide these requirements in a very efficient, reliable and cost effective manner for this application. As requested by NASA JSC, JLab designed the process, selected all the major components to be used in the system and divided the system into sub-systems for competitive procurement. Instead of a turnkey approach, JLab developed the detailed specifications and designs for each sub-system based on cost effective industrial practices.

Procurement of the Sub Systems

A LN sub-cooling/recovery cold-box was procured from PHPK in Ohio. Five 240-gallon phase separators were procured from EDEN Engineering, also in Ohio. Ambient vaporizers, provided by CRYOQUIP in California, replaced a steam vaporizer used to build up system pressure and to provide ambient GN. The piping, a combination of vacuum jacketed (VJ), insulated, and bare piping required to interface between the Chamber-A and the LN tank farm was provided by Chart Industries. A new steam trim heater was provided by CTS to heat the GN used to warm up the shrouds after test or for chamber bakeout. The specifications for the process, component and equipment designs, valves, instrumentation and controls, control philosophy and the component lay out were all provided to a build to print detail level by JLab for each sub-system including the field piping. NASA, JLab and the Jacobs Engineers conducted all the necessary design and fabrication reviews and over saw the production of the sub-systems at various industrial partners' locations.

Installation, Commissioning and Testing

Jacobs Engineering, NASA JSC's Engineering and Science prime contractor, provided the procurement contract support, field coordination of the sub-systems installation, and the integration of the total system in accordance with JLab technical direction. JLab provided commissioning test planning, direction and oversight to the NASA contractors and to the equipment sub-system vendors.

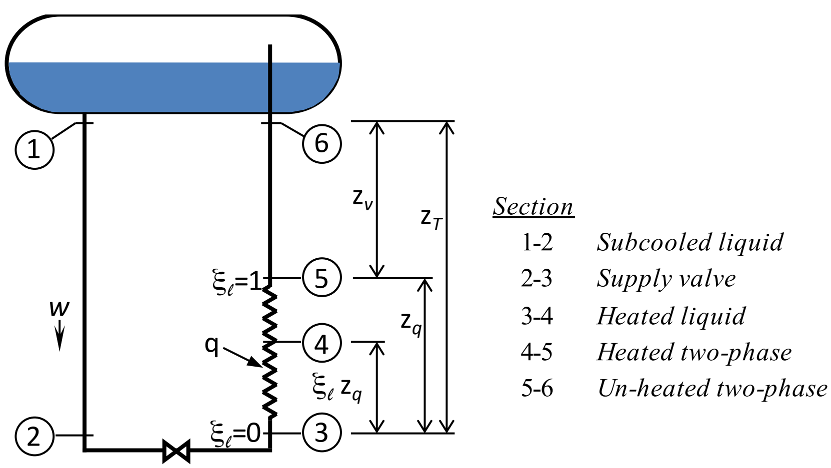

FIGURE 1. Diagram of simplified thermo siphon model

SIMPLIFIED THERMODYNAMIC ANALYSIS

A previous paper [2] presented and compared the thermo-hydraulic process analysis of the original forced flow system to the proposed thermo siphon design. The following simplified analysis, shown in Figure 1, provides a simpler analytical method to gain additional insight in the thermo siphon system design, commissioning and operation. This analysis provides the pressure potential ($p_2 - p_3$) available to support the actual pressure drop through the thermo siphon flow circuit for each assumed exit quality (x_6). The dewar pressure ($p_1 = p_6$), exit quality (x_6), total height (z_T) and un-heated two-phase height (z_v) are specified. Only the effect of gravity and heat input (in the heat section) are included. However, pseudo-efficiencies can be applied to correct for actual pressure loss due to single and two-phase flow.

Table 1 and Figure 2 depict the results for p_1 = 1.155 bar, z_T = 32 m, z_v = 0 m. Note that the specific volume, not the density, is an intensive thermo-dynamic quantity. As such, the exit two-phase density is, $\rho_6 = 1 / \left\{ \left(1 - x_6\right) / \rho_{l,6} + x_6 / \rho_{v,6} \right\}$ where $\rho_{l,6}$ and $\rho_{v,6}$ are the saturated liquid and vapor densities (at the dewar pressure, $p_1 = p_6$), respectively. We also note that the heat input per circulation mass flow rate $\left(\dot{m}/q\right)$ is proportional to the two-phase exit quality (x_6) and dewar liquid latent heat (λ); i.e., $q = x_6 \cdot \dot{m} \cdot \lambda$. So, for a given heat input and dewar pressure, the exit quality will decrease (i.e. there will be less gas in the two phase flow) inversely with increasing circulation mass flow. As seen from Figure 2, the driving pressure (difference) potential increases as the exit quality increases. Since the circulation mass flow will increase as the driving pressure potential increases, the system is self-regulating.

The success of the thermo siphon system operation strongly depends on the driving potential. Typically, it is preferred to have low quality (or very high liquid fraction) in the exit fluid to minimize flow disturbances (oscillations, vibrations) in the flow circuit. However, a low exit quality can also result in a large quantity of liquid circulation back into the phase separator (e.g., the dewar in Figure 1). As such it is important to properly size the phase separator for the anticipated circulation mass flow. Recognizing these issues and the huge pressure potential available, liquid recirculation balance valves, not typically needed in small systems, were provided as tuning mechanism to balance the exit quality and circulation flow by directly controlling the available pressure potential. These balancing valves allowed the phase separators to function as designed since without them there would be a very high circulation mass flow that can result in liquid carry over to the vent.

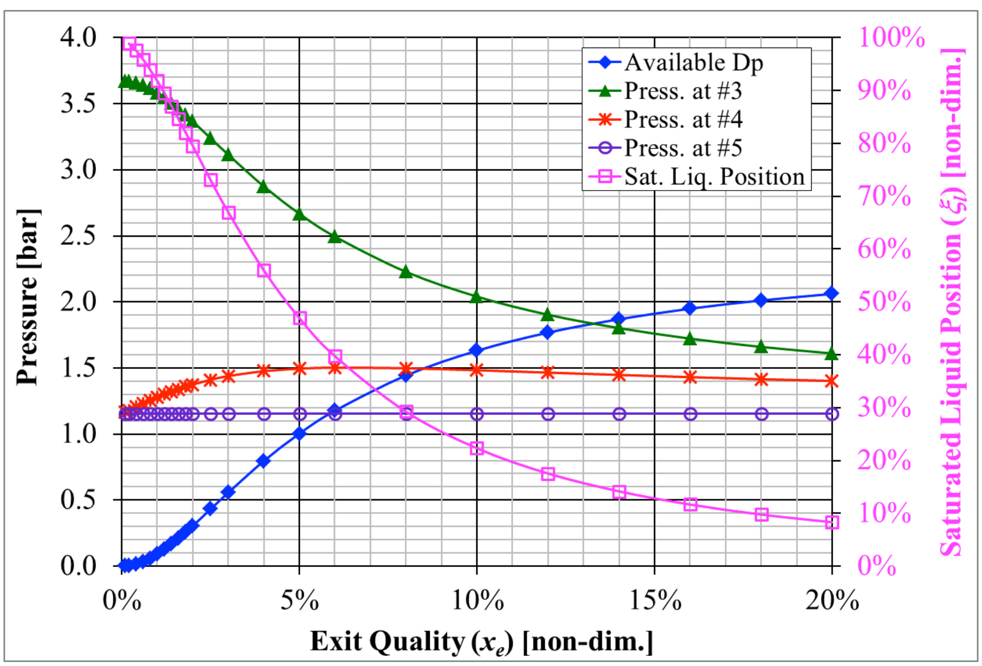

FIGURE 2. Simplified thermo siphon model results

TABLE 1. Available differential pressure vs. exit quality and exit density

Exit Quality (x_6) [-]	Two-Phase Return Density (ρ_6) [g/ℓ]	Supply Pressure at Bottom (p_2) [bar]	Available Differential Pressure (p_2 - p_3) [bar]
0.1%	695	3.62	0.00097
0.2%	614	3.62	0.00389
0.4%	498	3.62	0.0125
0.6%	418	3.62	0.0319
0.8%	361	3.62	0.0583
1.0%	317	3.62	0.0891
2.0%	198	3.62	0.305
4.0%	113	3.62	0.797
6.0%	78.9	3.62	1.18
8.0%	60.7	3.62	1.44
10.0%	49.3	3.62	1.63
14.0%	35.8	3.62	1.87
20.0%	25.4	3.62	2.06

REQUIRED MODES OF OPERATION FOR CHAMBER TESTING

The following are a required list of modes of operation for the LN system when operating the chamber:

a. Bake out: The 25 tons of LN aluminum panels are required to be warmed to > 45 ^{0}C while helium shrouds are heated to > 60 ^{0}C. This helps to clear (drive off) the contaminants from the panel surfaces to meet the chamber cleanliness requirements for housing the JWST optics.
b. Cool down: Bring the LN shrouds to steady state operating conditions at 80 K
c. Steady State Operation: The system needs to support long term 80 K operation in a reliable, stable and efficient way.
d. Drain: At the end of the test the LN needs to be drained quickly to minimize the time required for warm up.
e. Warm up: The system needs to be warmed up quickly to minimize the time required to access the test object.
f. Door and Scavenger panel operation: During 'drain' and 'warm-up' modes, the door panels and additional scavenger panels are maintained at 80 K to attract any impurities released during warm up so that the contaminants will move to these cold surfaces and not affect the JWST surfaces.

CHAMBER TEST RESULTS

In the summer of 2012, the major construction required to operate the chamber was completed, and a functional test of the new systems was performed. This was the first operation of the new LN thermo siphon system as well as the first operation of the chamber since 2005. Other systems that support chamber operations, such as vacuum pumps and the helium refrigeration systems could be operated independently, but it was not possible to test the thermo siphon system until the chamber was under vacuum. The chamber functional test was a tremendous success for NASA JSC, and the thermo siphon process performed very well. Table 2 summarizes the estimated and actual loads from the first test.

During the design phase, goals were set and analyzed for the different modes of operation. The new LN system performance exceeded all of the design goals and predicted performance; refer to Table 3. The overall LN and GN distribution is shown in Figures 3 and 4.

TABLE 2. Estimated loads and LN required flow.

		Original (Option-0)	Projected (Option-4A)	Test (Option-4A)
Chamber heat transfer	[kW]	176	176	89
Supply transfer lines	[kW]	15	9	5
Return transfer lines	[kW]	15	2	2
LN valves	[kW]	5	1	1
LN connections	[kW]	1	1	1
LN pump	[kW]	37	0	0
Phase separator	[kW]	2	1	1
LN helium plant	[kW]	5	10	10
Other loads (cryo-pumps etc.)	[kW]	0	5	5
Pressurization	[kW]	0	5	3
Estimated loads	[kW]	**256**	**210**	**117**
Supply pressure	[bar]	5.07	5.07	5.07
Supply temperature	[K]	94.1	94.1	94.1
LN supply enthalpy	[J/g]	-86.6	-86.6	-86.6
Return pressure	[bar]	2.23	1.01	1.01
Return temperature	[K]	84.7	93.1	93.1
LN return enthalpy	[J/g]	81.7	94.5	94.5
Enthalpy difference	[J/g]	168.3	181.1	181.1
Required LN flow rate	[g/s]	1521	1159	646
LN supply density	[g/ℓ]	722.7	722.7	722.7
Required LN volume flow rate	[m^3/day]	**182**	**139**	**77**
Savings compared to Option-0	[m^3/day]	N/A	**43**	**105**
	[%]	N/A	**24%**	**58%**

It is anticipated that the time to cool-down may be reduced even further with practice. In addition, the door and the scavenger panel were operated with LN circulation at 80 K independently while all the remaining chamber LN panels were drained of LN and warmed up to room temperature.

Lessons Learned

The following are some lessons learned during commissioning.

a. The overall heat load on the chamber has been reduced by approximately 50 kW due to the new radiant barrier on the old solar wall (100 m x 260 m) and by the removal of the drive shaft housing, as well as, other improvements

TABLE 3. Design goals vs. actual test

		Original	Goal (Predicted)	Actual
Average LN shroud bakeout temperature	[^{0}C]		> 45	70
LN zones to steady state from 300K	[hr]		16 (12)	9

LN required to cool-down [(§)]	[m^3]	220	(114)	68
LN steady state consumption	[m^3/day]	180	(130)	91

[(§)] 23 metric tons of aluminum

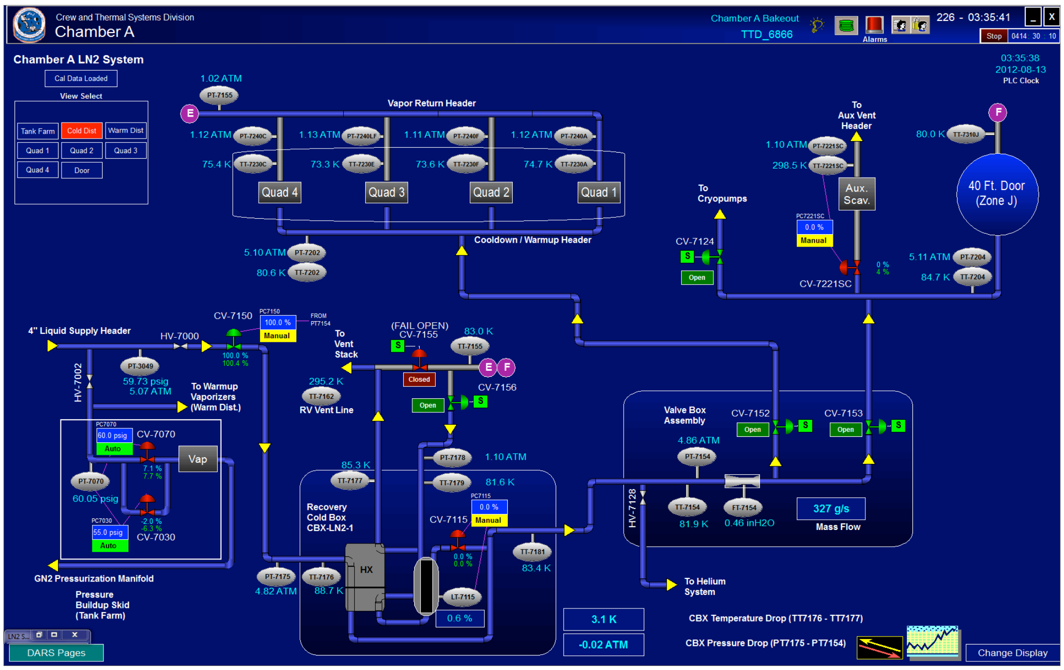

FIGURE 3. Overall LN Distribution

b. The pressure drop through panels was less than predicted. It was realized that the pressure drop from 1960's panels and piping is far less than assumed in the model. The reduced heat load and lower pressure drop in the circuits resulted in an exit quality of around 1% vs. the design point of 3 to 5%. Initially, this low exit quality resulted in extremely large LN circulation mass flow causing liquid to make it into the return gas return piping and vent stack. The recirculation balance valves were used to re-balance the system, reducing the available pressure potential and increasing the exit quality so that the phase separators could function as designed (without unnecessary LN usage by venting)

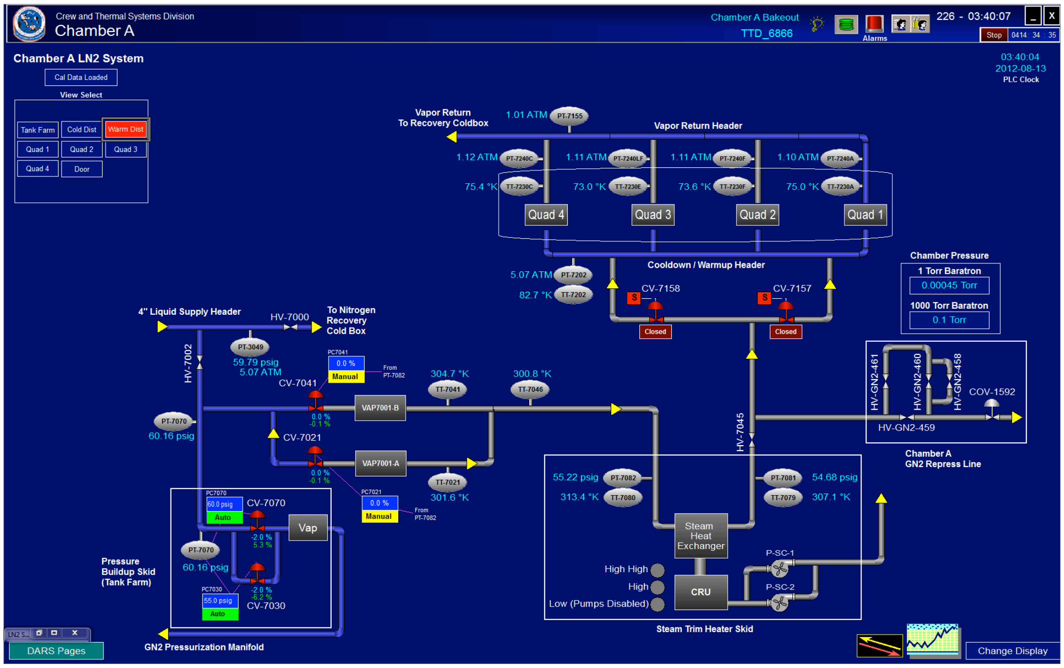

FIGURE 4. Overall GN Distribution

CONCLUSIONS

With the functional testing completed in August of 2012, NASA JSC successfully modified the original forced flow LN system for Chamber-A into a thermo siphon system. This system exceeded all the chamber test requirements and resulted in a more stable, reliable, and efficient system.

ACKNOWLEDGMENTS

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