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Liquid Oxygen Propellant Densification Production and Performance Test Results With a Large-Scale Flight-Weight Propellant Tank for the X33 RLV

Thomas M. Tomsik and Michael L. Meyer
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May 2010

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i. ABSTRACT

The NASA Glenn Research Center (GRC) has led the nation's effort in the development of practical densified cryogenic propellants for aerospace and launch vehicle applications. The technology of sub-cooling cryogenic propellants below their normal boiling point (NBP), and thereby making the fluid denser, is one of the key process technologies necessary to meet the challenge of single-stage-to-orbit (SSTO) and second-generation reusable launch vehicles (RLV). Densified propellants are critical to achieving lower launch costs because they enable additional cryogenic propellant to be packed into a given unit volume, thereby improving the performance of a launch vehicle, effectively reducing its overall size and dry weight. Density improvements of 8% greater for LH2 and 10% for LO2 are expected to substantially reduce the gross lift-off weight of a launch vehicle system, as studies project by up to 20 percent.

Glenn research engineers were formerly working on providing a method, hardware and critical test data for the continuous production of densified liquid hydrogen (LH2) and densified liquid oxygen (LO2) at a large scale. Both propellant densification production units were configured with a high-efficiency, sub-atmospheric boiling bath heat exchanger to cool the working fluid. A near triple-point liquid hydrogen boiling bath was used to condition and subcool hydrogen product down to 27 ^{o}R, and a nitrogen boiling bath at 117 ^{o}R to provide the heat sink to cool liquid oxygen down to 120 ^{o}R. Multistage high-speed centrifugal compressors, operating at cryogenic inlet conditions were used to maintain the ullage pressure in each heat exchanger bath below one atmosphere pressure. The LO2 propellant densification unit (PDU) that was constructed by GRC had a processing capacity of 30 lb_m/sec while the LH2 unit was designed to produce 8 lb/sec of high-density hydrogen. Both of the these larger cryogenic densification systems were 15:1 and 4:1 scaled-up versions, respectively, of a prototype 2.0 lb/sec LH2 densifier previously designed, built and tested at the GRC Plum Brook Station in 1996 [ref. 1, 2].

The purpose of this paper is to describe in-detail a test program that was initiated at the Glenn Research Center (GRC) involving the cryogenic densification of liquid oxygen (LO2). A large scale LO2 propellant densification ground support system (GSE) sized for the X-33 LO2 propellant tank, was designed, then fabricated and tested at the GRC. Multiple objectives of the test program included validation of LO2 production unit hardware and characterization of LO2 densifier performance at both design and transient conditions. First, GSE performance data is presented for an initial series of LO2 densifier screening and check-out tests using liquid nitrogen (LN2) as a surrogate fluid to be densified. The second series of test results described in this report is performance data collected during LO2 densifier operations and testing with liquid oxygen as the product fluid. Densifier experimental results will be summarized and compared against known design point values and predicted analytical conditions. Other key topical areas that this paper will address includes a general discussion of the thermodynamic model and process for super-cooling LO2 propellant, a description of the LO2 GSE system hardware, an explanation of the GRC South-Forty (S40) facility test-site and details of operational run procedures that were used during LO2 densifier testing.

Finally, one other very important facet of the overall test program that needs to be mentioned was that it was organized in collaboration with the Lockheed Martin Michoud Space Systems (LMMSS) group. A technology development plan was developed for the program with the objectives of investigating LO2 tank loading operations and testing the thermal stratification phenomenon inside of a flight-weight launch vehicle propellant tank. An overview of the LO2 X-33 tanking, de-tanking and loading tests with the 20,000 gallon Structural Test Article (STA) is reported on here.

In conclusion, the demonstration and testing of the LO2 propellant densification system, and its operational capability, was successfully completed at the GRC in December 2000. In excess of 200,000 gallons of densified LO2 at 120 ^{o}R was produced with the Propellant Densification Unit during the demonstration program. In tank thermal stratification conditions were also demonstrated during the densification of the STA propellant tank. These were milestone achievements in the field of cryogenic propellants that will allow subsequent private industry commercialization of a new technology having benefit to space applications involving potential future launch vehicle systems like VentureStar, Space-Liner 100, Kistler K1, Second Generation RLV and ARES V.

ii. LIST of FIGURES

ii. LIST of FIGURES (continued)

ii. LIST of FIGURES (continued)

ii. LIST of FIGURES (continued)

ii. LIST of FIGURES (continued)

iii. LIST of TABLES

iv. NOMENCLATURE

A	Area, ft^2
BHP	Brake horsepower
BN	Barber-Nichols, Inc. (pump and compressor manufacturer)
CATIA	Computer aided three-dimensional interactive application
CM	Cryo-Mach Corporation (pump manufacturer)
C_{m2}	Meridional fluid velocity, ft/sec
DLN2	Densified liquid nitrogen
DLO2	Densified liquid oxygen
FS	Full scale
GLOW	Gross lift-off weight, lb_m
GHe	Gaseous helium
GN2	Gaseous nitrogen
GO2	Gaseous oxygen
GRC	Glenn Research Center
GSE	Ground support equipment
h	Enthalpy, Btu/lb_m
H	Head, ft
Hg	Mercury
HP	Horsepower
Isp_v	Vacuum specific impulse, sec
KVA	Kilovolt-amperes
LH2	Liquid hydrogen
LMMSS	Lockheed Martin Michoud Space Systems
LN2	Liquid nitrogen
LOX, LO2	Liquid oxygen
LT	Level transducer
M	Mass, lb_m
MAWP	Maximum allowable working pressure, psi
MSFC	Marshall Space Flight Center
N	Speed, rpm
NBP	Normal boiling point
N_s	Specific speed, $N\, Q_v^{\,0.5} / H^{\,0.75}$
OC	Over-current
OD	Outside diameter
OEM	Original equipment manufacturer
P	Pressure, psia
PC	Personal computer
PID	Proportional, Integral, Derivative (controllers designed to automate the process)
PDT	Differential pressure transducer
PDU	Propellant densification unit
PLC	Programmable logic controller
PT	Pressure transducer
Q_e	Environmental heat transfer rate, Btu/sec

iv. NOMENCLATURE (continued)

Q_v	Volumetric flow rate, ft^3/sec
RCI	Reusable cryogenic insulation
RLV	Reusable launch vehicle
S40	South Forty Densification Test Facility at GRC
SCF	Standard cubic feet
SiD	Silicon diode
SLI	Sierra Lobo, Inc.
SOFI	Spray-on foam insulation
SS	Steady-state or stainless steel
SSTO	Single-stage-to-orbit
STA	Structural Test Article
t	Time, sec
T	Temperature, ^oR
TC	Thermocouple
TP	Triple point
TSP	Test Support Platform (T153 tool)
U	Internal energy, Btu/lb_m
U_2	Impeller tip speed, ft/sec
V	Volume, ft^3
VAC	Voltage alternating current
VFD	Variable frequency drive
VJ	Vacuum-jacketed
W	Mass flow rate, lb_m/sec

Greek symbols:

Δ	Difference or change
Ψ	Head coefficient
Φ	Flow coefficient
η	Efficiency
ρ	Density, lb_m/ft^3

Subscripts:

1	in
2	out

1. INTRODUCTION

1.1 Background

The propellant densification demonstration subproject under the X-33 and Advanced Space Transportation Programs was a NASA led Glenn Research Center effort primarily conducted in-house to validate densification technology at the X-33 scale. The densification units and project plan were originally established to be integrated with the X-33 launch facility at Edwards Air Force Base (**figure 1**) and to culminate in actual flight testing with densified propellants during the X-33 flight test series. During program changes, the X-33 densified propellant flight test was eliminated, but the densification effort was redirected to a ground demonstration test of a liquid oxygen densifier and fabrication and check-out of the hydrogen densifier. Glenn Research Center was ultimately selected to perform the liquid oxygen and liquid hydrogen propellant densification testing.

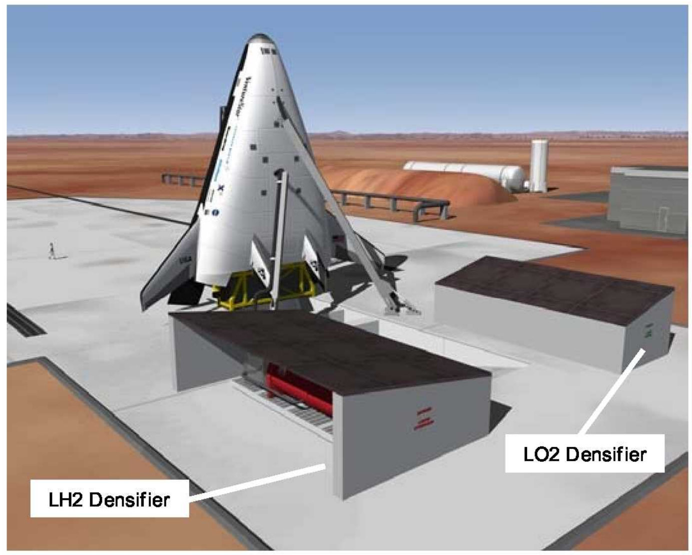


Figure 1. Propellant densification GSE integration concept with RLV.

The densification units were designed to subcool propellant in the X-33 propellant tanks within 2 hours to 27 °R for hydrogen and 120 °R for oxygen. The units were to be portable but large with a 65-ft long by 18-ft wide footprint and about a 12-ft height. They each included heat exchangers, compressors, pumps, a structural skid, electrical and instrumentation and controls as major subsystems. The liquid oxygen test set-up included LN2/LO2 supply dewars, vent stacks, safety and controls hardware, and a full-sized X-33 LO2 tank, all of which were located at the Glenn South Forty (S40) test area. A subsequent second-generation RLV program subproject was funded to test the "sister" hydrogen densifier with liquid nitrogen and a different propellant tank configuration in the same test area with much of the installation in common with the LO2 densifier. The total combined densification effort spanned over a 4 year schedule to allow completion of the designs, fabricate the units, build-up the S40 facility and execute the testing.

A liquid oxygen densification unit, shown in **figure 2**, was designed, built and tested in December 2000 at the NASA Glenn Research Center (GRC). Development of system requirements and preliminary design work began at GRC in September 1997. The X-33 scalable unit was designed to process subcooled liquid oxygen at a nominal rate of 30 lb_m/s down to an outlet temperature of 120 °R. A full-up steady state demonstration and performance verification test series was then conducted. Testing started in October 2000 and continued through December 2000. Upon completion of the GRC test matrix, a series of five thermal stratification tests with LO2 were run in collaboration with Lockheed Martin Michoud Space Systems (LMMSS) using the 20,000 gallon Structural Test Article (STA) LO2 propellant tank from the X-33 program. It becomes very important in terms of quantifying the propellant inventory by test through the verification of in-tank thermal stratification characteristics over a range of inlet recirculation flows as demonstrated by previous investigators [ref. 3, 4].

Figure 2. The Liquid Oxygen Propellant Densification Unit (PDU) in the final stages of check-out and assembly at the NASA GRC Hangar.

This report presents the results of LO2 Propellant Densification Unit (PDU) performance testing and thermal stratification tests obtained during the STA closed-loop recirculation and cryogenic tankage experiments conducted at the S40 test facility seen in **figure 3**. In general, test operational and performance goals with the 30 lb_m/sec LO2 densifier were successfully demonstrated with sustained production of densified LO2 at 120 ^oR. The achievement of the planned LO2 demonstration testing was identified as a "Level 1 Advanced Space Transportation Program milestone", and the design of the densifiers was given the first Access to Space Turning Goals Into Reality (TGIR) Award in 1998. Some of the difficulties and problems that were overcome during the LO2 PDU test demonstration included structural mounting of the X-33 LO2 STA tank on its support platform, rework of facility electrical deficiencies that occurred during original construction, funding gaps, and technical problems including hardware failures with LO2 pumps, GN2 compressor stages and control systems are described herein as lessons learned.

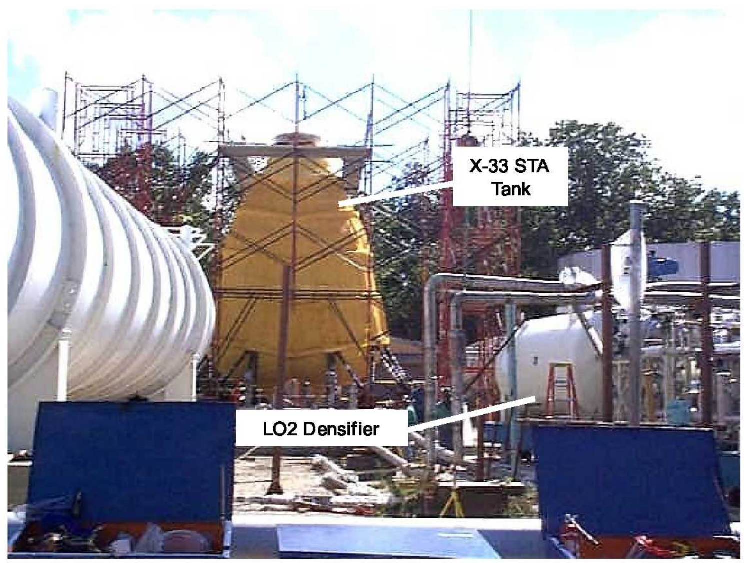


Figure 3. The LMMSS tank designated the Structural Test Article (STA) shown integrated with the densification unit at the GRC South Forty Test Facility.

1.2 Benefits of Densified Propellants

Propellant densification was identified as a critical enabling technology in the development of single-stage-to-orbit (SSTO) reusable launch vehicles (RLV). The densification of a cryogenic propellant through active sub-cooling allows approximately 8 % to 10 % more propellant mass to be stored in a given unit volume. This allows for a higher propellant mass fraction than would otherwise be possible with conventional normal boiling point (NBP) cryogenic propellants. In 1998, densified propellants were base-lined (**figure 4**) and considered an enabling technology for the Lockheed Martin RLV, designated the VentureStar as a result of the significant advantages to be derived from their use.

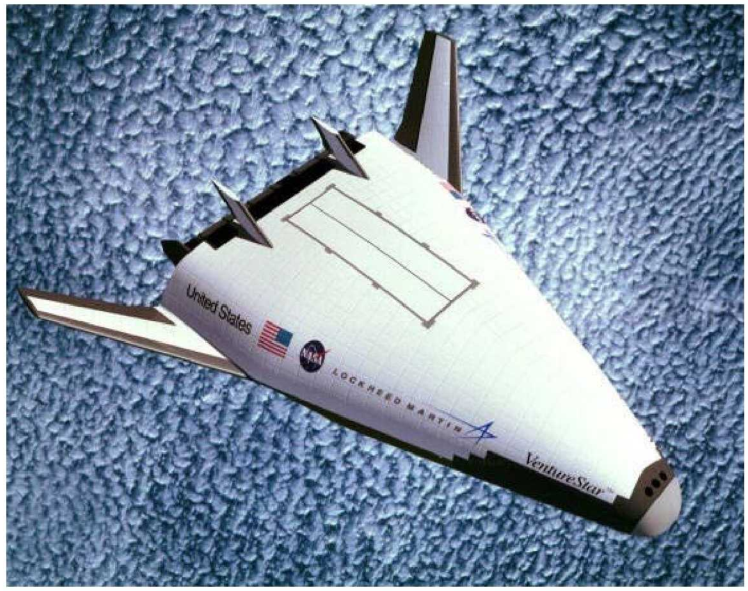


Figure 4. Propellant densification was base-lined for use on the Lockheed Martin reusable launch vehicle VentureStar.

The enormous benefits involved for using densified propellants not only contribute to vehicle weight reductions, reported to be on the order of 15 – 25 percent according to engineering trade studies [ref. 5, 6, 7 & 8], but densified propellants could also lower launch vehicle capital and operating costs by 11 percent or more and significantly increase mission payload capability for various launch vehicles and mission scenarios. **Figure 5** illustrates typical mission payload enhancements from several data sources, results of which indicate a range from 2 – 26 percent increase in payload capability [ref. 9].

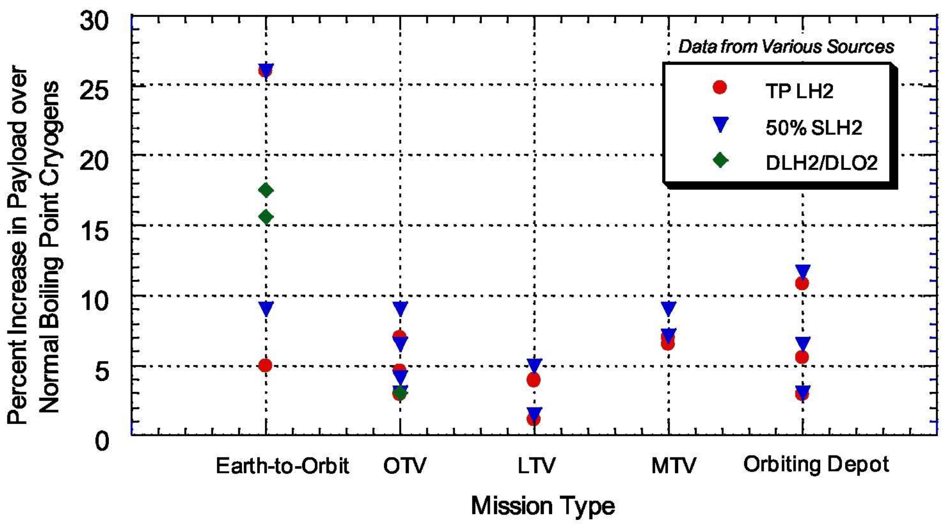


Figure 5. Propellant densification mission benefits include increased payload capability over NBP cryogenic bi-propellants.

In addition to the benefit of a smaller tank size and greater payload capability, other physical properties (**figure 6**) of subcooled and densified LO2/LH2 are improved as a function of temperature (T_{LO2}). Liquid oxygen at its NBP of 162.4 °R has a density of 71.2 lb/ft^3 and a vapor pressure of 14.7 psia. Subcooling LO2 from the NBP to 120 °R, the density is increased 9.7 percent giving a ρ_{LO2} of 78.1 lb/ft^3. At this reduced temperature there is a significant improvement due to its vapor pressure, which naturally is lowered to 0.50 psia. The benefit derived from a propellant with a lower vapor pressure allows the tank design pressure, or the MAWP, to be reduced accordingly, thereby permitting thinner walled tanks of less mass to be used on an RLV. Finally, lower vapor pressure results in a cryogenic fluid with inherently more stability that is safer to handle. This results from the fact that over-pressurization of a containment vessel becomes more difficult as it would take more time to absorb energy in comparison to a fluid at its NBP because of the additional sensible heat available that the subcooled fluid would absorb before it begins to boil. Lower vapor pressure reduces the potential for propellant vapor leaks as the absolute ΔP between tank and the environment is less for a pressurized vessel containing densified fluid.

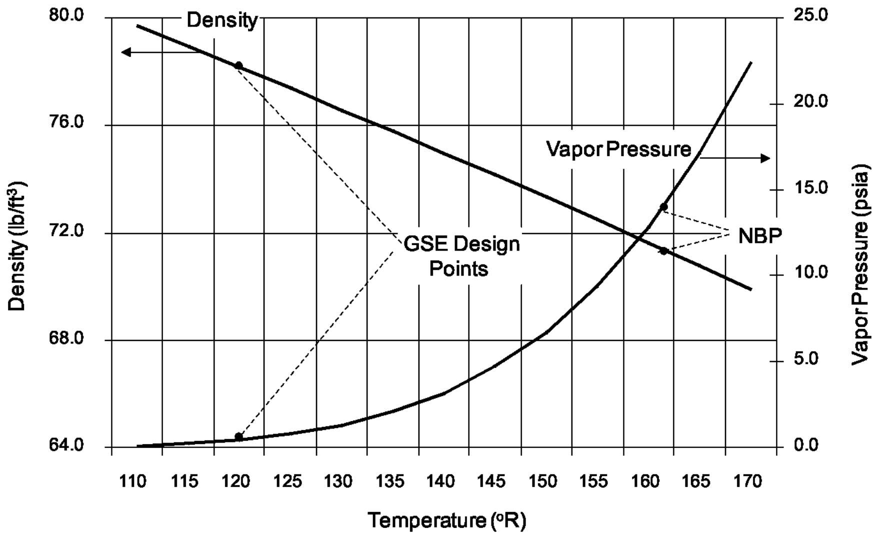


Figure 6. Liquid oxygen density and vapor pressure curves illustrates fluid property enhancement by super-cooling.

1.3 LO2 Densification GSE Design and Analysis

The densification of liquid oxygen is based on the well-characterized thermodynamic venting process [ref. 10, 11]. In this section, some fundamental equations for modeling the performance of the LO2 densification process are presented. The basic densification GSE unit itself, when integrated with an STA propellant tank as depicted in **figure 7**, consists of an LO2 recirculation pump, a pair of LN2-to- LO2 heat exchangers in series and a gaseous nitrogen (GN2) compressor. Assuming a pseudo-steady-state process and constant liquid volume inside of the STA tank, the LO2 volumetric mass balance around the propellant tank to be densified becomes

$$\frac{W_1^{LO2}}{\rho_1^{LO2}} = \frac{W_2^{LO2}}{\rho_2^{LO2}} \qquad (1)$$

Equation (1) is based on maintaining a constant fluid volume inside the tank, thus implying zero liquid level change, resulting in the inlet and outlet volumetric flows being equal $(Q_{v1} = Q_{v2})$. To elaborate the point, by specifying the inlet temperature (T_1^{LO2}) as a design requirement, the inlet fluid density (ρ_1^{LO2}) is established. Assuming ideal conditions, whereby the propellant tank is perfectly stratified, the outlet temperature will be at or near the saturation temperature at the tank operating pressure. Conversely though, the outlet temperature could also be the initial bulk temperature of the propellant at the start of the densification process. Either of these known boundary conditions establishes the outlet fluid density (ρ_2^{LO2}). Therefore, a priori knowledge of the recirculation flow rate, defined as the inlet mass flow (W_1^{LO2}) to STA along with inlet (ρ_1^{LO2}) and outlet fluid densities (ρ_2^{LO2}), the mass flow rate exiting the propellant tank (W_2^{LO2}) is easily determined with the above simplified identity.

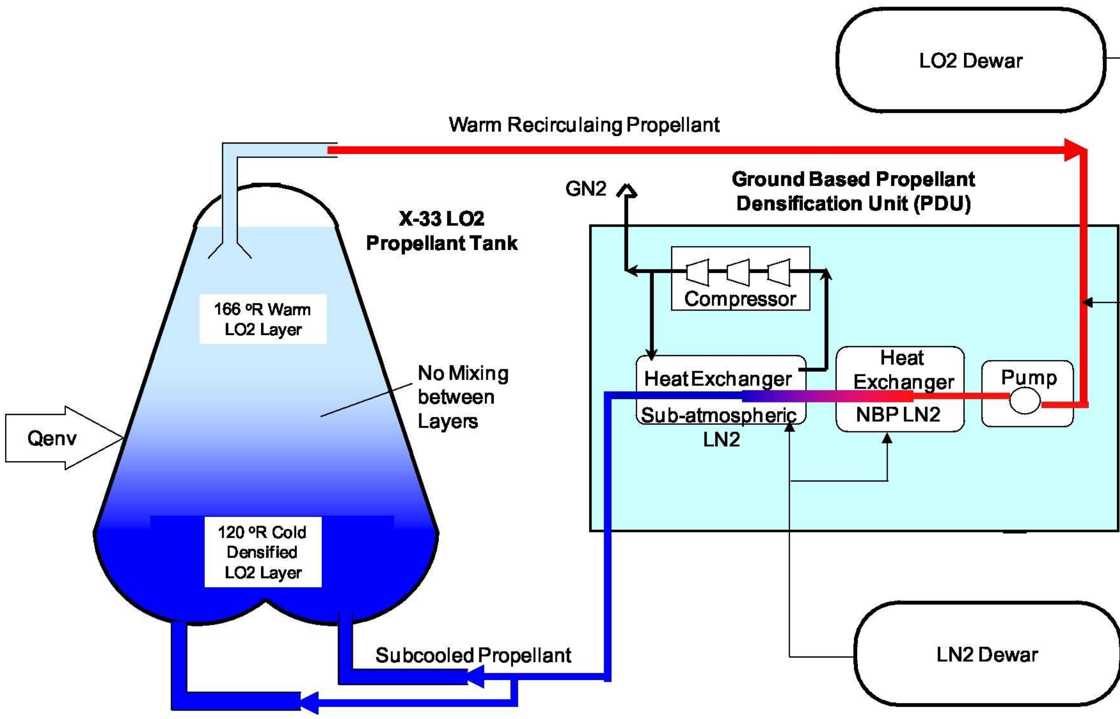


Figure 7. Recirculation of Liquid Oxygen from X-33 tank through ground based Propellant Densification Unit (PDU).

Thermal stratification enhances the densification process by maximizing the temperature difference between the fluid exiting the tank and the cold sink that's used to extract heat from the propellant. In order to achieve and maintain the propellant tank at thermally stratified conditions, a very important aspect in the overall performance of the densification process in terms of the time (Δt) required to accomplish the desired densification (**figure 8**), warm saturated liquid is withdrawn off the top (W_2^{LO2}), physically using either a siphon tube or fluid manifold and the subcooled propellant from the GSE is returned to the bottom (W_1^{LO2}).

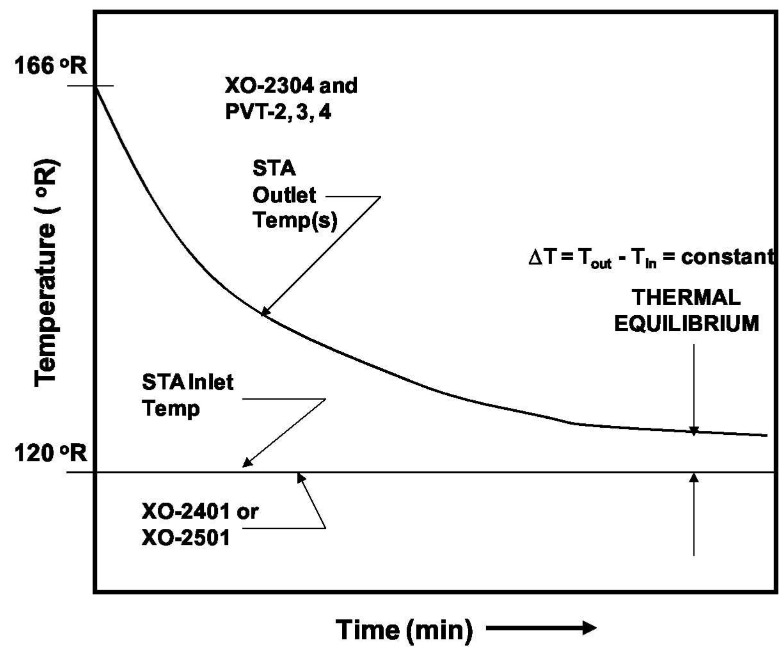


Figure 8. Thermal stratification of STA tank and temperature equilibrium condition at completion of LO2 densification process.

Cold denser fluid entering the bottom displaces the warmer less dense LO2 propellant vertically upward in what could be described as an ideal "plug-flow" pattern. An inlet propellant diffuser located at the bottom of the tank can be used to uniformly disperse the propellant. Relatively low bulk fluid velocity at near laminar flow conditions tends to promote the plug flow pattern and the thermal stratification gradient that develops inside of the tank. The theoretical time-line Δt required to densify the initial mass M_i^{LO2} of NBP LO2 propellant in a propellant tank is presented in-terms of an ideal and generalized energy equation for achieving both a net fluid internal energy change (ΔU^{LO2}) and a mass gain (ΔM^{LO2}) of the STA tank contents.

$$\Delta t = \frac{M_i^{LO2} \ \Delta U^{LO2} + U_i^{LO2} \ \Delta M^{LO2}}{Q_e - W_1^{LO2} \left(h_1^{LO2} - \frac{\rho_{2LO2}}{\rho_{1LO2}} h_2^{LO2}\right)} \tag{2}$$

The production of super-cold LO2 temperatures is essentially accomplished by withdrawing saturated liquid oxygen (W_2^{LO2}) off the top of the thermally stratified STA tank through a vertical siphon tube outlet, circulating it through the LO2 pump and heat exchangers of the propellant densification unit, and returning the propellant subcooled at 120 °R from the GSE back into the bottom (W_1^{LO2}) of the STA tank. Sub-atmospheric pressure LN2 boiling at 2.4 psia provides the 117 °R thermal heat sink required to condition the propellant in the LO2 second stage heat exchanger. The first stage of the heat exchanger system cools LO2 down to about 142 °R using multiple parallel coils submerged in an NBP bath of LN2. The LN2 coolant mass feed rate (W_1^{LN2}) into the critical stage-two heat exchanger is derived from an energy balance on the exchanger that's given by:

$$W_1^{LN2} = \frac{W_1^{LO2}(h_1^{LO2} - h_2^{LO2}) + W_1^{gN2}(h_1^{gN2} - h_2^{gN2})}{(h_2^{gN2} - h_1^{LN2})} \tag{3}$$

The GN2 vent rate (W_2^{GN2}) from the 2nd stage heat exchanger is then derived from the nitrogen overall mass balance on the exchanger, whereby this gas flow rate directly feeds the inlet to the first stage GN2 compressor.

$$W_2^{gN2} = W_1^{LN2} + W_1^{gN2} \tag{4}$$

The tubes make-up a large surface area (*A*) of the GSE heat exchanger and are submerged in a low temperature boiling bath of LN2 maintained at sub-atmospheric pressure. To generate sub-cooled LO2 at 120 °R, the heat exchanger bath operating filled with LN2 is reduced to a lower pressure of 2.4 psia causing the liquid to boil at the saturation temperature (T_{sat}^{LN2}) of 116.9 °R. The design and performance equation for the cryogenic heat exchanger in terms of the heat rejection rate from the fluid (Q^{LO2}), the overall heat transfer coefficient (U_o) and the log mean temperature difference (ΔT_{LMTD}) allows prediction of the LO2 outlet temperature (T_2^{LO2}) albeit a trial-and-error approach, assuming U_o is known or calculable.

$$Q^{LO2} = W_1^{LO2}\,(h_2^{LO2} - h_1^{LO2}) = U_o \ A \ \Delta T_{LMTD} = U_o \ A \ \frac{T_1^{LO2} - T_2^{LO2}}{\ln \dfrac{(T_1^{LO2} - T_{sat}^{LN2})}{(T_2^{LO2} - T_{sat}^{LN2})}} \tag{5}$$

A low temperature nucleate pool boiling heat transfer process provides the thermal conditions required to remove heat from the propellant. The inlet LO2 stream is gradually subcooled as it flows through the D-shaped extruded tubes of the heat exchanger's <u>constant temperature bath</u> and exits at the desired 120 °R outlet temperature (assuming the surface area is sufficient). The outside heat transfer coefficient (h_o) on the shell-side is best represented by the nucleate pool boiling heat transfer correlation based on a modified Kutateladze equation correlated by Brentani & Smith [ref. 12, 13] while the Dittus and Boelter empirical relation for turbulent flow heat transfer inside a tube of known diameter (d_i) can be used for calculating the inside heat transfer coefficient (h_i).

$$h_o = 4.87 \times 10^{-11} \frac{(c_{pL}^{1.5}\, k_L\, \rho_L^{1.282}\, P^{1.75})}{(\lambda \rho_V)^{1.5}\, \sigma^{0.906}\, \mu_L^{0.626}} (\Delta T)^{1.5} \qquad (6a)$$

$$h_i = 0.023 \frac{k_L}{d_i} \mathrm{Re}_d^{0.8}\, \mathrm{Pr}^{0.3} \qquad (6b)$$

$$U_o = \frac{1}{\dfrac{1}{h_i} + A_i \ln\left(\dfrac{d_o}{d_i}\right)\dfrac{1}{2\pi k_m} + \dfrac{1}{h_o}} \qquad (7)$$

The symbols shown in the heat transfer equations (6a), (6b) and (7) above are defined as follows:

c_{pL} = saturated liquid specific heat, J/g-K
k_L = saturated liquid thermal conductivity, W/cm-K
P = pressure, dynes/cm2
ΔT = temperature difference, K
λ = heat of vaporization, J/g
ρ_v = sat'd vapor density, g/cm^3
σ = liquid surface tension, dynes/cm
μ_L = saturated liquid viscosity, g/cm-sec
Re = Reynolds number
Pr = Prandtl number
h_i = inside forced convection heat transfer coefficient, W/cm^2-K
h_o = nucleate pool boiling convection heat transfer coefficient, W/cm^2-K
k_m = tube wall thermal conductivity, W/cm-K
d_i = tube inside diameter, cm
d_o = tube outside diameter, cm
A_i = tube inside area, cm^2/cm

The LO2 recirculation pump on the PDU is sized to provide sufficient motive energy (*BHP*) to force the flow through the complex circuitry of the GSE-STA-VJ piping systems and heat exchangers. The theoretical work required for the recirculation pump is expressed in terms of the LO2 volumetric flow rate (Q_v^{LO2}), the total pressure rise (ΔP^{LO2}) and pump efficiency (η).

$$BHP = \frac{\Delta P^{LO2}\, Q_v^{LO2}}{3.82\ \eta} \qquad (8)$$

The GN2 compressor is a high-speed centrifugal machine designed to maintain the heat exchanger ullage pressure constant at 2.4 psia and to reject the boiled-off GN2 inlet saturated vapor to the atmospheric pressure vent. The basic performance equations for the GN2 compressor are defined in terms of the dimensionless head (Ψ) and flow (Φ) coefficients and, the ideal head rise

(H) done on the gaseous nitrogen based on isentropic, adiabatic compression.

$$H = z\,\bar{R}\,T_1 \frac{k}{k-1}\left(\left(P_2/P_1\right)^{(k-1)/k} - 1.0\right) \tag{9}$$

$$U_2 = \frac{\pi\,N\,D}{720} \quad \textit{and} \quad \Psi = \frac{H\,g_c}{U_2^2} \quad \textit{then} \quad \Phi = \frac{Q_v}{A_m\,U_2} \tag{10}$$

where, the GN2 compressor performance variables have the following definitions:

A_m = flow discharge area of the stage, ft^2
T_1 = suction temperature, ^oR
P_1 = suction pressure, psia
P_2 = discharge pressure, psia
Z = compressibility factor = 0.990
k = specific heat ratio = C_p/C_v = 1.40 at T_1 > 200 ^oR
R = molecular weight constant = 55.171 ft-lb/lb_m-^oR
N = compressor stage speed, rpm
D = impeller diameter = 14.0 inch (constant for all three stages)
H = compressor stage adiabatic head rise, ft
U_2 = impeller stage tip speed, ft/sec
g_c = gravitational acceleration constant = 32.174 ft/sec^2

With the preceding fundamental relationships, some of the key propellant densification processes and the basic GSE performance may be either designed or analyzed at an engineering level of accuracy.

1.4 LO2 Densification Test Objectives

The primary research objectives were to conduct testing to demonstrate flight-similar processes for large scale, in-tank, cryogenic propellant densification and, to provide engineering data for the validation of mathematical simulations of these processes. In the approach taken to accomplish the objectives, the X-33 LO2 STA tank was used in combination with the X-33 LO2 propellant densification unit (**figure 9**) that was fabricated by NASA GRC to explore the effects of different densified propellant production, loading and recirculation scenarios so that the process of densification

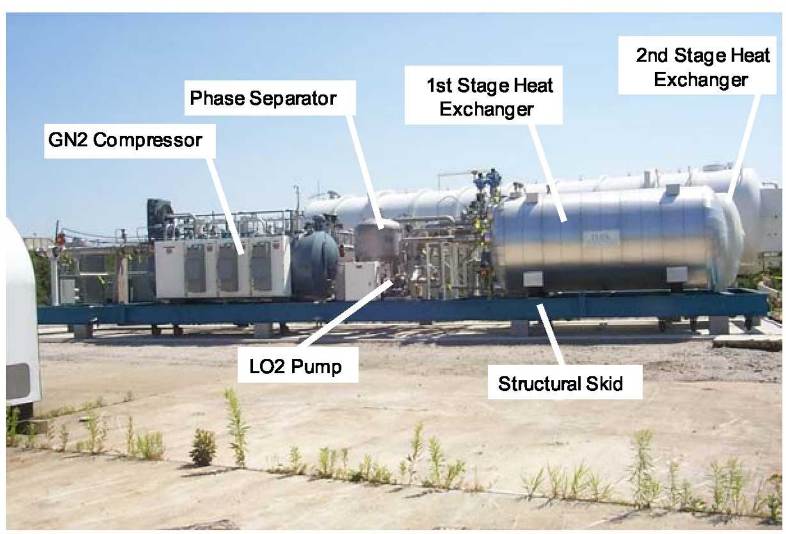


Figure 9. Liquid oxygen propellant densification skid equipped with five major components: the GN2 cryogenic compressor, two LO2-to-LN2 heat exchangers in series, a phase separator and the LO2 recirculation pump.

for launch vehicles can be further optimized and better understood. The specific test objectives of the LO2 densification and STA tank thermal stratification experimental program can be summarized by the following verifications that were performed:

- Evaluate LO2 densifier performance operations including start-up, shutdown and steady state operations over a range of flow rates and heat exchanger bath pressure operating conditions.
- Demonstrate densifier performance and verify in-tank thermal stratification characteristics over two discrete inlet LO2 recirculation mass flow rates, 20 lb_m/sec and 30 lb_m/sec.
- Vary the STA inlet flow path of LO2 to determine their affects on tank thermal stratification. The LO2 inlet flow paths tested would be through both bottom lobes, the instrumented lobe and the un-instrumented lobe.
- Obtain sufficient LO2 PDU performance data including recirculation and tanking operations to allow validation of mathematical, analytical tank models under development by GRC and LMMSS [ref. 14].
- Characterize the STA tank environmental heat leak by LN2 and LO2 boil-off testing.
- Demonstrate operational densified propellant production, loading and recirculation processes using a tank and ground support equipment (GSE) similar to that which would be used on a flight vehicle with LO2.

2. DENSIFIER HARDWARE TEST ARTICLES

2.1 LO2 Densification Skid (LO2 PDU)

The LO2 densification system was comprised of a cryogenic pump, a two-stage LO2-to-LN2 heat exchanger, a phase separator, a three-stage GN2 compressor, and all the necessary valves, instrumentation, flow elements, piping, tubing, and electrical hardware. All of these components seen in **figure 10** were attached to a skid frame made-up of welded structural steel sections. By connecting the LO2 densifier to a facility propellant test tank (i.e. the STA), a closed-loop system was created. The LO2 densifier as designed could be used in any cryogenic facility that has such a propellant tank, consumables including LO2, LN2, GHe, and GN2, sufficient electric power, and enough space for the 65' x 18' x 11' skid.

The PDU was designed so that densified LO2 could be provided to a propellant tank at a maximum flow rate of 30 lb_m/sec and a temperature as low as 120 ^oR. The cryogenic pump first forces LO2 to flow through the tube bundle of the first stage heat exchanger. Here is where it would be partially cooled to 142 ^oR by the atmospheric pressure normal boiling point LN2. Then the LO2 passed through the tube bundle of the heat exchanger second stage where the cooling was completed through the use of sub-atmospheric pressure LN2. The three-stage compressor created the sub-atmospheric pressure condition on the shell-side of the heat exchanger second stage ullage. The heat exchanger second stage bath could be operated at pressures ranging from 2.5 psia up to 10 psia in order to achieve different temperature levels of sub-cooled LO2. A phase separator installed upstream of the compressor removed any entrained LN2 droplets from the

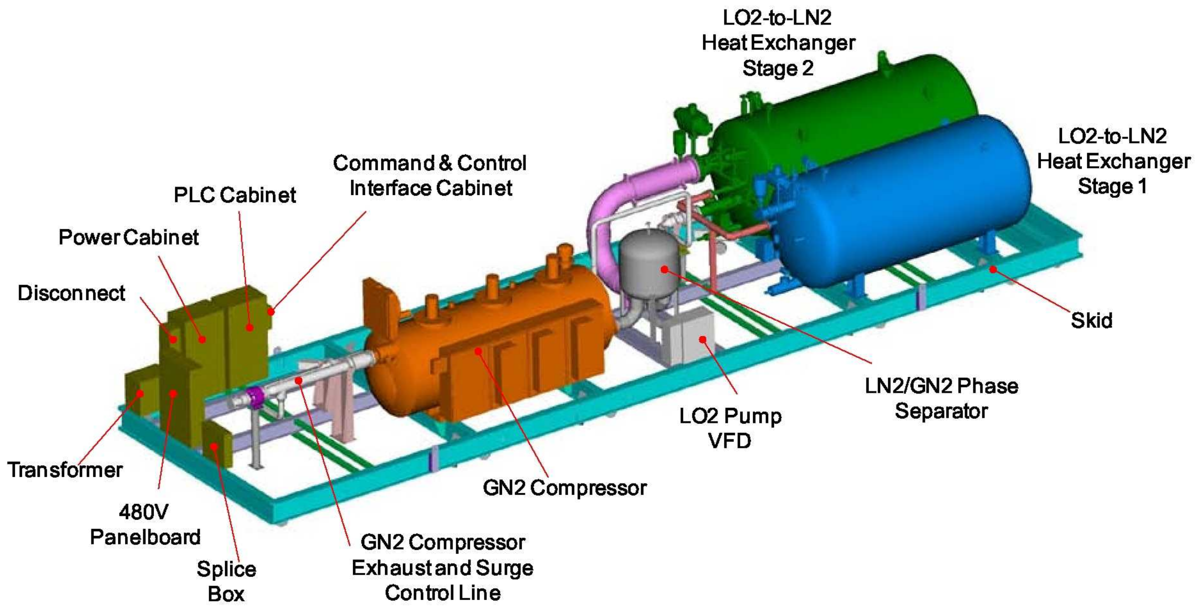


Figure 10. LO2 propellant densification skid equipment layout and overall size of 65' long x 18' wide x 11' tall.

gaseous GN2 entering the first stage of the compressor. Automatic compressor controls with a PLC were used to regulate the heat exchanger ullage pressure and to provide surge control. The compressor discharge gas was sent directly to a facility vent stack. A simplified process flow diagram of the LO2 PDU, shown in **figure 11**, indicates the typical operating conditions of the rig.

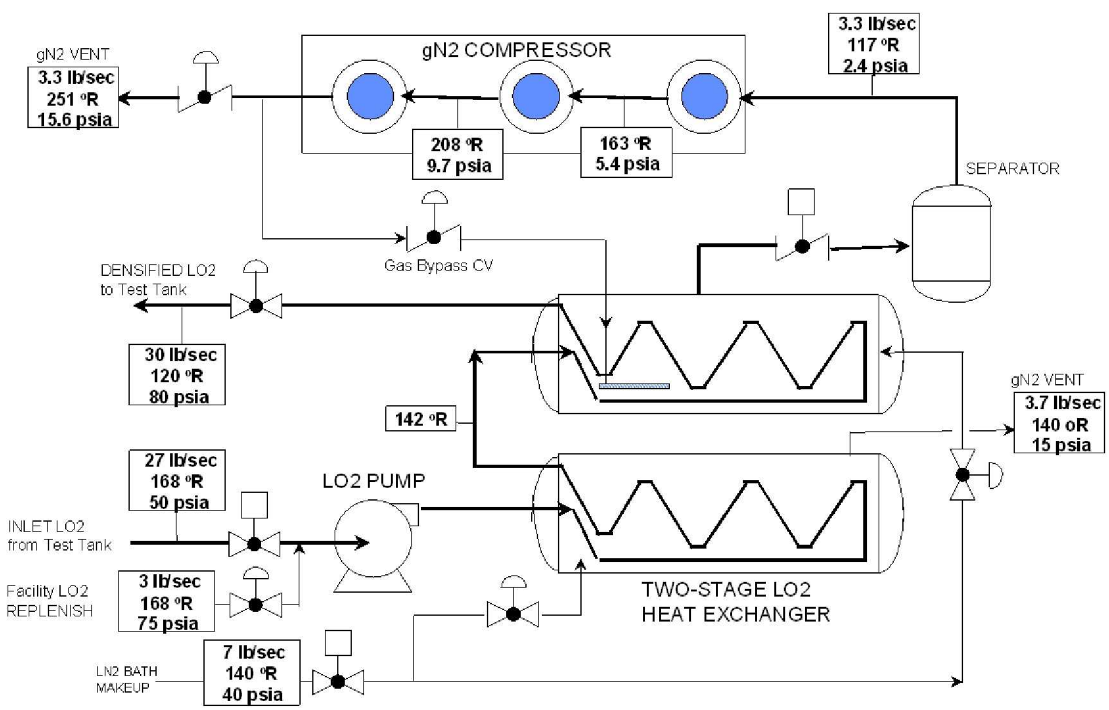


Figure 11. Simplified process flow diagram of the LO2 PDU.

2.2 LO2 Recirculation Pump

The LO2 recirculation pump was a full emission, horizontal-shaft, closed impeller, centrifugal type pump with a design head rise of 50 psid at a volumetric flow rate of 190 gpm and operating speed of 4200 rpm. The pump, shown in **figure 12**, had the following general design and construction features: ASME/ANSI class 150 flat-face flange connections; mechanical foam insulation (SOFI) with a metal protective outer cover; integral support structure; an accelerometer (0 – 0.5 in/sec) for vibration monitoring; a Variable Frequency Drive (VFD) controller; 460 VAC three phase, 2-pole induction motor rated for 10.5 HP at 70 Hz and directly coupled to the pump; and provisions for a GHe purge to the pump seals. All components but the VFD were mounted on a rigid, stainless steel pump support pallet. The LO2 mass flow rate was controlled by varying the pump motor speed with the VFD based on a 4 – 20 mA input control signal from a 3-inch Coriolis mass flow meter (FT-535) measurement. This allowed adjustment and control of the pump speed to produce any desired head and LO2 flow rate within the available power range of the variable speed drive. Details of the technical specifications for the LO2 recirculation pump are seen listed in **Table 1.0**.

Table 1.0: LO2 recirculation pump design and performance specifications.

Design Parameter ***Hydraulic Design Point Data***	***BNCP-42-000***
Manufacturer (OEM)	Barber-Nichols Inc.
Fluid	Liquid Oxygen
Volumetric flow rate, gpm	190.
Mass flow rate, lb_m/sec	33.1
Pump ΔP, psid	50.
Design speed, rpm	4200.
Inlet temperature, ^oR	120.
Suction pressure, psia	60.
Impeller size, inch	4.8
NPSHR, psia	2.8
Specific speed, N_s	91.9
Head coefficient, Ψ	0.41
Flow coefficient, Φ	0.09
Efficiency, %	72.1
Shaft power, HP	7.7
Electric Motor Data	72
Power, HP	10.5
Voltage/Current/Phase/Poles	460 / 13. / 3 / 2
Enclosure	TEFC
Base frequency, Hz	40
Speed, rpm	4200.
Mechanical Data	
Mech. design pressure, psig	150.
Dimensions, in (w x h x l)	29.7 x 24.5 x 36.6
Weight, lbs	450
Inlet / Outlet size, in	3.0 x 1.5

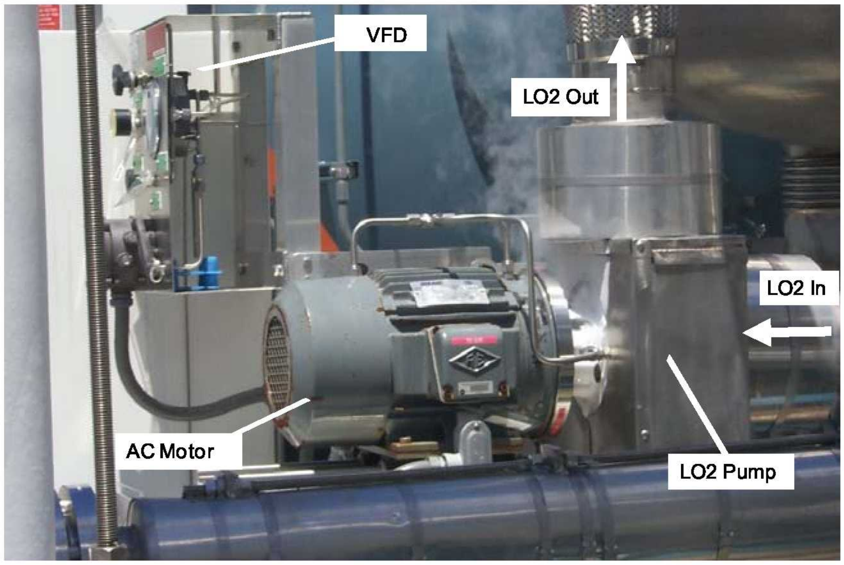


Figure 12. Liquid oxygen centrifugal recirculation pump, drive motor and VFD.

2.3 LO2 Heat Exchangers

The LO2 heat exchanger system was fabricated by PHPK Technologies, Inc. and is pictured in **figure 13**. The heat exchanger assembly consisted of two ASME-rated, single-pass, shell and tube heat exchanger stages arranged in series. LO2 would flow through the tube bundles while LN2 filled the shell-side baths. Each stage had the following construction features: ASME/ANSI class 150 raised-face flange process connections; an aluminum tube bundle; a LN2 silicon diode temperature rake; a liquid level capacitance probe and transmitter; an LN2 bath supply control valve; a low-point LN2 drain; an internal phase separator to remove LN2 droplets from the GN2 vent gas; temperature and pressure transmitters at the LO2 inlet/outlets; and redundant temperature transmitters in both the ullage space and LN2 bath.

The first heat exchanger stage was vented to atmosphere through an 8 inch SS line. The vessel was insulated with two layers of 3.5 inch thick Foam Glass insulation, with a thin metal protective outer cover installed. The second stage exchanger was a vacuum jacketed pressure vessel. The pressure relief system was set for a nominal 50 psig relief pressure, even though the design pressure of the vessels and coils was 150 psig. The stage two vent discharged gas

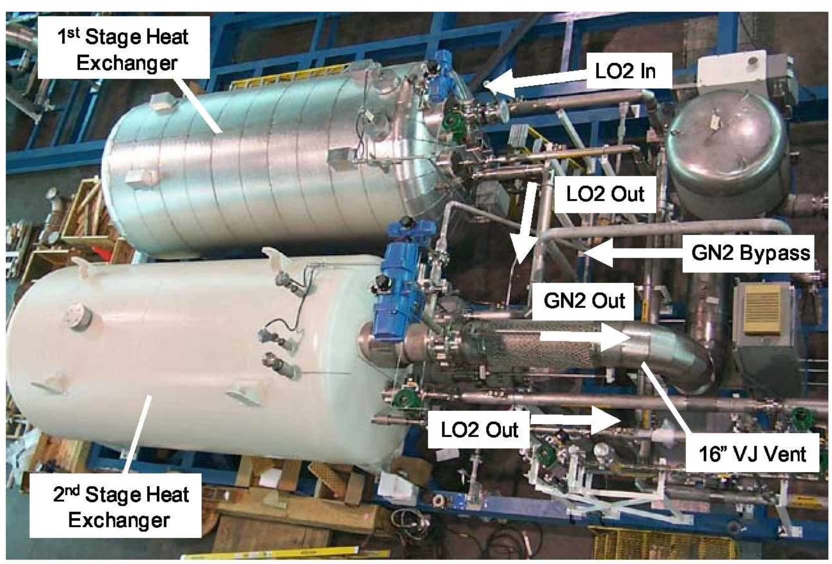


Figure 13. LO2-to-LN2 heat exchanger vessels in series designed to subcool LO2 (top view).

into a 16 inch VJ line leading to the phase separator that was attached to the GN2 compressor inlet. The second stage heat exchanger contained an internal diffuser/bubbler tied into the GN2 compressors' surge control recirculation line. When the compressor approached a surge condition, the compressor recirculated some of the GN2 from its stage 3 discharge, back into the second stage LN2 bath to increase the GN2 boil-off flow rate into the compressor, and prevent a surge from occurring. The interconnecting LO2 piping between stages was 3 inch vacuum jacketed, except for the flanges. All flanges were covered with Foam Glass insulation.

The basic design of the exchanger surface area was a group of parallel pancake style coils (**figure 14**) attached to 4 inch supply and return manifolds, submerged in a horizontal tank of liquid cryogen. The pancake coils were formed in a "D" shape to provide maximum vapor space above the coils and reduce the vapor velocity at the liquid-gas interface as much as possible to give good separation and minimize entrainment. The manifolds, which extended the full length of the inner vessel, distributed the heat load uniformly throughout the liquid bath. All coils were formed from extruded "D" shaped 3003 aluminum tubing. The tubing was 1 inch OD net with 1/8 inch thick walls. The heat exchanger tube bundles in Stages 1 and 2 comprised 72 parallel D-shape coils with each pass having lengths of 64 feet and 96 feet, respectively. **Table 2.0** presents some of the pertinent design and performance requirements for each of the heat exchanger stages.

Table 2.0: LO2 heat exchanger system design and performance data.

Design Parameter	***1st Stage LO2***	***2nd Stage LO2***
Tube Side		
Inlet flow rate, lb_m/sec	30.	30.
Inlet temperature, ^oR	168.	142.
Inlet pressure, psia	110	100
Outlet temperature, ^oR	142.	120.
Max. allowable ΔP, psid	7.5	7.5
Total tube length, ft	4608	6912
No. of parallel coils	72	72
Surface area, ft^2	905	1357
Mech. design pressure, psig	150.	150.
Shell Side		
Bath temperature, ^oR	139.	117.
Bath pressure, psia	14.6	2.5
GN2 vent flow rate, lb_m/sec	3.7	3.3
Max.GN2 surge (270 ^oR) lb_m/sec	–	1.8
Surface area, ft^2	1372.	2057.
Volume (total), gal	3630	3460
Volume (operating), gal	3230	2540
Inner vessel OD, inch	78.	78.
Mech. design pressure, psig	150.	150.
Insulation	Foam Glass	VJ

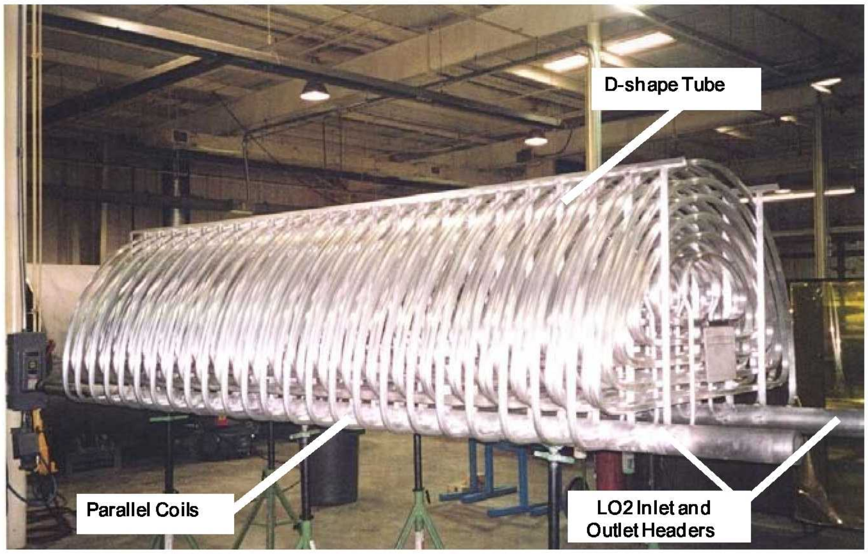


Figure 14. LO2 heat exchanger pancake coil D-shaped tube bundle assembly.

2.4 GN2 Compressor System

The GN2 compressor system, fabricated by Barber Nichols Inc., was a three-stage, full emission, centrifugal unit designed to control and maintain the heat exchanger second stage ullage pressure between 2.5 psia and 10.0 psia. The compressor system (**figure 15**) itself was a completely self-contained assembly that came with all of the necessary auxiliaries. These included a motor cooling system, instrumentation, VFD motor drives and a PLC-based controller system. At the nominal inlet design conditions of 2.4 psia at 118 ^{o}R, the compressor was designed to pump up to 3.3 lb_m/sec of GN2 from the heat exchanger second stage, and compress it to 15.6 psia at 251 ^{o}R. The compressor system design had the following general mechanical and construction features: a vacuum-jacketed, LN2 phase separator vessel; ASME/ANSI class 150 raised-face process flange connections; a closed-loop water propylene glycol cooling system for the compressor motors; a perlite insulation filled enclosure vessel; a GHe pressure purge for the compressor enclosure; annubar flow meters in the exhaust and surge piping; a 4 inch surge bypass control valve; silicon diode temperature sensors; pressure transducers; and a PLC device.

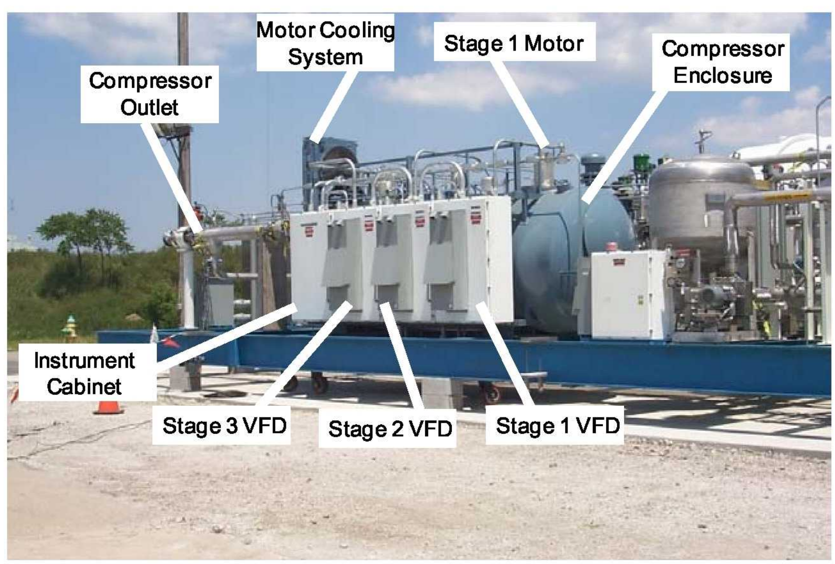


Figure 15. Three stage GN2 compressor system.

Each of the three compressor stages (**figure 16**) had near identical components that included VFD controlled 460 VAC three phase, 4-pole electric inverter duty motors (70 HP) directly mounted to and hermetically sealed from the compressor housing (i.e. this means there were no rotating seals), an accelerometer for vibration health monitoring, motor winding thermocouples, and interstage pressure and temperature transmitters. The pressure ratio across each stage was balanced by design such that it allowed PLC control or adjustment of the compressor speed to produce any desired suction pressure within the available power operating range of the drive. The compressor stage subassemblies including electric motors, VFD enclosures, and all related piping were directly supported by a horizontal cylindrical carbon steel enclosed vessel. In addition, all interconnecting piping in-between the stages were routed and supported inside of the compressor enclosure. At the inlet of the GN2 compressor, a vapor-liquid phase separator (**figure 17**) was installed to maintain a gas quality range in-between 98 and 100% at the compressor inlet. The phase separator was a vertical mounted cylindrical VJ tank with hemispherical end-caps and was supported by three legs that were welded to the bottom.

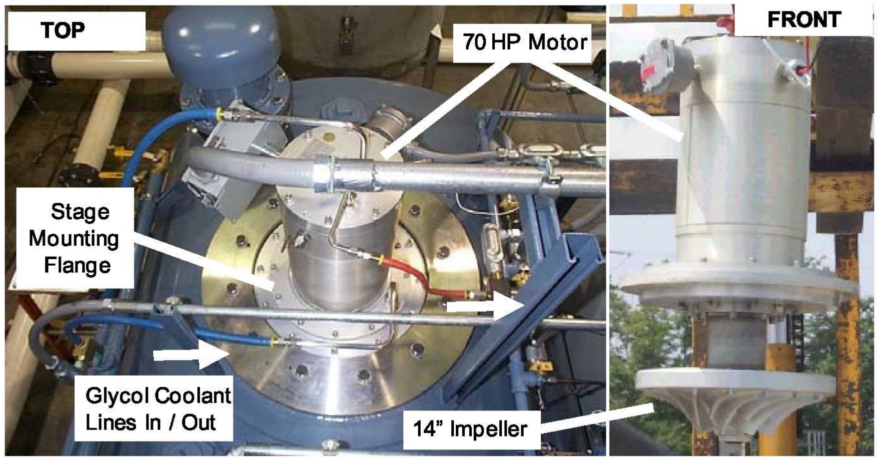


Figure 16. GN2 compressor system stage number 3 – top and front view.

Figure 17. The GN2 phase separator final assembly.

There were two major control loops in the GN2 compressor system. These included suction pressure control, achieved by varying stage speeds and, one loop to prevent the compressor from going into surge, both of which used active PID software control. To avoid compressor surge at low GN2 flow rates, a GN2 recirculation line as part of a surge avoidance system was utilized. During compressor operation, if the compressor PLC determined that surge was imminent via flow coefficient (Φ) monitoring, the gas bypass recirculation control valve opened. This would happen when the mass flow rate falls below the design control set-point ($\Phi_{sp} = 0.18$), in which case the valve positioned itself to maintain the flow coefficient at or above the predetermined surge avoidance line where Φ equals 0.18. The recirculated flow was then injected back into the heat exchanger second stage LN2 bath, through an 8 inch perforated diffuser/bubbler pipe, to increase the GN2 boil-off flow rate to the compressor inlet and prevent the compressor surge instability. If in the event that the first stage inlet Φ would fall below 0.12 then an automatic surge shut-down would be initiated by the PLC. **Table 3.0** summarizes the GN2 compressor stage design point characteristics.

Table 3.0: GN2 compressor design point conditions.

Stage No. →	*1*	*2*	*3*
Inlet temperature, °R	118.	163.	208.
Inlet pressure, psia	2.40	5.44	9.73
Discharge temperature, °R	161.	206.	251.
Discharge pressure, psia	5.64	9.93	15.6
Mass flow rate, lb_m/sec	3.3	3.3	3.3
Head rise, ft	6224	5835	5742
Pressure ratio	2.35	1.82	1.60
Stage pressure rise, psid	3.24	4.49	5.87
Speed, rpm	10,060	9,840	9,670
Impeller diameter, in	14.0	14.0	14.0
Tip speed, ft/sec	615.	601.	591.
Specific speed, N_s	112.5	90.2	75.8
Head coefficient, Ψ	0.53	0.52	0.53
Flow coefficient, Φ	0.33	0.30	0.28
Shaft power, hp	49.4	49.0	49.0
Stage efficiency, %	75.7	71.4	70.4
Motor nameplate hp @ max. N = 11,500 rpm, 400 Hz	70.	70.	70.
Stage outlet area, A_m, ft^2	0.1784	0.1480	0.1264
Mech. design pressure, psig	50.	50.	50.

2.5 VJ and Process Piping

All process piping (**figure 18**) on the LO2 densifier was designed, fabricated and tested in accordance with the ASME B31.3 Process Piping code requirements. Both the inner line and vacuum jackets were fabricated from Schedule 5 or Schedule 10 stainless steel, ASTM A312, Type 304/304L. With the exception of process flanges and compressor exhaust piping, all cryogenic piping and components not previously mentioned, were vacuum jacketed with a design pressure rating of 150 psig. The flanges and compressor exhaust piping were non-VJ but instead were covered by removable mechanical Foam Glass insulation. The LO2 piping and LO2 components were each cleaned to meet the oxygen cleanliness specification requirements defined by MSFC-SPEC-164B, Level IIIA for non-volatile residue (NVR) and particulate matter.

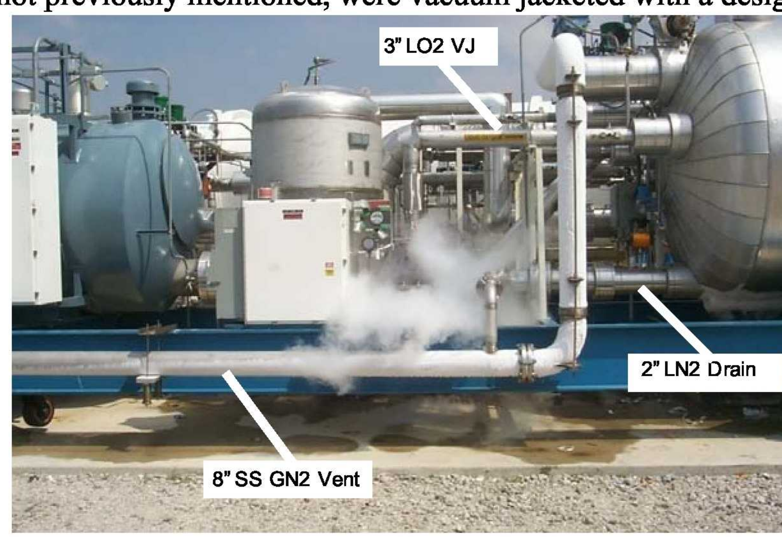


Figure 18. LO2 densifier process piping, GN2 vents, LO2 VJ lines, and LN2 VJ system.

2.6 PDU Utility Gas Systems

The LO2 densifier was designed with both utility GN2 and GHe support systems. These systems were essentially, manually operated pressure reduction stations consisting of hand isolation valves, hand loaded regulators, relief valves, filters, pressure gages, pressure switches, and pressure transmitters. The GHe system on the skid reduced the facility supply pressure, typically at 500 psig, to those pressure levels required for purging hardware and piping from 25 to 100 psig. The GN2 utility system reduced the test facility delivery pressure from 500 psig to three levels required for low-pressure purging the electrical enclosures (10 psig) and purging the LN2 piping (40 psig) on the LO2 densifier, in addition to the 125 psig GN2 for actuation of all the remote operated valves on the densifier.

2.7 LO2 Densifier Electrical Systems

The densifier electrical system consisted of four major parts: power; control and instrumentation; fail safe shutdown; and operator interface and data logging. Each of the parts, with the exception of operator interface and data logging, were physically located on the densifier skid so that the densifier function was self-contained and relatively easily transported as shown by the PDU skid being moved in **figure 19**. The facility interface to each of these systems was minimized in order to simplify the integration of the densifier at its test destination. The recommended electrical feeder size from the facility was 500 KVA of power to run the densifier. The entire LO2 densifier skid was classified electrically as a Class 1, Division 2 Group D hazardous area per the National Electric Code. The electrical area hazard requirement of the LO2 rig was driven by the initial integration plans of the PDU with the X-33 launch facility at Edwards Air Force Base.

Figure 19. The LO2 densifier is self-contained and modular for ease of transportability as illustrated by this move at the NASA GRC in 1999.

The LO2 densifier skid required a single 460 VAC three phase feed conductor from the test facility. Once tied into the skid, the power was distributed through a panel board to three major on-skid feeders to supply the individual densifier loads. The three main power feeders were directed to the compressor system motors, the LO2 pump, and the densifier instrumentation and controls. Each feeder was protected at the panel board by a circuit breaker. A single 460 VAC power feed was used to tie into the Barber-Nichols compressor motor system. This feeder was tapped and fused for each individual motor/VFD unit. To reduce potential VFD induced harmonics generated from the three 70 hp motors, line reactors and filters were used at the VFD power inputs. The LO2 pump feeder supplied a fuse protected 10.5 hp motor/VFD unit. A line reactor and filter was also used here to reduce the harmonics induced by the pump VFD. The third major electrical feeder on the densifier skid was tied into a 15 KVA transformer to supply 120/208V power for instrumentation and control. The transformer was a filtered-shielded type to reduce AC transients and noise from the large motors connected nearby. With these devices, data transmission signals were un-affected by the AC drives during motor operation.

2.8 Skid Instrumentation and Controls

The LO2 densifier skid was fully equipped with all of the necessary hardware to perform data acquisition and control with minimal interfacing and outside intervention. A skid-mounted Programmable Logic Controller (PLC) communicated with locally mounted sensors and effectors on the skid for densifier operation. The PLC had dual functions for basic process control and data acquisition. The PLC system controlled the densifier propellant mass flow rate, heat exchanger bath level, control valves and safety-health monitoring systems. Sensors consisted of those elements for pressure, temperature, flow, speed, vibration, level, and position. Effectors included control valves, isolation valves, and the VFD motor on the LO2 pump.

The PLC controlled motorized, air-actuated, and solenoid valves in addition to performing interlocking of critical safety systems. The PLC also performed sequenced startup and shutdown of certain systems. Emergency shutdown circuitry was hardwired and operated independently of the PLC by removing power from the select devices. A PLC scan-loss would generate an emergency shutdown while an Input/Output module failure would generate an alarm. A separate embedded control system (*slave controller*) was installed on the GN2 compressor assembly to allow the control of that process to remain autonomous. Although the compressor PLC system was independent from the skid, all of its data and control parameters were accessible to the densifier operators. At the skid, a single control-data bus fiber optic cable linked the LO2 densifier system to the facility control room.

The LO2 PDU had five basic types of research and control instrumentation. Temperature sensors used on the PDU system were predominantly silicone diode (SiD) type probes made by LakeShore Cryotronics with a typical accuracy of +/- 0.5 ^{o}R. A total of twenty-six installed SiDs provided temperature data for the LO2 recirculation system, heat exchangers, LN2 subsystem and GN2 compressor systems. Twenty-two capacitance type pressure transducers made by Setra and Rosemount were installed on the PDU to indicate LO2, LN2 and GN2 system pressures ranging from less than 5 psia to over 50 psia. Pressure measurements had an accuracy of ± 0.11% FS. Three Micro Motion Coriolis mass flow meters accurate to ± 0.15% FS and located on the liquid cryogen fluid transfer systems provided data for LN2 heat exchanger feed, LO2 recirculation and LO2 tank make-up flow rates. Capacitance type liquid level sensor elements by American Magnetics were installed inside each heat exchanger stage for bath level indication to ± 0.1% accuracy.

Differential pressure transducers sensing ΔP for each of the two Deiterich Standard annubar flow meters provided information for calculating compressor mass flow rates including discharge and surge bypass flow at ± 0.1% accuracy. There were also ΔP transducers installed across each of the three process filters to verify whether a filter became fouled or clogged. The VFD's themselves provided feedback and data on motor run parameters like voltage, current, speed and torque. Piezoelectric quartz accelerometers were installed on each skid located VFD pump and compressor motors to monitor abnormal vibration conditions (0.0 – 0.5 in/sec) in the event of a bearing problem. Three Type T thermocouples, each bonded to the stator inside each of these VFD motors, allowed continuous health monitoring of motor operating temperatures that normally were designed to run at about 200 – 250 °F. The LO2 PDU test article instrumentation listing and details are provided in **Appendix A**.

2.9 Densifier Operator Interface and Data Logging

The LO2 PDU control room was located in a protected environment and remote from the hazardous densification area. Here, a video graphics control station (**figure 20**) provided operator interface to the PLC via a Modbus Plus network. At this site the operator had access to the densifier process through the control panel which consisted of a rack-mounted industrial PC computer, touch-screen displays, and a hardwired interface consisting of an emergency stop button, reset, and master key switch. Through the touch-screens the operator could manually command the process or issue high level script commands to execute a sequence of events. In all cases the PLC, mounted locally at the skid, executed the commands and provided closed-loop process control.

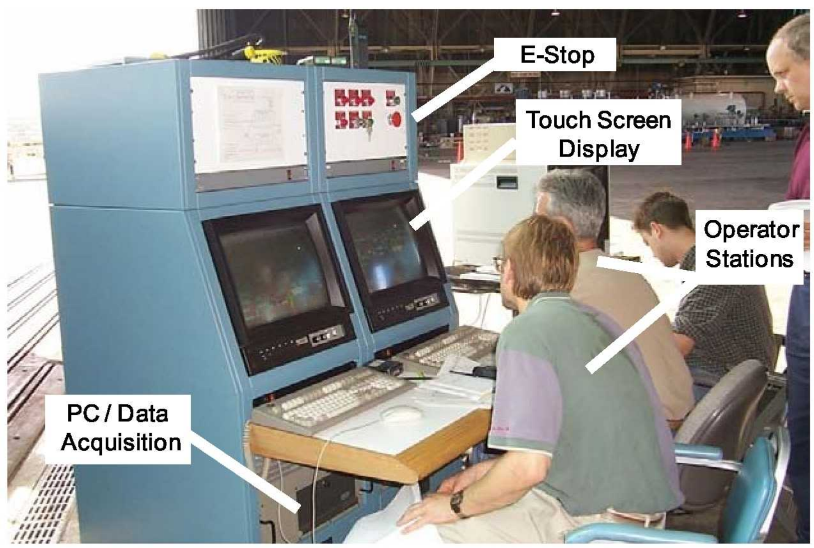


Figure 20. Operator interface and control console for LO2 densifier.

A variety of touch-screens could be accessed to allow the operator as fine a level of detail as necessary to perform the desired function. Typical operations were performed from one or two window screens to minimize effort and confusion. In case of alarm conditions the operator interface utilized an annunciator function which required the operator to perform any necessary actions to restore the process. Since the PLC always maintained control, it could shut down the densification process if the operator did not respond. Conventional push button operators were provided for emergency shutdowns. First-out annunciation through the PLC provided visual and audible indication of alarm and shutdown conditions. Data logging was accomplished at the operator workstation using the PC and its mass storage capabilities. A continuous one scan per second log of all instrumentation data channels to the densifier control and data acquisition systems, as well as operator commands issued, were stored on a 4.3 GB hard disk drive.

3. STA TEST ARTICLE – LO2 PROPELLANT TANK

3.1 LO2 STA Tank Description

The next most significant test article of the LO2 PDU test program was a propellant tank designed and built by the Lockheed Martin Michoud Space Systems (LMMSS) group. It was the structural test article (STA) for the X-33 RLV liquid oxygen tank. The LO2 STA tank was a critical item of the X-33 Vehicle: it was to provide storage of the oxidizer for the X-33 Linear Aerospike Main Engines; and its structure would form part of the main load carrying path of the vehicle. The Liquid Oxygen Tank would be used to provide oxygen propellants to the X-33 main propulsion system and provide the vehicle's primary structure for the forward landing gear and the aeroshell support.

The STA tank employed during the GRC test was identical to the tank that would have flown on the X-33 vehicle and the tank was designed and built specifically for simulated ground load testing that was previously conducted at the MSFC. The test tank article was a dual-lobe, conformal design, constructed of Al 2219 aluminum. Empty the tank weighed approximately 6,900 lb_m and when filled with densified LO2, the combined tank and propellant mass exceeded 203,000 pounds. Sitting in the vertical position, as it was for the S40 densification test, the STA was nearly 27 ft. tall, 18 ft. long, and 10 ft. wide. The propellant tank, shown being erected in the vertical position at the GRC S40 test facility in **figure 21**, required a two-crane lifting procedure, was mounted on a structural support platform and was fixtured by a series of cylindrical steel struts located around the two barrel sections of the STA's base.

Figure 21. Installation of the STA Tank at the GRC South Forty Test Facility.

3.2 STA Mechanical Design

The LO2 STA tank was described as a dual-lobe, axisymmetric, flight-weight prototype tank, designed and constructed of Type 2219 aluminum with a nominal capacity of 20,000 gallons. The tank accommodated two aft tank outlet fittings for the LO2 fill and drain system and three outlet fittings forward for the LO2 syphon outlet, vent/relief valve, and ullage pressurization line. The tank was capable of being purged and pressurized with either helium or nitrogen gas through a forward opening. Purge flow into the STA could be achieved through either the fill, the syphon, and drain line and/or the pressurization line. Vent gas flow could exit the tank via the fill, syphon and drain line and/or the 3 inch vent line. A CATIA diagram of the STA tank in the upright horizontal position without applied insulation is shown in **figure 22**.

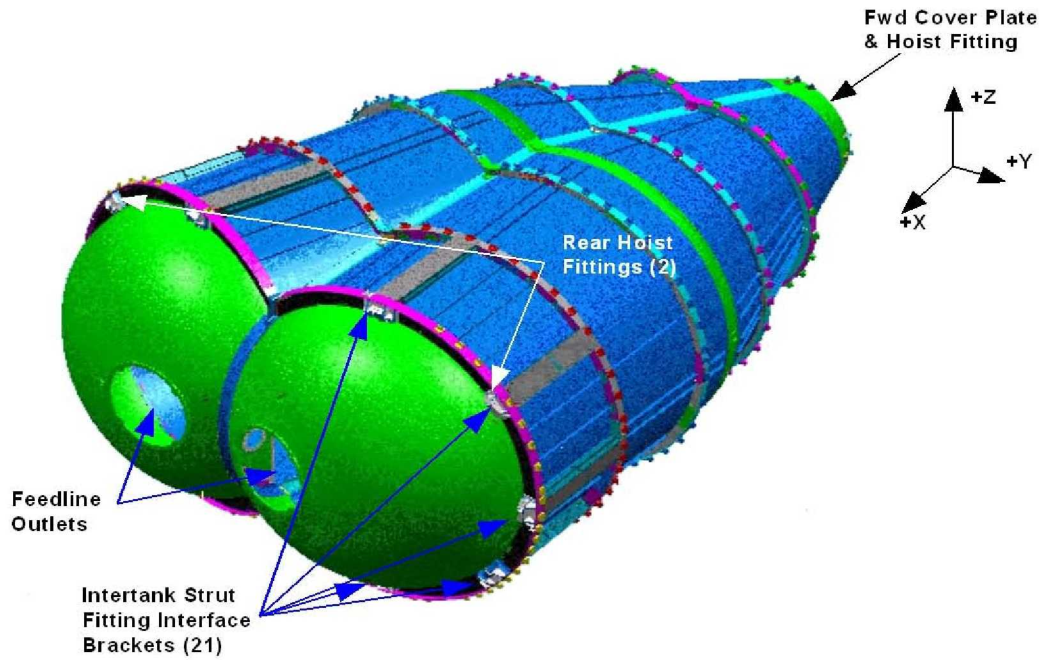


Figure 22. CATIA general arrangement model of the LO2 STA tank densification test article.

The STA geometric volume at ambient pressure and temperature was 2,596 ft^3 or 19,420 gallons. The normal fill and operating volume of the STA was 18,860 gallons for LO2 densifier testing. The tank had a maximum design and operating pressure of 37.0 psig. The minimum operating pressure was not less than 0.0 psig as the STA was not designed for the stresses of vacuum. The design relief valve set pressure on STA was 25.0 psig based on a hazards analysis and safety requirements since the tank was not an ASME rated pressure vessel. The tank was designed for a maximum bottom pressure of 60.0 psig in the aft domes when filled and pressurized with cryogen. For the S40 testing, the STA tank normal operating pressures would range from 28 to 32 psia, and were nominally run at 30 psia ullage pressure during densifier closed-loop recirculation testing. **Appendix B** provides the STA tanking-detanking table with information regarding fill height, percent liquid and ullage volume, diode sensor locations and theoretical densified propellant mass loads for both LN2 and LO2.

3.3 STA Insulation

The STA tank had a Reusable Cryogenic Insulation (RCI) protection system bonded to the outer surface. Insulation design was based on spray-on foam insulation (SOFI) with thermal characteristics much like that used for the Space Shuttle External Tank. The SOFI was sized to meet the specified X-33 propellant delivery requirements, to maintain propellant quality during all cryogenic tanking operations, and for control of thermal stresses associated with extreme temperature gradients. A nominal baseline thickness of 1.0 inch of RCI was applied to the STA tank exterior cryogenic surfaces. Additional thickness was applied to areas that would experience localized heating. Another RCI design requirement was to preclude air condensation external to cryogenic systems that could result in hazards to personnel, hardware, or cause operational anomalies during ground testing. The predicted heat leak value estimated by LMMSS designers was 130,600 Btu/hr with the tank filled with NBP LO2 at a 2.9 percent ullage volume. Based on the average STA tank surface area of 1,058 ft^2, the as-designed analytical heat flux was 123 Btu/hr-ft^2.

3.4 STA Fluid Interfaces

Tank pressurization interfaces utilized LMMSS hardware designed to comply with the interface requirements of the GRC LO2 Densification Unit and the S40 Facility Control System. A forward cover plate was equipped with an internal siphon tube (**figure 23**) to support the LO2 densification recirculation experiments. A 1.0 inch straight pipe-line on the forward plate was provided for GHe/GN2 inlet gas pressurization. A 3.0 inch straight pipe line was also installed here for pressure venting and relief. The LO2 tank aft feedline interface also utilized LMMSS designed hardware. The twin aft feedline cover plates were designed to comply with the interface needs of the densification test. The aft cover plates (**figure 24**) each featured an internal splash plate to support fluid dispersion during the LO2 densification experiments. Connections to the densifier inlet and recirculation lines utilized 4.0 inch PHPK PBA-40 vacuum-jacketed male and female bayonet type fittings that interfaced with the densifier inlet VJ hoses. Here on the STA side, two 4.0 inch VJ bayonet male fittings were provided to interface with the densifier fill and drain lines.

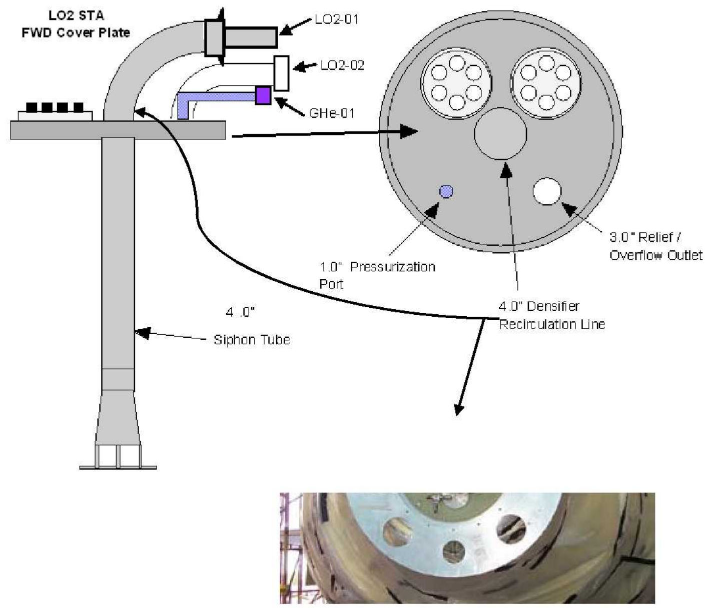


Figure 23. STA tank forward cover plate fluid interfaces.

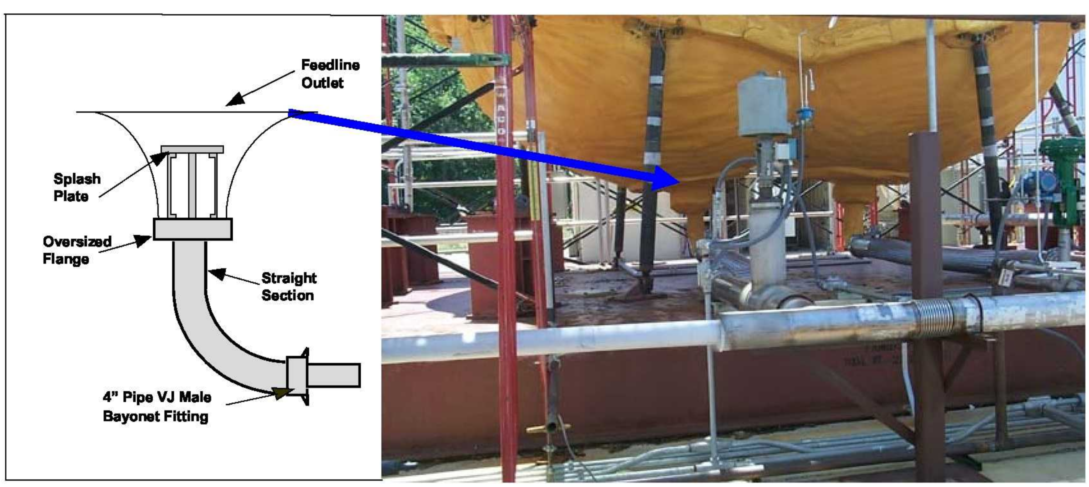


Figure 24. STA tank 4" VJ fill and drain line Aft cover plate interface with S40 test site.

3.5 STA Structural Support Platform

The STA tank was mounted in the vertical upright position on the Test Support Platform (TSP) also identified as the "T153 Tool". The tank was structurally fixtured to the TSP with rack-and-pinion strut pedestals welded to the T153 base and connected to steel cylindrical strut members. There were twenty-four (24) original struts attached to the Test Support Platform. These length-wise adjustable struts were the main static and dynamic load bearing members to transmit forces from the STA to the support platform. During cryogenic LN2/LO2 testing with STA, only 7 of the 24 struts were installed to support the combined loads. This change in philosophy regarding the strut design was based on extensive thermal stress analyses conducted by LMMSS. Their results indicated that the STA was "structurally over-constrained" with the original 24-strut arrangement as thermal stresses develop at cryogenic temperatures that were considered in the operation.

A significant amount of time and effort was expended in the field to "balance" the STA on the seven struts at S40. These alignment adjustments were based on field transit measurements and strain gage data before a full tanking test could safely be performed. The T153 platform was positioned over a massive 42 ft x 30 ft x 4 ft concrete foundation, serving as the primary structural support for the 100 ton plus LO2 STA Tank when fully loaded with DLO2. An access platform surrounding the STA was constructed of scaffolding. The scaffold structure was designed to support operations personnel as well as the required forward and aft interface piping and instrumentation loads generated by the cryogenic test profiles. **Figure 25** provides a generalized view and orientation of STA on the TSP with scaffolding in-place.

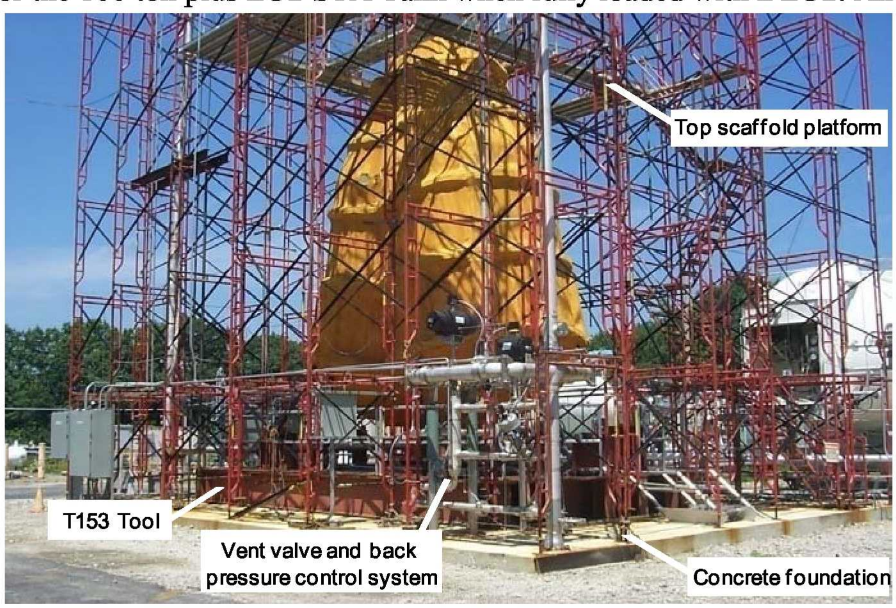


Figure 25. STA tank structural support platform (T153) and access scaffold at S40.

3.6 STA Tank Internal Instrumentation

The STA tank was equipped with internal liquid level and temperature data measurement capability (**figure 26**) for the LO2 PDU loading and recirculation experiments. The STA instrumentation and data collected was via the S40 test facility data acquisition system. The STA specific instrumentation transducers consisted of the following: internal STA vertical and lateral silicon diodes; LO2 inlet and outlet temperatures at the boundaries of STA; tank ullage pressure; STA liquid level; and LO2 mass flow rates which included both tank inlet and STA make-up flow via the PDUs Coriolis mass flow meters.

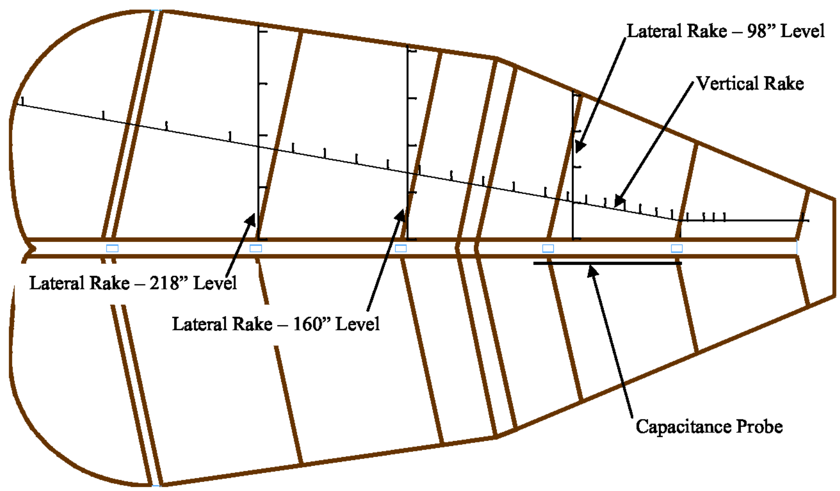


Figure 26. STA internal instrumentation mounting arrangement – horizontal view.

The capacitance liquid level probe, manufactured by B.F. Goodrich, was located internal to STA and was positioned on the right lobe. The probe was used to monitor and control propellant liquid levels within the STA. The design utilized one 32 inch long capacitance level probe sensor positioned 13.5 inches below the forward cover plate. Temperature transmitters included forty (40) silicon diodes (SiD) mounted on a rake inside the left lobe or “instrumented lobe” of STA.

The instrumented rake assembly consisted of an aluminum structure, silicon diode temperature sensors and associated wiring. The rake assembly was located approximately along the centerline axis of the left hand lobe of the STA. The SiD temperature sensors used on the rake assemblies were sensors manufactured by Lakeshore Cryotronics, model DT470-SC-11A, with an accuracy of +/- 0.5 ^{o}R over an operating temperature range of 3.6 – 180 ^{o}R. **Table 4.0** shows measurement requirements and internal instrumentation specific to STA thermal stratification test run data output. Vertical and laterally mounted silicon diodes were used to allow characterization of STA propellant temperature gradients that developed during thermal stratification and closed-loop recirculation testing.

Table 4.0 : STA test article internal instrumentation.

ID Number	***Measurement***	***Type***	***X-Coord. / Location†***	***Left Lobe***	***Right Lobe***	***Total Sensors***
LL1	Liquid Level	Capacitance Probe	Fwd Cone Strongback	-	1	1
PVT1 - PVT25	Temperature	Silicon Diode Sensor	Vertical Rake – 14 to 302 inch Level	25	-	25
PLT1 - PLT5	Temperature	Silicon Diode Sensor	Lateral Rake - 98 inch Level	5	-	5
PLT6 - PLT10	Temperature	Silicon Diode Sensor	Lateral Rake - 160 inch Level	5	-	5
PLT11 - PLT15	Temperature	Silicon Diode Sensor	Lateral Rake - 218 inch Level	5	-	5
Total	—	—	—	***40***	***1***	***41***

Note: † The X coordinate designation for the STA is from top at X = 0 inch to the tank bottom at X = 306 inch.

4. SOUTH FORTY TEST FACILITY

4.1 General Facility Description

The main South Forty (S40) test facility and integrated hardware – designed, acquired and built-up over the course of more than one-year's time for the LO2 PDU test series – consisted of the following nine major facility subsystems:

- LN2 Facility Dewar (N-71, 13,000 gallon)
- LO2 Facility Dewar (N-83, 28,000 gallon)
- GN2 Vaporizer w/LN2 Supply Dewar (N-43, 4,000 gallon)
- GN2 High-Pressure Bottle Farm (2400 psig, 221,000 scf, total capacity)
- GHe High-Pressure Tuber Stations (2400 psig, 70,000 scf, qty. two)
- LO2/LN2 Vacuum-Jacketed Piping
- Pressurization, Vent and Safety Relief Systems
- S40 Facility Instrumentation Systems
- Building 100 Control Room

The following sections of this report present brief technical descriptions of each of these common elements including how they were integrated as a facility. **Figure 27** shows some of the major subsystems and features associated with the S40 densification test site at GRC, which required an overall foot-print area size of approximately 180 ft. by 140 ft.

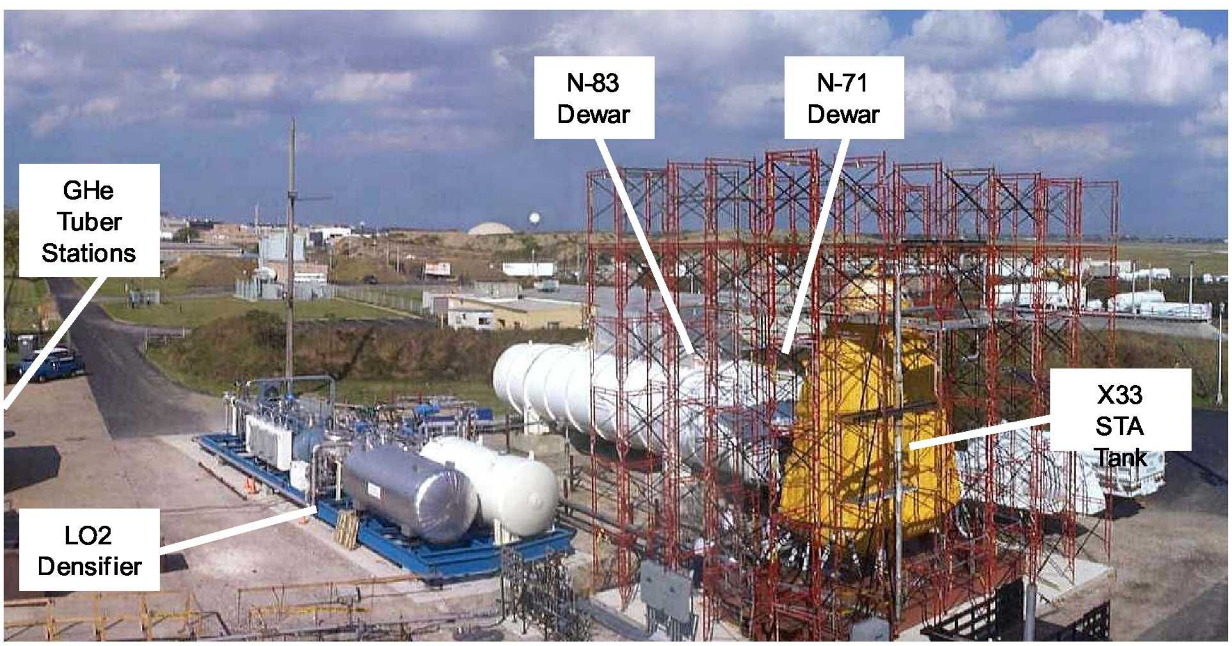


Figure 27. GRC South Forty (S40) LO2 propellant densification test facility.

4.2 Liquid Nitrogen System – Dewar N-71

Liquid Nitrogen (LN2) was used during facility LN2 cold shock procedures and densifier checkout and performance testing. Two different facility dewars would be used in LN2 service. Dewar N-83 supplied LN2 for the LN2 densification checkout tests of the LO2 Propellant Densifier Unit (PDU). Dewar N-71 was used to supply LN2 for the heat exchangers on the LO2 PDU during both LN2 and LO2 testing. Note that dewar N-83 also acted as the principal LO2 supply dewar for LO2 testing of the LO2 PDU.

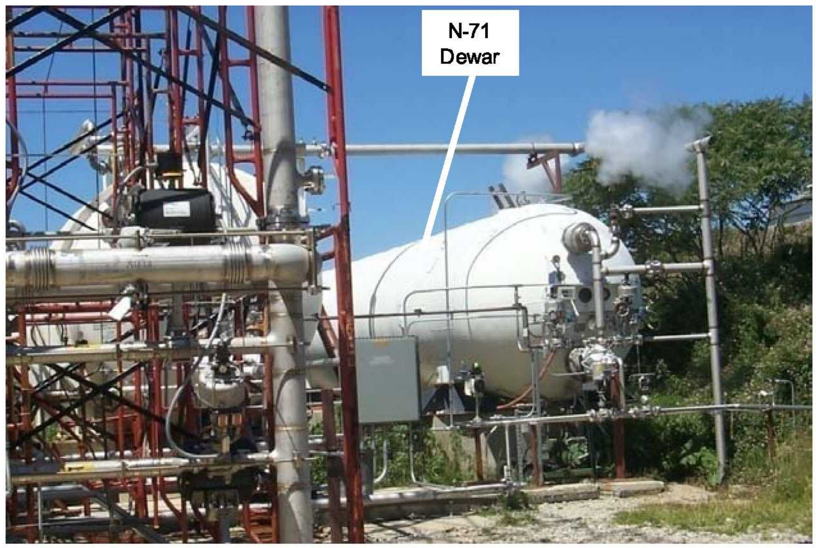


Figure 28. Working end of 13,000 gal. liquid nitrogen dewar N-71 at South Forty.

Dewar N-71 was a 13,000 gallon capacity liquid nitrogen stationary dewar which was installed at the S40 area specifically for these tests. The dewar, with the working end shown in **figure 28**, had a double-wall vacuum jacketed construction that was back-filled with perlite insulation. The maximum allowable working pressure for N-71 was 89 psig, however the dewars' primary relief valve was set at 50 psig. During PDU testing, N-71 was filled from the supplier's mobile dewars with a fill station located at the southern most corner of the storage vessel. Pressurization of this dewar was accomplished using an external GN2 source for ullage pressure control, operated at nominally 30 psig during PDU testing. Dewar N-71 was equipped with a remote operated vent valve, a back-pressure control valve, pressure safety relief devices, an LN2 fill/drain control valve and the operator fill station. Instrumentation and controls for this dewar included silicon diodes for liquid and ullage temperature measurement, a ΔP level indicator gage and a pressure transducer for remote ullage pressure indication and control.

4.3 Liquid Oxygen System – Dewar N-83

Dewar N-83 was a 28,000 gallon capacity LO2 storage vessel designed to supply LO2 for testing of the LO2 PDU as well as LN2 during checkout testing of the densifier with LN2. The dewar (**figure 29**) was modified to handle both LN2 and LO2 cyrogenic fluids and N-83 plans would be to warm, purge and inert the dewar before loading the dewar with different cyrogenic fluids during the transition. Pressure in N-83 was controlled at approximately 60 psig during a PDU test. Approximately 13,000 to 25,000 gallons of cryogenic fluid was expelled from N-83 while in a test mode. External pressurization of the dewar was by a GN2 pressurant gas supply line that was regulated by remote control valve XO-8315. This vacuum jacketed stationary dewar had a maximum operating pressure below 80 psig.

Early on in facility build-up, the dewar was cleaned in accordance with MSFC Spec 164B for liquid oxygen service. Remote operated valves installed on N-83 included liquid discharge, vapor vent, and gaseous nitrogen pressurization valves. Following each PDU test the sub-cooled cryogens, either LN2 or LO2, were reconditioned (i.e. warmed back up to NBP) and then were back-transferred from the STA tank to N-83. Vacuum jacketed piping on N-83 was installed to permit the dewar to be filled from the government supplier's mobile dewar at a remote fill station located to the north of N-83 near the site entrance. Instrumentation and controls for N-83 consisted of silicon diodes for liquid and ullage temperature measurement, a ΔP level indicator gage and a pressure transducer for remote ullage pressure indication and control.

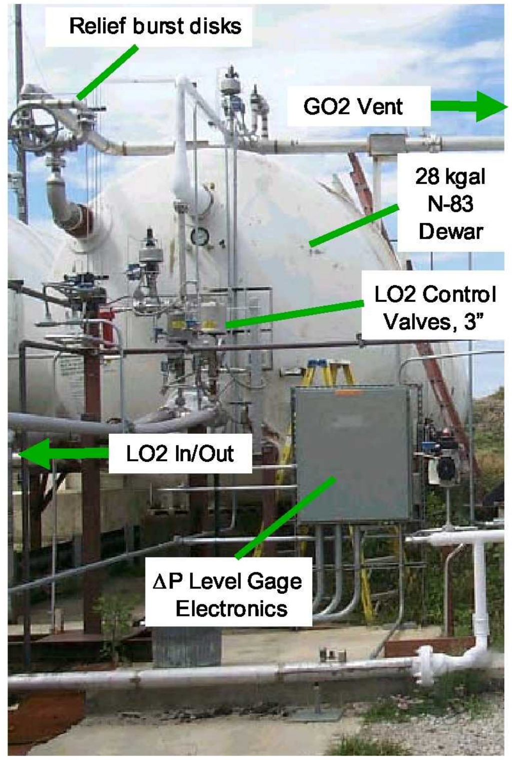


Figure 29. Liquid oxygen supply dewar N-83 during cryogenic flow testing.

4.4 Gaseous Nitrogen System

The Propellant Densification test site in the Upper South Forty area made use of the old Rocket Engine Test Facility (RETF) 4000 psig GN2 bottle farm (**figure 30**) that supplied the nitrogen needed for the testing. A portable LN2 vaporizer system consisting of a high-pressure pump, LN2 vaporizer coils, air fan, automatic controls and a 4,000 gallon LN2 Supply Dewar (N-43) was installed down at RETF adjacent to the C-Stand. This equipment was used to continuously maintain pressure in the GN2 bottle farm at approximately 2400 psig. An existing 2 inch pipeline from the 4000 psig bottle farm to the upper South Forty fed nitrogen gas to the boundary of the densifier test site. Gaseous nitrogen was used for purging and pressurization during the liquid nitrogen and liquid oxygen tests of the LO2 PDU. This arrangement was chosen due to the very high nitrogen usage requirements. The total capacity of the eight high pressure cylinder bottles was 1283 cu.ft (water volume). When fully pressurized, the system provided a reserve of nearly 300,000 standard cubic foot (scf) of gaseous nitrogen. All gaseous nitrogen flowing from

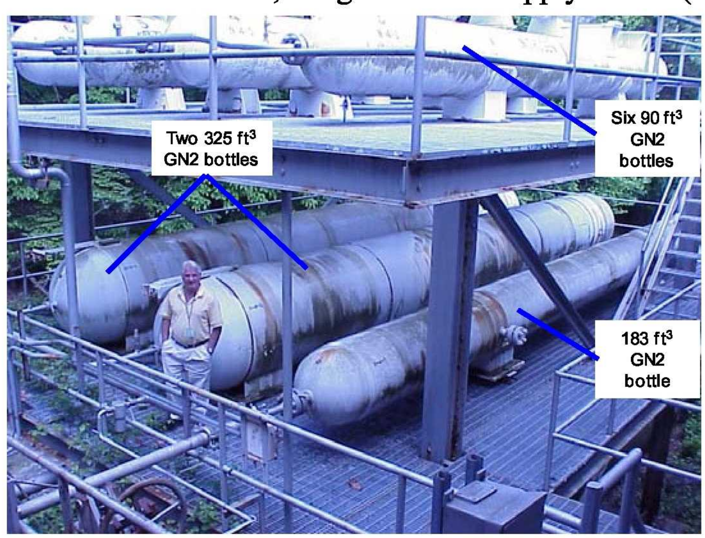


Figure 30. South Forty high pressure GN2 storage system rated at 2400 psig and 300,000 scf GN2 capacity.

the RETF bottle farm was initially regulated down to 450 psig. Nitrogen then fed into a low-pressure GN2 distribution system and was routed to the various points-of-use including valve actuators, the LO2 PDU, facility purge points and pressurization for N-71, N-83, and the STA tank. A new 2 inch gaseous nitrogen XXS stainless steel line was extended, from the S40 ridge where the line from RETF ended, and was run inside a trench before terminating at the facility GN2 pressure reduction station. The XXS nomenclature is a standard designation for an extra heavy wall pipe thickness which in this case was 0.436 inches for the 2 inch GN2 line.

4.5 Gaseous Helium System

The gaseous helium system (**figure 31**) for the propellant densification testing consisted of two GHe tuber stations installed at the S40 test site. Each supply station was a NASA tuber trailer with a 70,000 scf rated capacity per tuber. This system provided up to 140,000 scf of GHe maximum reserve. The trailers had an initial charge pressure of 3100 psig. Each tuber was connected to a common new 1.5 inch SS piping manifold that was routed to a single GHe pressure reduction and valve station. Here the GHe pressure was regulated down to 450 psig before the gas entered the low-pressure distribution and piping system. Gaseous helium was provided at 450 psig to the STA pressurization system and to the LO2 PDU interface. Other helium uses at the S40 test site included purges located at the STA vent and various facility purges to VJ transfer lines.

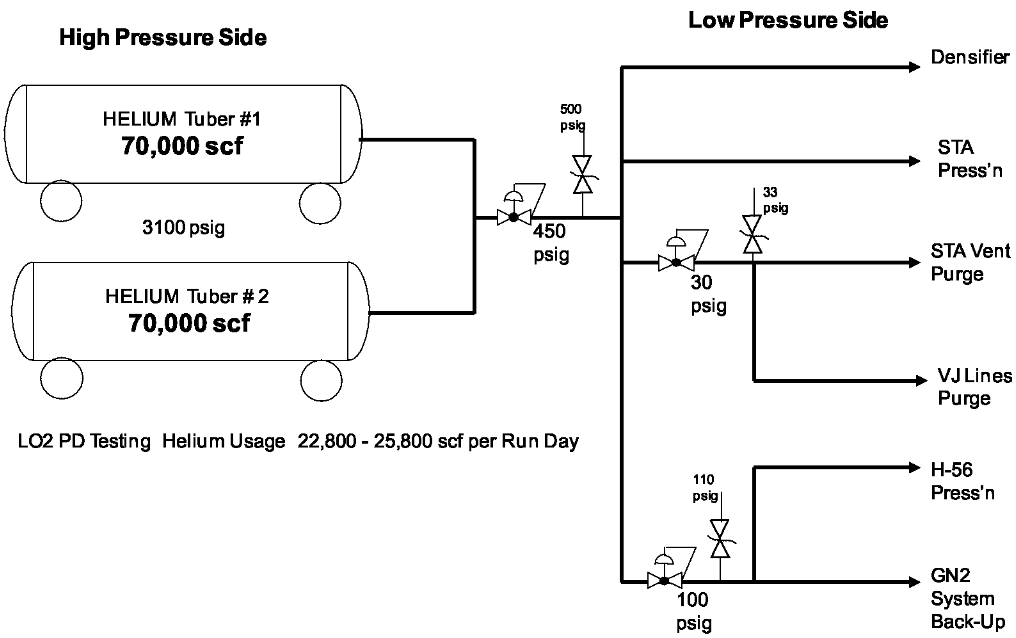


Figure 31. Gaseous helium system schematic for facility LO2 densification test article.

4.6 Facility Vacuum Jacketed Piping

The S40 facility vacuum jacketed (VJ) piping system consisted of ten prefabricated piping spool sections of sizes 2 , 3, and 4 inch diameters. These VJ lines were used to interconnect the LO2 densifier with the dewars and the STA tank. The densifier/STA test articles and a simplified facility flow schematic of cryogenic fluid systems is seen in **figure 32**. Specifically the VJ piping system design accomplished the following:

- For LO2 PDU testing, the vacuum-jacketed piping layout interconnected the LO2 densifier skid with the STA tank, and dewars N-71 and N-83.
- Critical fluid temperature and pressure sensors at the boundaries of the skid and STA were incorporated into the facility VJ piping systems.
- The VJ piping provided an easy bypass drain system from STA back to N-83.
- Miscellaneous foam insulated piping spools between dewars N-71, N-83, and the LO2 PDU facilitated other operations like post-test LN2 draining of the heat exchangers.

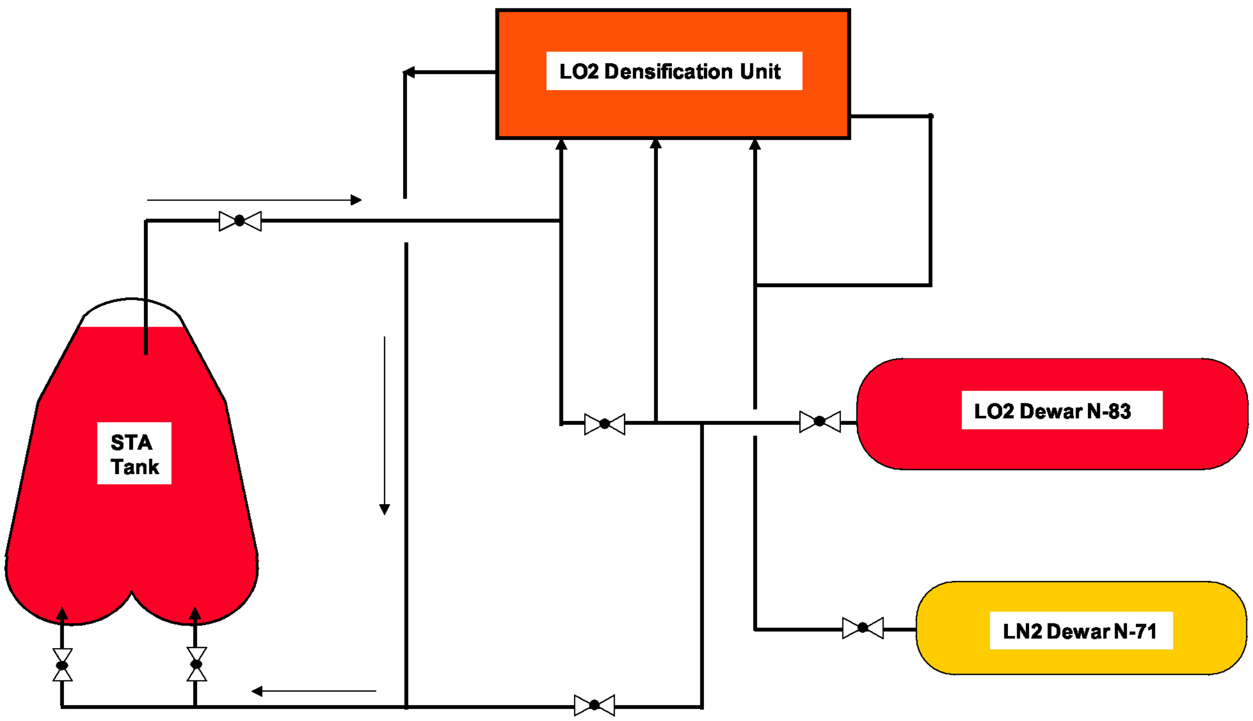


Figure 32. Densification process facility schematic for LO2 and LN2 systems.

Although much of the VJ piping for the S40 test was built and reconfigured from existing facility lines, the piping system had the following seven general design features: *(1)* the inner and outer lines of the VJ piping spools were constructed of Schedule 5 type 304 seamless or welded SS pipe per ANSI Process Piping Code B31.3; *(2)* the inner line design pressure was 150 psig at 530 ^{o}R while normal design operating temperature was 120 ^{o}R – 170 ^{o}R; *(3)* the inner line was wrapped with fifteen layers of aluminized mylar insulation and supplied with a chemical gettering system; *(4)* the vacuum annulus had a maximum acceptable vacuum level of 30 microns of Hg; *(5)* each spool assembly was fabricated with a seal-off and relief valve, a bellows sealed isolation valve and a thermocouple vacuum gauge tube; *(6)* mechanical bayonet field joints with warm O-ring seals and V-band connections were installed at the end of each spool piece to allow ease of field assembly and maintenance; and *(7)* expansion joints and VJ piping supports were located to allow for the thermal movement and flexibility of the finished piping system.

4.7 S40 Facility Test Article Vents

There were two principal facility test article vents installed at the S40 area: the densification unit 12 inch atmospheric vent for compressor exhaust; and the STA vent/valve package system. The design basis for the compressor discharge facility vent was defined from requirements for another densification system built at the GRC. This sister unit was an 8 lb_m/sec LH2 densifier with a four stage GH2 compressor and, this PDU too was also sized for the X-33.

The gaseous hydrogen compressor on the LH2 densifier was designed to vent up to 1.1 lb_m/sec of GH2 to the atmosphere. In order to safely disperse this very high gH2 flow rate by a non-flared type of system and stay within the allowable pressure drop margin (< 1.0 psid) of the compressor, a 12 inch vent system was designed and installed. This newly fabricated vent line at the S40 tied the exhaust of the compressor into a 12 inch Schedule 5 main trunk-line. The main vent line extended 210 feet horizontally and east away from the PDU skid. The line intersected with a 12 inch tee-branch and was split into five 6 inch vertical pipes that were terminated with a tee to further divert the flow both left and right. The calculated pressure drop for this system venting GH2 was 0.8 psid maximum. A thermocouple installed at each 6 inch vent outlet would allow monitoring gas temperature in the event of an accidental GH2 light-off ignited by static electrical discharge. During LO2 PDU testing, this same 12 inch facility vent system (**figure 33**) was connected to the GN2 three-stage compressor exhaust to allow safe dumping of GN2 away from the densifier skid. This safety feature was designed into the system in the likelihood that operators needed to be present near the LO2 unit while the GN2 compressor was running.

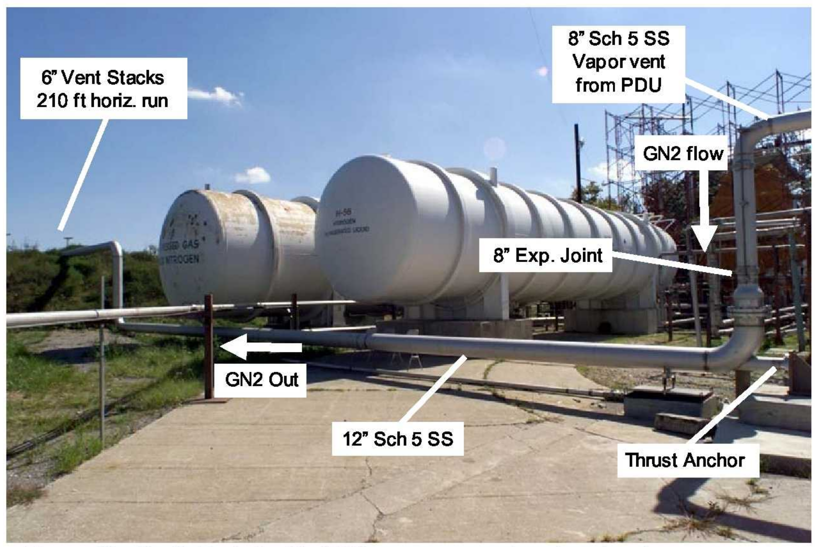


Figure 33. South-Forty facility GN2 compressor exhaust vent system.

The STA vent and valve package assembly was designed to prevent over-pressure of the STA as well as control tank ullage back-pressure by vent valve operation. This 3inch diameter Schedule 10 system (**figure 34**) consisted of two burst-disks in parallel each at 25 psig cracking pressure downstream of a 3-way valve (XO-2105), a 2 inch back-pressure control valve (XO-2104) and a 3 inch main vent valve (XO-2109) set to open by the facility PLC at a high ullage pressure of 24 psig. Instrumentation provided with the system included temperature and pressure transducers and an orifice run designed to measure the STA heat leak by a boil-off gas determination. The line size of the 3 inch assembly was increased to 6 inch Schedule 10 in a vertical riser section downstream to reduce gas pressure drop at high vent flow conditions. This particular system could vent several types of vapor during STA loading tests including GN2, GO2, GH2 and GHe. The nominal design value for venting GH2 vapor through the system was 0.5 lb_m/sec. (Note: Hydrogen densifier testing with the LH2 PDU and STA tank was cancelled by the MSFC Program Office. The LH2 densifier was however cold flow tested with liquid nitrogen at the S40 in 2002).

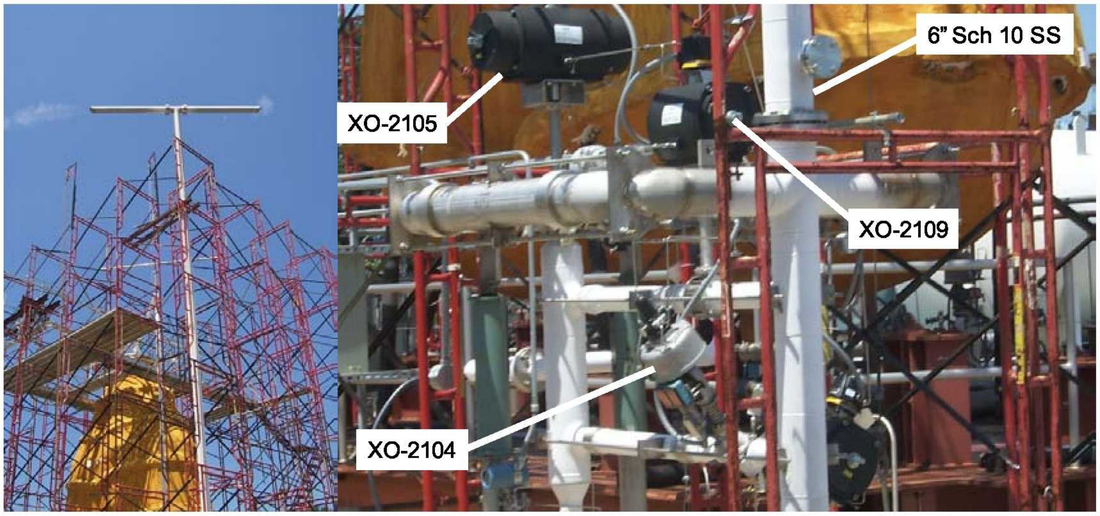


Figure 34. STA test article vent / valve package assembly.

4.8 S40 Electrical Systems

The South-Forty electrical system could provide up to 1000 KVA of power to the densification unit test site upper area. The main power supply cable ran from feeders located inside Building 202 to the densifiers 480 V, 3-phase, 60 Hz interface power feeder panel on the skid. The Substation at Building 202 was equipped with a 1200 Amp breaker which provided sufficient over current margin for densifier operations. The power supply requirements for the LO2 and LH2 densification units were 500 KVA and 750 KVA, respectively. The LO2 and LH2 PDU's would require up to 500 Amps and 800 Amps at 480 VAC, 3 Φ and 60 Hz, respectively.

In a GH2 test environment, electrical devices installed at the S40 test site were rated for Class I, Division II, Group B per the National Electric Code (NEC) for hazardous substances given the potential presence of hydrogen in the area during LH2 PDU testing. Other S40 electrical safety design features implemented to conform to the NEC included the use of purged electrical NEMA 4 cabinets, intrinsically safe circuits and explosion proof enclosures. The facility was equipped with lightening protection in the form of an aerial seven strand copper clad steel wire running diagonally over the test site. Three closed-circuit video cameras with zoom lens and pan/scan capability were positioned through-out the facility. The video cameras by Panasonic allowed remote visual monitoring of the STA tank, facility dewars and the densifier skid. An elaborate perimeter grounding system was constructed with 4/0 ground loops and 10 ft x 0.75 inch diameter grounding rods. Electrical grounds were installed on all facility dewars, the STA tank, the densifier skid as well as other required electrical and mechanical subsystems.

4.9 Facility Safety Systems

All systems at S40 were designed and installed to provide fail-safe, trouble-free operation. Design practices required that engineered systems conformed to the NASA Glenn H2 & Pressure Systems Safety Manuals and the Occupational Safety & Health Administration rules. To further assure quality assurance and worker safety, other standard design codes employed for facility systems included the ANSI/ASME B31.3 Process Piping Code, ASME Section VIII Div I

Pressure Vessel Code, MSFC Spec 164B for LO2 Cleanliness and the Compressed Gas Association Standard CGA S-1.3 for Pressure Relief Devices. Other features of safety devices implemented for the S40 test site included PLC health monitoring of critical system parameters and GH2 detectors in the event of LH2 testing. All pressure relief valves that were out-of-service for longer than one year were checked-out and re-certified by flow test.

4.10 Facility Instrumentation and Controls

The control room used for the S40 PDU testing was the Rocket Operations Building (ROB), commonly referred to as ROB, Bldg. 100. The building 100 control room was located approximately 2100 feet north-west of the S40 upper area. Temporarily located inside the control room (**figure 35**) was the densification skid operator control station, a S40 facility operator control station, four researcher PC work stations and video monitors with camera controls. A fiber-optic cable linked the densifier PLC with the PDU operator control station. South Forty facility instrumentation associated with the PDU testing included silicon diodes, pressure transmitters, differential pressure indicators, flow meters, thermocouples and capacitance liquid level probes. The densifier PC was set-up to be responsible for all facility data acquisition requirements. Facility data was recorded at a maximum record rate of one scan per second. Approximately 220 facility Input/Output data/Control channels fed the S40 facility PLC which was linked to the densifier IBM PC mass data storage via a ModBus Plus coaxial cable. Presented in **Appendix C** is a listing of the S40 facility instrumentation that was utilized at the test site.

Figure 35. Building 100 control room set-up for LO2 densification test operations.

5. TEST OPERATIONS and PROCEDURES

The following sections of the report provide general descriptions and a discussion of operations and test procedures with the LO2 propellant densification unit (PDU), the STA tank and S40 facility systems. Due to the scope of the program, testing would involve several different test setups and two different test fluids, which were LN2 then LO2. The planned test events at the GRC S40 densification site in the order of their occurrence were:

- GN2 Compressor Check-Out Tests
- LO2 Pump Check-Out Tests with LN2

- LN2 Performance Testing with LO2 PDU
- STA Boil-Off with LN2
- LN2 Thermal Stratification Tests with STA
- LO2 Performance Testing with LO2 PDU
- STA Boil-Off with LO2
- LO2 Thermal Stratification Tests with STA

5.1 Gaseous Nitrogen Compressor Check-Out Test Procedures

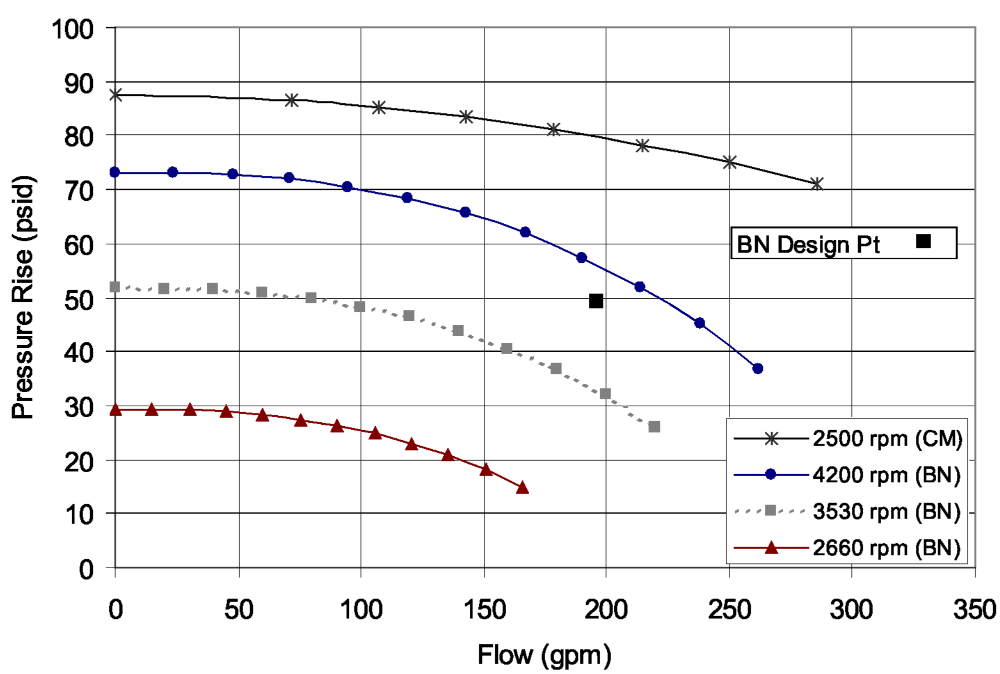
The purpose of the compressor tests were too evaluate compressor controls software, tune PID surge and pressure control loops, trouble-shoot hardware, verify start-up procedures, identify and test transients and achieve steady-state operation. Compressor start-up and check-out tests involved running the GN2 compressor under no external exchanger heat load. This means without an LN2 or LO2 flow stream moving through the heat exchanger tubes. Inlet gas flow rate conditions to the compressor were satisfied with the surge bypass system that dumped warm gas into the liquid bath causing nitrogen vapor to boil-off. Initially dewar N-71 was pressurized to 30 psig (45 psia) and was placed in a back-pressure control mode. Following line chill-down, the stage 2 heat exchanger bath level was replenished with LN2 to its normal operating level of 48 inches and the level controller was engaged. All of the appropriate LN2/GN2 valves positions were verified prior to compressor start. A “Reset” on the operator control console was activated which established a “Ready” light meaning proper communication existed between the PLCs. A test pressure control set-point in-between the control limit range of 2.4 – 10.0 psia was established and the compressor “Start” button depressed. The compressor spin-up process would begin as the rig would accelerate through two phases of ramp and then its speed would level-out as the test inlet pressure set-point at pressure transducer PT-715A was approached, at which point the compressor speed would stabilize to a constant value. The compressor would be allowed to run for a long enough period of time to demonstrate steady state conditions and then the test was stopped. After the compressor coasted to a stop following the aborted or controlled shutdown, the subcooled LN2 in the second stage heat exchanger would be re-warmed and brought back up to its NBP by GN2 injection into the LN2 bath.

5.2 LO2 Pump Check-Out Test Procedures

The purpose of tests with only the LO2 pump in operation were to verify actual pump performance in terms of measured head rise (ΔH) and delivered flow rate (Q_v). In addition, the testing was designed to trouble-shoot and tune the flow control loop of the pump’s variable speed control logic. The test operations involved initially pressurizing the pre-chilled STA to 30 psia. Before pressurizing, the STA vessel would normally contain some small quantity of liquid that wetted a lower vertical diode sensor near PVT-24. Dewar N-83 was pressurized with GN2 anywhere from 25 – 35 psig and then placed in a back-pressure automatic control mode with valve XO-8313. To add flow resistance to the fluid transfer system downstream of the LO2 pump, the skid control valve FCV-555 was manually throttled back to a designated percent open position. In the manual performance mapping tests, the LO2 pump was started and ran at a constant predetermined speed for a short period of time to allow collection of pump pressure rise (ΔP) and mass flow rate data points. As the test progressed, either the position of control valve FCV-555 was manually varied or the pump speed was step-changed, both over the allowable power capability of the motor drive at that particular operating speed. The range of operating speeds for test ranged from approximately 1000 rpm to 4200 rpm (design speed), and with control valve positions anywhere between 30% and 100% open. The flow path direction in these pump check-out tests was from dewar N-83, through the LO2 pump, across the densifier skid and then into the STA tank which acted as a collector vessel. The other variation of the pump test procedure was for control loop tuning purposes. In this test, a designated mass flow rate on the operator control console was selected, the pump started and then it was monitored for proper response of the pump to achieve and maintain the desired mass flow (W). Pump speed control was accomplished by an analog 4 – 20 mA control signal corresponding to a synchronous speed range of 0 – 4800 rpm.

Figure 36 shows the calculated ΔP-flow curve for the Barber-Nichols LO2 pump at its rated design speed of 4200 rpm. A reduced speed curve displays the predicted performance at 2660 rpm, and the dashed line indicates an intermediate LO2 pump performance envelope at 3530 rpm. For initial tests of the LO2 pump with LN2 as the test fluid, the differential pressure rise across the pump were different than design values and would naturally be reduced due to the lower LN2 density at the same pump operating point. A performance curve for a 200 gpm LO2 pump with a 15 HP close-coupled drive manufactured by the Cryo-Mach Corporation is also presented in the **figure 36** performance curve (CM). This particular centrifugal pump (**figure 37**) was used as a spare back-up during a significant portion of the LO2 PDU test series. Early on in the testing, the originally furnished LO2 pump from Barber-Nichols suffered reoccurring mechanical shaft seal leakage problems. Seal redesign and repairs were made, successfully correcting the problem near the end of the six-month LO2 PDU test program.

Figure 36. Barber-Nichols (BN) and Cryo-Mach (CM) LO2 pump performance curves.



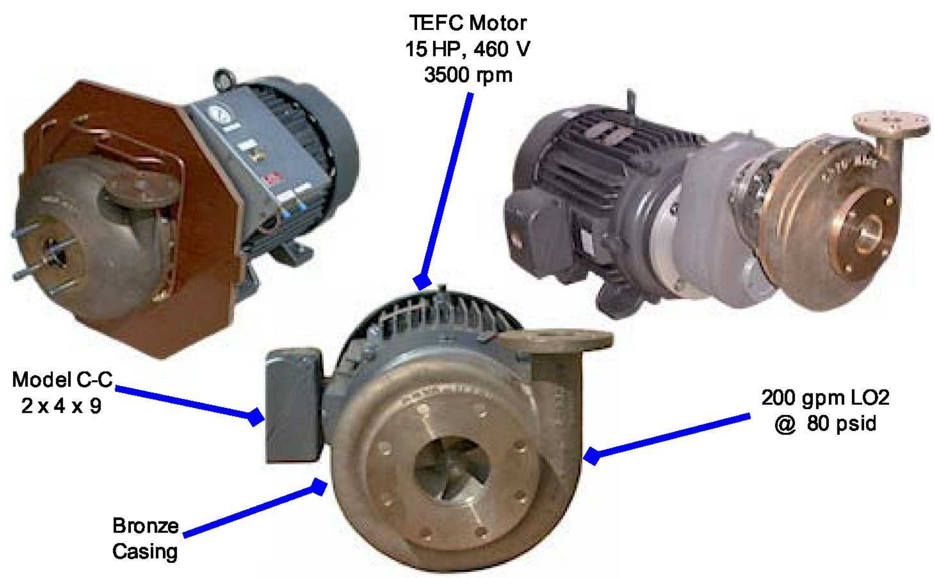


Figure 37. Cryo-Mach spare LO2 pump used during Barber-Nichols pump seal failure and repairs.

5.3 LO2 and LN2 Performance Test Procedures with LOX PDU *

The LOX densifier performance test procedure with liquid oxygen involved pumping NBP LO2 from the N-83 supply dewar through the densifier skid heat exchangers where the fluid was subcooled by an indirect heat transfer process as previously described. The densified LO2 at approximately 120 °R to 130 °R, this dependant upon compressor set-point pressure, exited the skid and was admitted into the STA which served as a receiver vessel or catch tank. The densifier performance flow test was continued until the STA tank became nearly filled to a normal operating liquid level set at 28 inches from the top of the tank. These STA Fast-Fill loading tests were conducted with both the GN2 compressor and the LO2 pump in concurrent operation. A simplified flow diagram (**figure 38**) of the LO2 PDU performance testing conducted with either LO2 or LN2 depicted the major flow-paths and test setup configurations utilizing the S40 facility dewars and the STA tank. The operational test procedures with LN2 as the product fluid exiting the densifier was essentially identical to when running performance tests with LO2.

General operations of the LO2 PDU performance test was first to pressurize the dewar N-71 to 30 psig (45 psia) for LN2 heat exchanger bath level maintenance. For these tests dewar N-83 was always filled or partially loaded with at least 20,000 gallons of liquid oxygen to accommodate the STA total fill volume available. The LO2 supply dewar ullage pressure was set to 35 psig (50 psia) by placing its controller (PIC-8390) in an automatic back-pressure mode while valve XO-8313 regulated GN2 pressurant flow to maintain the ullage set-point pressure. Prior to test, a liquid oxygen chill down of the following systems would take place: LO2 facility transfer lines; LO2 densifier skid fluid subsystems; and initial STA receiver tank chill-down and "partial" fill up to diode PVT-24 located at the 1,340 gallon mark. Liquid nitrogen facility transfer lines and skid LN2 systems were prechilled and primed from dewar N-71.

* *The densifier performance test procedures used for LO2 and LN2 were the same. The only significant process difference noted was the N-83 dewar service change, depending on the cryogen to be tested and the use of GHe purges on select LO2 transfer systems.*

The STA would then be pressurized with GN2 to 30 psia and was placed in automatic back-pressure control regulated by a pressurant supply valve (N-2214) and a vent control valve (XO-2104) both working in tandem to maintain the set-point pressure within ± 0.5 psi based on feed-back from the STA ullage pressure transducer (XO-2103). Three solid-state video cameras mounted near the skid were positioned to view the STA and skid test articles during the performance testing.

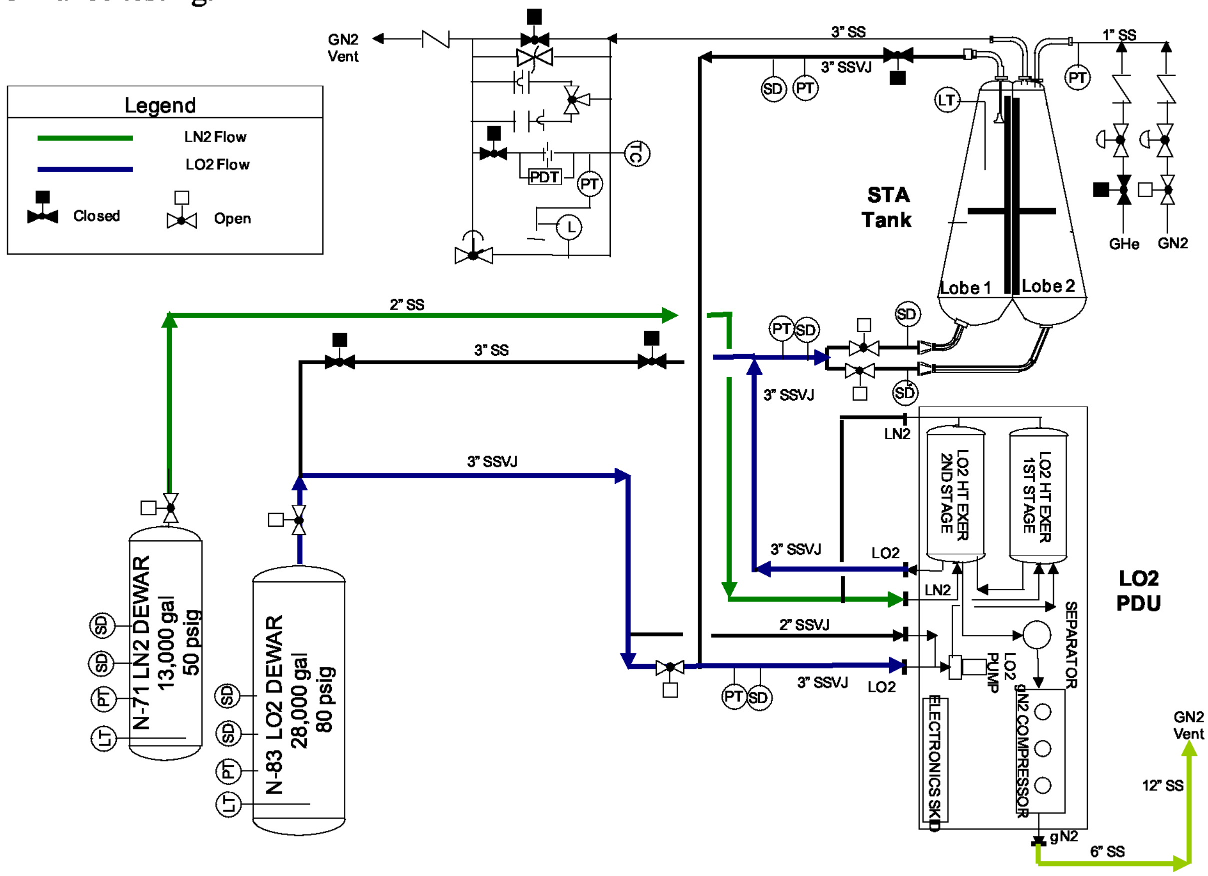


Figure 38. Simplified schematic of LO2 or LN2 Performance tests of LO2 Propellant Densification Unit at S40.

At the PDU, the LN2 supply flow path and continuous bath level control on both skid heat exchangers would be established, this originating at dewar N-71. Here, the liquid level control (LT-620) on the 1st stage heat exchanger LN2 bath was set to 51.8 inches while the 2nd stage bath level transducer (LT-615) set-point was 48.1 inches. A verification of valve positions was made for both the compressor and then subsequently the LO2 pump operation. Initially the start-up procedure of PDU rotating machinery consisted of GN2 compressor start with no heat load until stable operation was reached and then start-up of the LOX pump at a preset and constant speed to achieve the test mass flow rate of LO2. Typically the LO2 mass flow rate would be varied during the course of an STA loading test by changing control valve FCV-555 position to obtain performance mapping data of the PDU across a range of LO2 flows.

Densified LO2 entering the STA would be into both bottom inlet lobes for all of the Fast-Fill performance tests conducted. Termination of the LO2 performance test occurred when liquid oxygen reached a level associated with diode sensor PVT-3 at which point the LO2 pump was stopped and then the compressor was shut-down. Following rpm coast spin-down of the GN2 compressor, approximately 1,200 gallons of subcooled LO2 would be drained-back from STA to increase ullage volume as the fluid warmed and expanded during the 48 – 56 hour hold period inside the STA. Ambient heat leak to the STA would essentially re-saturate the fluid and warm the LO2 back to its natural NBP state of 162 °R. It's noted that due to the lower mass present and smaller temperature difference, the warm-up time for densified LN2 in the STA was only 24 – 36 hours. Prior to start of the next densifier performance test cycle, the 17,400 gallons of NBP LO2 inside of STA was back-transferred to dewar N-83 for reuse.

5.4 STA Boil-Off Test Procedure with LO2 or LN2 *

A single boil-off test would be run with the STA filled with normal boiling point (NBP) liquid nitrogen and, later on in the program with NBP LO2. The test was designed to measure the tank's steady-state heat leak and provide data for the LMMSS thermodynamic tank models. The general procedures for conducting a boil-off test of the STA tank would involve filling the tank with NBP LO2 to the 28 inch liquid level up to silicon diode PVT-2. The LO2 volume at the initial fill point was about 18,835 gallons of liquid, this corresponding to an ullage volume of 0.9 percent. The STA main vent valve (XO-2190) was closed while the orifice run isolation valve (XO-2112) would be opened. The GO2 boil-off vapor vent path would be through a 3 inch SS Sch 10 vent line where a square-edged orifice plate with a 2.12 inch ID was installed. Inlet gas temperature (T_1), upstream pressure (P_1) and orifice ΔP measurements were taken at one-second intervals. The boil-off test was continued for a minimum of three hours or until a steady-state thermal condition in the tank was reached while data was continuously recorded. The test was terminated after sufficient steady-state data was gathered as indicated by a constant boil-off mass flow rate (W_1). The orifice equation (eqn. 11), combined with the ideal gas law (eqn. 12) were used in the post-test data reduction process of the LN2 and LO2 STA boil-off tests conducted.

$$W_1 = 0.525\, Y\, C\, d_o^2 \sqrt{\Delta P\, \rho_1} \tag{11}$$

$$\rho_1 = \frac{P_1\, MW}{Z\, R\, T_1} \tag{12}$$

where

- C = orifice flow coefficient = 0.67
- d_o = orifice diameter, inch = 2.120 inch
- MW = molecular weight = 28.0 lb/lb-mol GN2 ; 32.0 lb/lb-mol GO_2
- P_1 = upstream pressure, psia
- ΔP = orifice pressure drop, psi
- R = gas constant = 10.7315 psia-ft^3/lb-mol °R
- T_1 = upstream temperature, °R
- W_1 = gaseous nitrogen or oxygen boil-off mass flow rate, lb_m/sec
- Y = expansion factor = 0.99
- Z = compressibility factor at 14.7 psia, 200 °R = 0.986 GN2 ; 0.982 GO2
- ρ_1 = upstream gas density, lb/ft^3

** The STA boil-off test procedures used for both LO2 and LN2 were the same with the exception of minor differences in the post-test data reduction equations for vapor density ρ_1 used to compute boil-off vent rates.*

5.5 LO2 or LN2 Closed-Loop Thermal Stratification Test Procedures with the LOX PDU *

The densifier closed-loop thermal stratification test procedure involved recirculating LO2 from the pre-filled STA and through the densifier skid where the fluid was subcooled. Initially the tank started out fully loaded with NBP LO2 at a constant 162 °R and then the recirculating flow would begin. The subcooled LO2 exiting the skid at 120 °R – 122 °R was then readmitted into one or both bottom lobes of the STA tank. The recirculation flow test would continue until the STA tank reached its thermal equilibrium limitation. This would take up to 4 hours depending on the recirculating mass flow rate during the test. The equilibrium condition by definition occurred when STA became completely chilled down with densified LO2 as indicated by the characteristic stabilization of the syphon outlet temperature at facility diode sensor XO-2305. A simplified process flow diagram (**figure 39**) of the STA tank with principal interfaces and S40 facility tie-ins illustrated the major fluid flow paths that were employed during an LO2 or LN2 closed-loop thermal stratification test. The operational run procedures with LN2 as the recirculating fluid were identical to the thermal stratification tests conducted with LO2.

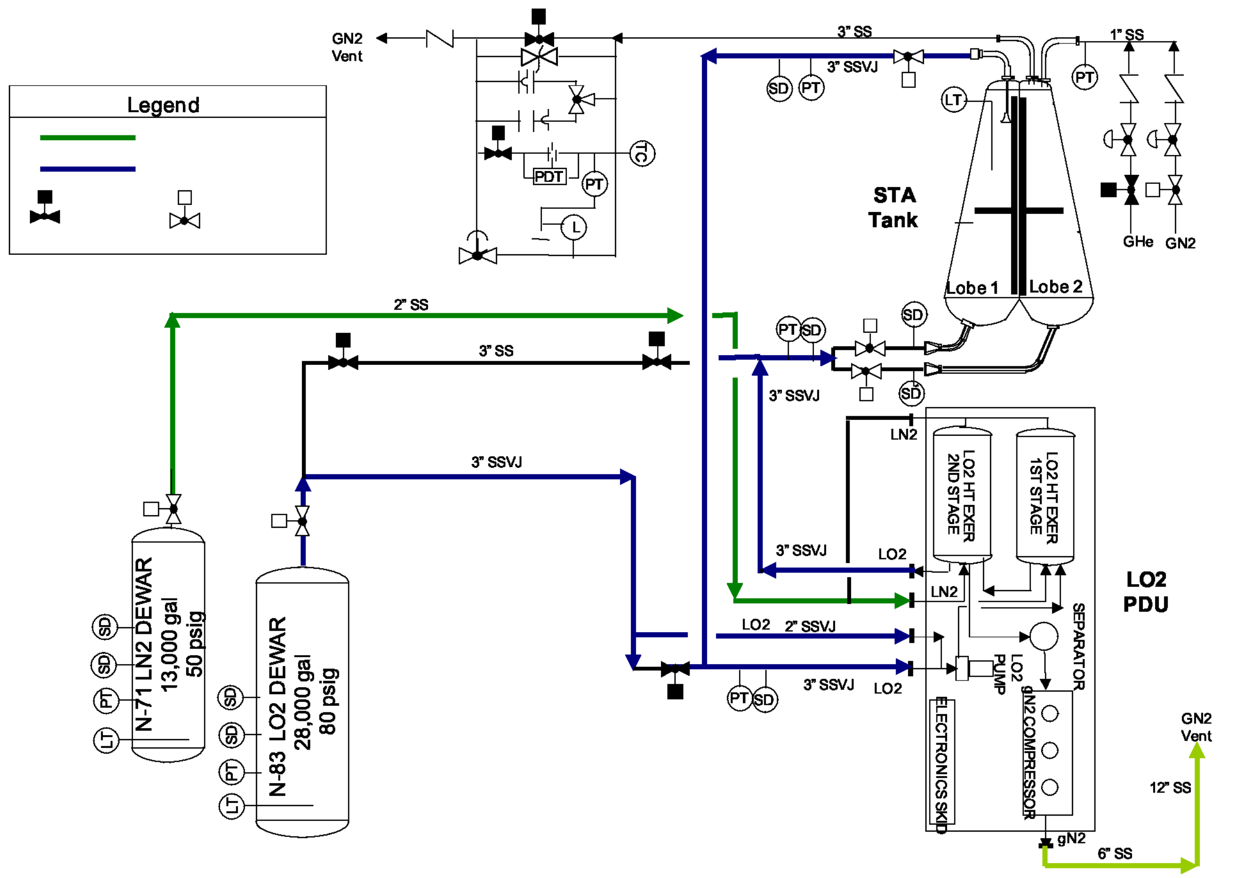


Figure 39. Simplified schematic of LO2 or LN2 closed-loop thermal stratification tests of LO2 PDU at S40.

** The densifier closed-loop thermal stratification test procedures used for LO2 and LN2 were the same. This only exception to this was the N-83 dewar service change, depending on the cryogen to be tested, LN2 or LO2, and the use of GHe purges on select LO2 fluid transfer systems.*

A key test article of operational importance, used during the LN2 and subsequent LO2 closed-loop thermal stratification testing, was the STA dual-lobe liquid oxygen tank. The significance of the test was to simulate on a large scale the production and loading operations of densified LO2 that would be used in an actual launch pad environment. The normal mode of operation for a typical LO2 closed-loop recirculation–thermal stratification test involved filling STA with NBP LO2 from dewar N-83 by pressure transfer. After liquid top-off, the STA ullage was pressurized to 30 psia with GN2 and set in a back-pressure control mode. Final chilling and priming of the LO2 syphon line 4 inch downcomer would take place by flowing from the top of STA and through the LO2 skid. High point and low-point bleeds in the STA outlet piping connecting the skid enhanced the operation for pre-establishing the flow. Operation of skid mounted equipment including pump, compressor and heat exchangers was as previously described. Closed loop flow of LO2 would be established by turning on the LO2 recirculation pump. The LO2 pump start-up occurred only after the GN2 compressor, that was pre-started earlier, had stabilized and reached its inlet pressure set-point typically running at 2.8 psia.

The LN2 supply dewar N-71 pressure was maintained at 45 psia for LN2 bath heat exchanger make-up and level control. The LO2 N-83 dewar pressure was held constant at 50 psia. The facility valves in-between N-83 and the LO2 PDU were configured to allow LO2 make-up flow to maintain the STA liquid level constant as a result of the densification process which lowered the fluids specific volume ($1/\rho_{LO2}$). The LO2 makeup valve on the skid was controlled based on the STA capacitance level probe (LIC-2000) which had a control set-point of 24.0 inches. A steady-state thermal stratification was achieved within about 4 hours of continuous recirculation of the densified cryogen. Steady-state was defined to occur when the STA siphon outlet temperature at diode XO-2305 stabilized with respect to the incoming fluid inlet temperature at diodes XO-2402/XO-2502 and this delta temperature ($\Delta T_{LO2} = T_{out} - T_{in}$) reached a minimum and steady condition. Like in the PDU performance test procedures, following shutdown of the GN2 compressor, approximately 1,200 gallons of subcooled LO2 was drained-back from STA to increase ullage volume and allow room for fluid expansion during the ground-hold. The densified fluid would then go into a hold period while it was stored in the STA to allow the fluid to re-saturate to its NBP, this typically being 24 – 36 hours for a load of LN2 and 48 – 56 hours for densified LO2. Prior to start of the next thermal stratification test cycle, the STA level was replenished with NBP LO2 from dewar N-83.

6. TEST RESULTS

6.1 Test Results Summary

This section of the report provides detailed results of each phase of testing conducted at the NASA GRC with the X-33 LO2 PDU, its components and the STA. In general, these month-long efforts culminated in successful demonstrations of the production and loading of densified LO2 inside the large-scale STA propellant tank. In excess of 150,000 gallons of densified LO2 and over 200,000 gallons of densified LN2 each at about 120 ^{o}R were produced with the PDU during the demonstration program. Of the original planned experimental matrix, the following major test accomplishments were completed during the five-month test campaign at the S40 facility: ***four*** PDU performance tests with LN2; ***one*** closed-loop thermal stratification test with

LN2; ***five*** PDU performance tests with LO2; and, ***four*** closed-loop thermal stratification tests with LO2. At the beginning of the program an STA LN2 cold shock test followed by a pneumatic proof pressure test at 60 psia were conducted with the STA tank as well. In addition, over ***150*** individual GN2 compressor start-up/performance tests and in excess of ***ten*** LO2 pump mapping/check-out test series were run. **Table 5.0** provides a chronological summary of the S40 test activities along with the date or period of actual test completion.

Table 5.0: Program summary of South-Forty LOX densification test activities.

	Chronological Densification Test Events
6/30 - 7/10/00	S40 facility LN2 cryogens on-site.
7/11/00	STA LN2 cold shock test.
7/13/00	STA pneumatic proof pressure test.
7/15 - 8/3/00	GN2 compressor start-up, trouble-shooting & check-out tests, Phase 1.
7/7 - 8/25/00	STA LN2 loading tests. Strain gage refurbishment & strut characterization.
7/21 - 9/15/00	BN LOX pump check-out, trouble-shooting & seal repairs.
8/22 - 10/4/00	GN2 compressor start-up, trouble-shooting & check-out tests, Phase 2.
8/25/00	STA boil-off test with LN2.
9/29/00	Replacement Cryo-Mach LO2 pump installed & tested.
9/22 - 10/7/00	LN2 performance tests of LO2 PDU (qty 4).
10/8/00	LN2 closed-loop thermal stratification test with LO2 PDU (qty 1).
10/10 - 10/14/00	S40 facility conversion from LN2 to LO2. LO2 cryogens on-site.
10/14 - 11/15/00	LO2 performance tests of LO2 PDU (qty 5).
10/26/00	STA boil-off test with LO2.
11/18 - 12/5/00	LO2 closed-loop thermal stratification tests with LO2 PDU (qty 4).
12/12/00	BN LO2 pump reinstalled, tested OK then LO2 STA loading test (qty 1).
12/13 - 1/15/01	Termination of densification testing. S40 facility clean-up of LO2.

The next eight sections of this report cover major test results, anomalies, tanking and de-tanking operations, ground hold of STA with densified fluids and densifier performance data for the following series of check-out and test events: GN2 compressor check-outs; LO2 pump performance tests; STA boil-off measurements, LN2 performance runs with LOX PDU, LO2 performance runs with LOX PDU, STA LO2 closed-loop thermal stratification testing, and finally a summary of system performance analysis results made in comparison to select design points of the densifier.

6.2 Gaseous Nitrogen Compressor Tests

A series of gaseous nitrogen (GN2) compressor and associated auxiliary system checkout tests were conducted over the course of eight weeks. This work started the week of July 15, 2000 in preparation for the start of actual S40 Propellant Densification planned test matrix runs. Through two phases of compressor testing, a total of approximately 150 individual GN2 compressor start-up and check-out test runs were ultimately made. On average at least 15 – 20 start-up tests were run during any given week, while in-between test runs, the transient and steady-state performance data was analyzed and corrective actions were made prior to re-test.

Preliminary start-ups of the GN2 compressor conducted early-on by GRC research personnel resulted in identification of numerous premature shut-down problems associated with specific compressor hardware and its PLC code. Even though the compressor was originally tested by the OEM in a series of shop air tests at their plant, new untested problems would only become evident while running fully loaded with the actual GN2 test fluid at cryogenic conditions and near compressor design point speeds. Beginning in late July, and with the assistance and on-site support from a Barber-Nichols technical representative, a systematic GN2 compressor start-up, trouble-shooting and check-out test program began. Typical compressor speed, interstage pressure profiles, gas interstage temperature profiles and GN2 mass flow rate transients as they developed during a nominal compressor start-up test are as shown in **figure 40** through **figure 43**, respectively.

Figure 40. gN2 compressor speed vs. time profile.

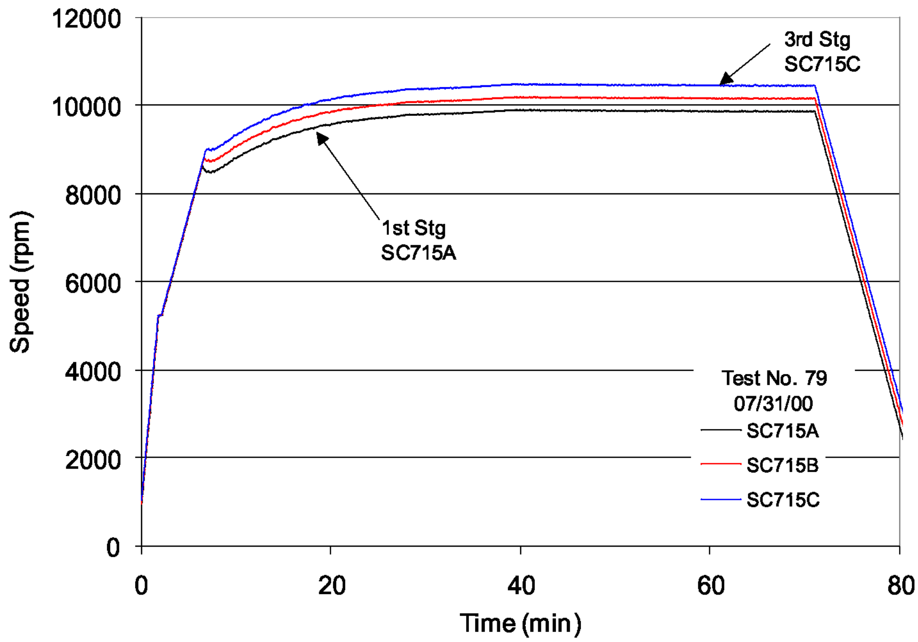


Figure 41. Compressor interstage pressure profile.

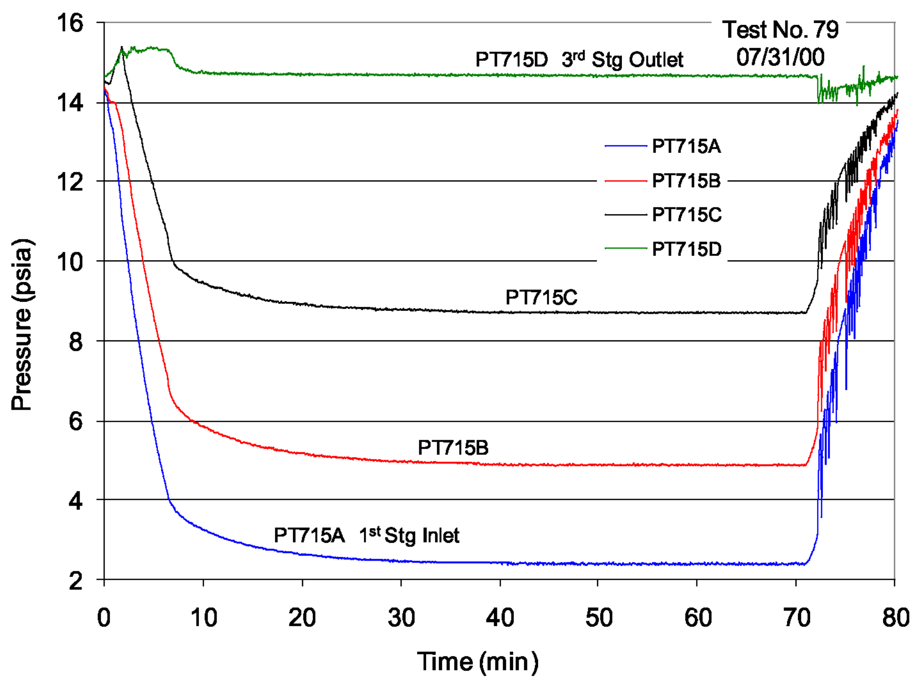


Figure 42. Compressor interstage gas temperature vs. time.

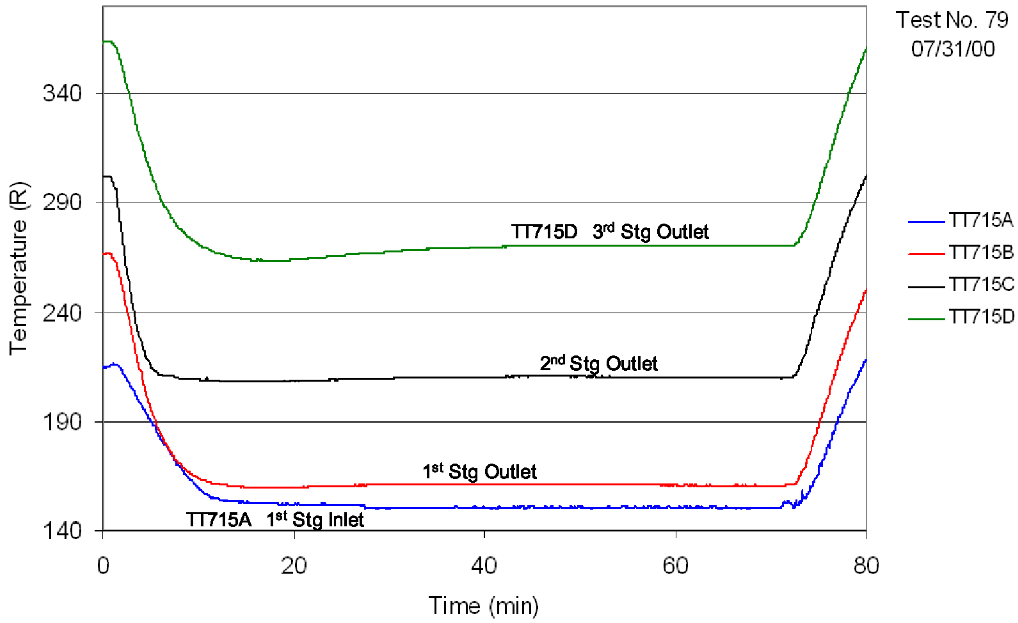
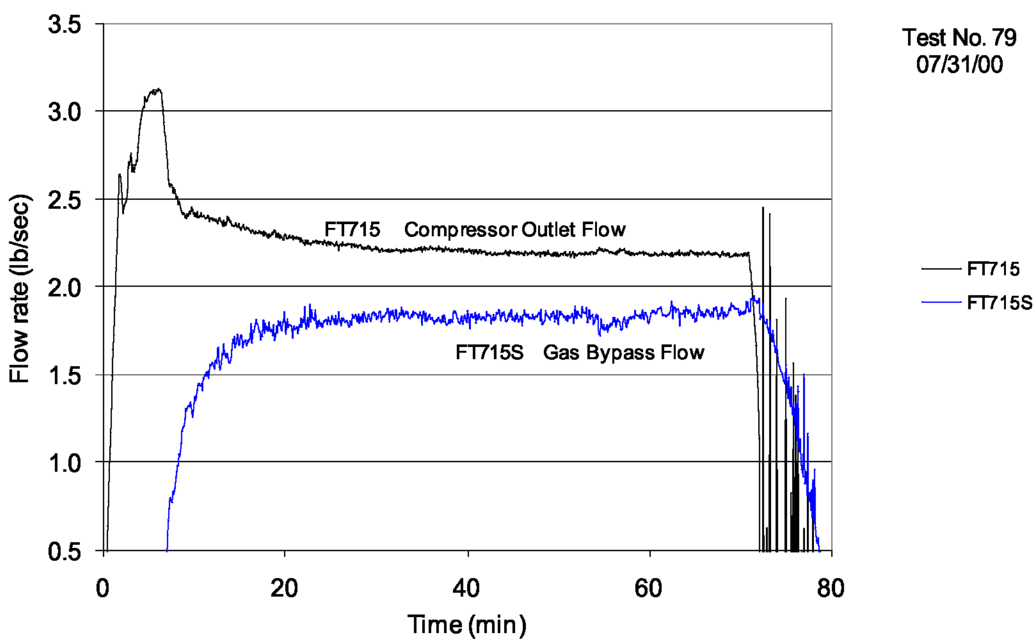


Figure 43. Compressor mass flow rate and gas bypass flow vs. time.



Initially several PLC tuning parameters and compressor control software changes were made and then tested. The majority of these changes resulted in gradual improvement to obtain a more stable, lengthy and fault-free operation of the compressor. Troubleshooting of the compressor PLC settings continued on with the goal of achieving the desired inlet pressure design point condition of 2.4 psia without a fault shutdown occurring.

Four prevalent types of fault shut-downs the test team faced included the following: 1) over-current (OC) shut-down events indicated in **figure 44**; 2) a surge instability shut-down as illustrated in **figure 45** with resultant loss or reversal of flow; 3) nuisance high "spike" vibration shutdowns shown in **figure 46**; and 4) a high motor winding temperature shutdown that affected all three stages. The vibration shutdown was perceived as a nuisance issue because the high vibration data peak lasted just momentarily. Issue number four was likely the most challenging of these problems. This problem would repeatedly occur during normal sustained compressor operation and then lead into an early shutdown (**figure 47**) on a high motor winding temperature redline specified at $T_{motor} > 310$ °F (770 °R) that developed after only about two-hours of run-time. It is noted that the LOX densification production timeline requirement for X-33 was 2.5 hours. Numerous PLC tuning parameters and compressor control software changes were made, downloaded to the slave PLC and then retested. These included for example, stage speed ratio constants, flow coefficient control

Figure 44. Compressor over-current (OC) fault shutdown.

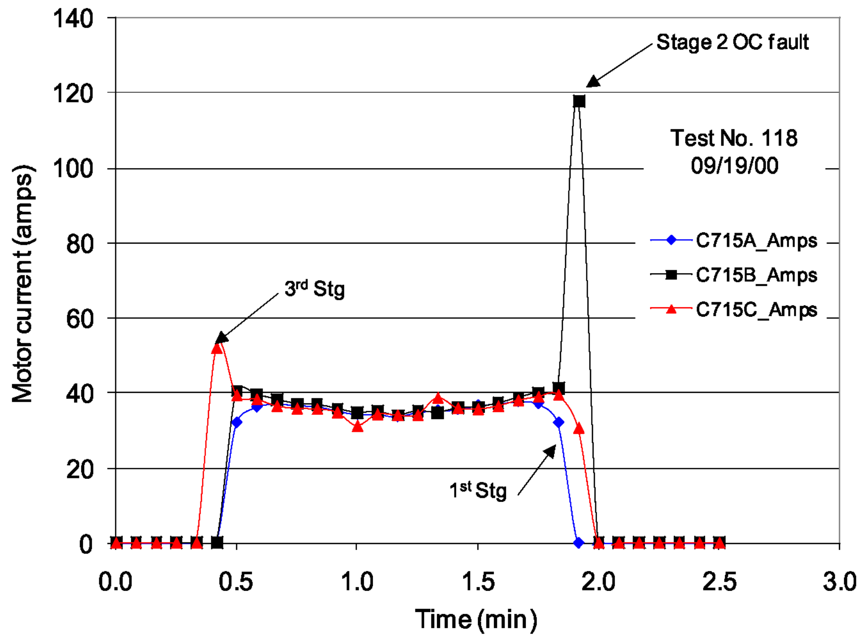
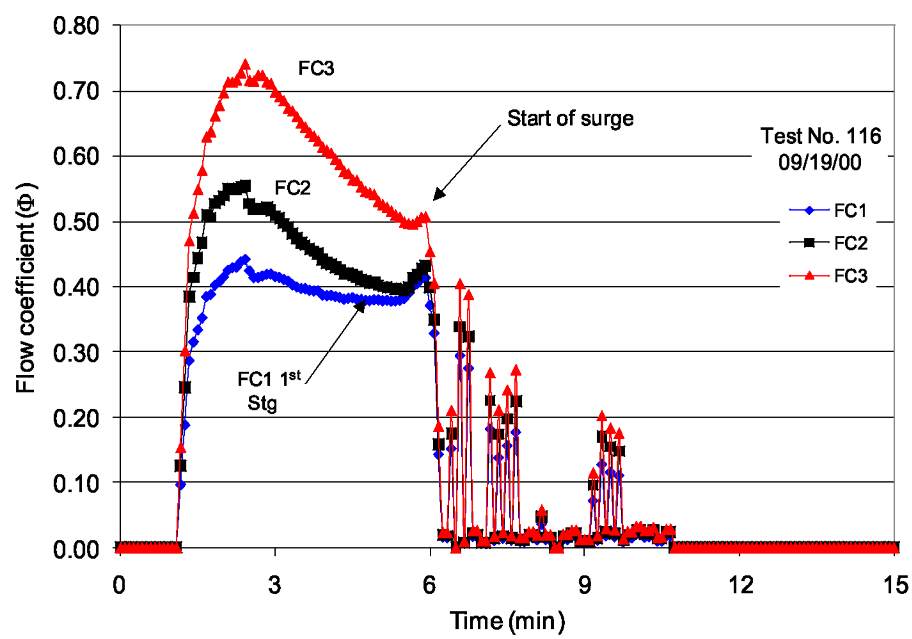


Figure 45. Compressor flow coefficient surge instability shut-down.



set-points, PID gain constants for inlet pressure and surge avoidance control, high and low shut-down limits, and internal PLC scaling parameter adjustments.

Figure 46. GN2 compressor high vibration shutdown event.

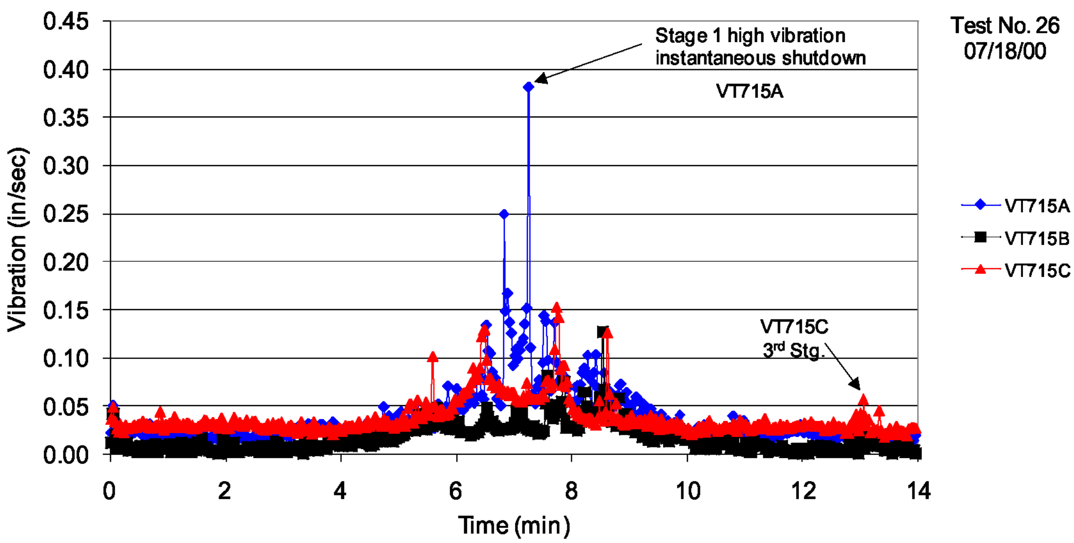
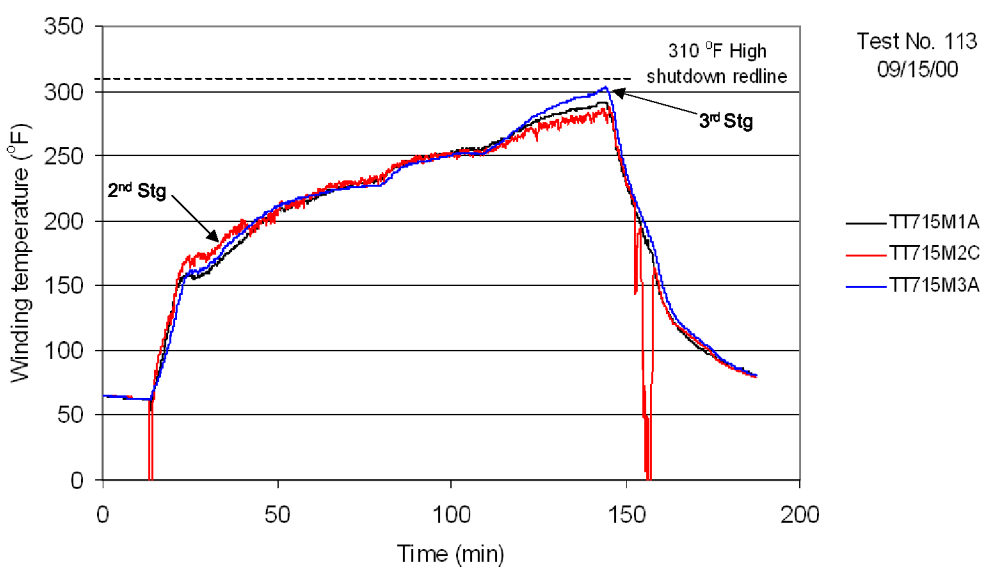


Figure 47. Compressor high motor winding temperature performance issue



A remote RS485 interface from the Building 100 control room to the compressor PLC located at the S40 site was subsequently set-up and put into operation. This added feature helped allow expedite changes being made to the compressor controls software. The compressor control problems appeared to be effectively resolved after about six weeks of continuous onsite set-up, testing and adjustments by Barber Nichols and GRC research engineers. These operating successes were compounded by several critical hardware failures and performance issues which had occurred with the GN2 compressor skid during the six month S40 test program. **Table 6.0** describes the more significant GN2 compressor hardware problems that GRC encountered during test operations with follow-on descriptions of key activities briefly discussed below.

Table 6.0: Gaseous nitrogen compressor hardware failures and operational issues.

Date(s)	***Location / Stage No.***	***Failure / Fault Condition***	***Corrective Action Taken***
8/1/00	Stage 3 drive	Motor winding ground fault short	Motor stator replaced by BN
8/31/00	Stage 2 VFD	VFD control and genius card failures	Parts replaced inside VFD2
9/13/00	Stage 2 VFD	Internal corrosion on contacts causing VFD fault shut-downs	New VFD installed on Stage 2
10/04/00	Stages 2 and 3	Current induced harmonics on drive motors	Reduced operating speeds to stay below 10,000 rpm critical speed where currents would fluctuate.
10/31/00	Stage 1 drive	Lower bearing failure	New bearings installed by BN
As-built	All Stages	High motor winding temperatures at less than design full load current	Reduced flow coefficient controller set-point from 0.25 to 0.18. De-rated inlet pressure performance from 2.4 to 2.8 psia

As previously mentioned, the GN2 compressor AC drive motors were found to run too hot at or near the normal design point of the compressor system. The lowest attainable set-point pressure the PDU could be operated at would be 2.8 psia which is 0.4 psi above design. It was determined that this would be a necessary condition in order to prevent the compressor system from shutting down by a high-motor winding temperature shut-down during a sustained compressor test run. According to BN the OEM, the normal expected SS motor operating temperature should be about 220 °F while the shutdown was automatically setup in the PLC to occur at 310 °F. This protected the motor internals from insulation burn-out. The de-rated operation resulted in a moderate performance loss on the expected PDU outlet LO2 temperature by about 1 – 2 °R because of a resultant 3 – 4 °R higher stage two heat exchanger bath temperature. The high motor winding temperatures was later diagnosed to be due to an inadequate thermal design of the glycol cooling system on the 70 HP drive motor system. This deficiency attributed to marginally low ΔT measurements (~ 3 °F) of the coolant fluid. Internally generated heat could not be sufficiently removed from the motor stator walls when the compressor was running "near fully-loaded" at the 2.2 to 2.4 psia design inlet pressure while drawing current well below its rated design Full Load current of 88 amps as shown in the **figure 48** plot of motor temperature and current transients during LN2 performance Test 1A run on 09/22/00.

Another operational issue associated with the GN2 compressor was an observed current-induced harmonics phenomena as shown in **figure 49**. A high amplitude current oscillation was typically found to occur on Stages 2 and 3 but only when the GN2 compressor would approach and was operated at approximately 10,000 rpm. Neither the GRC test operations team nor the BN field service engineers could identify the cause or resolve this current oscillation problem. This therefore became another reason for "de-rating" the compressor design point speeds by at least 100 rpm to stay below the 10,000 rpm "critical-speed" region where the Stage 2 and 3 currents were observed to start to fluctuate.

Figure 48. Compressor current and motor winding temperature vs. time.

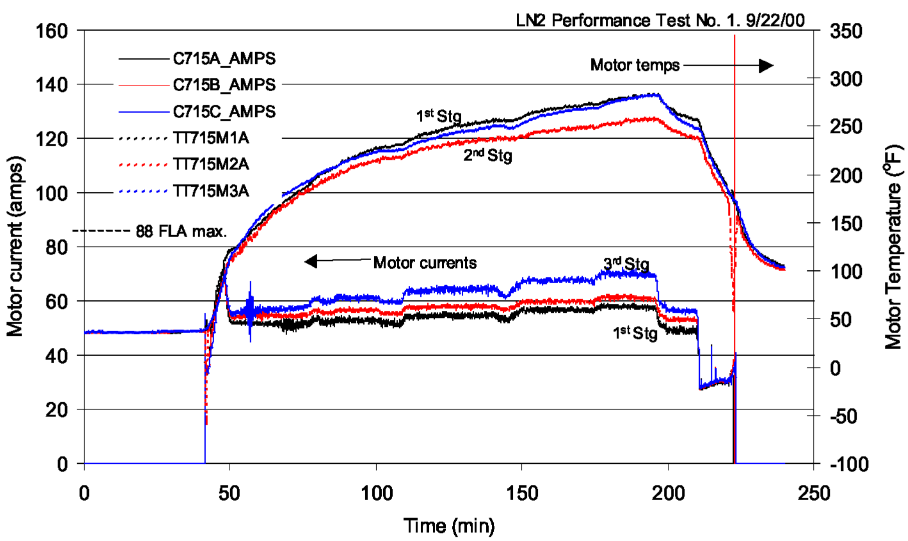
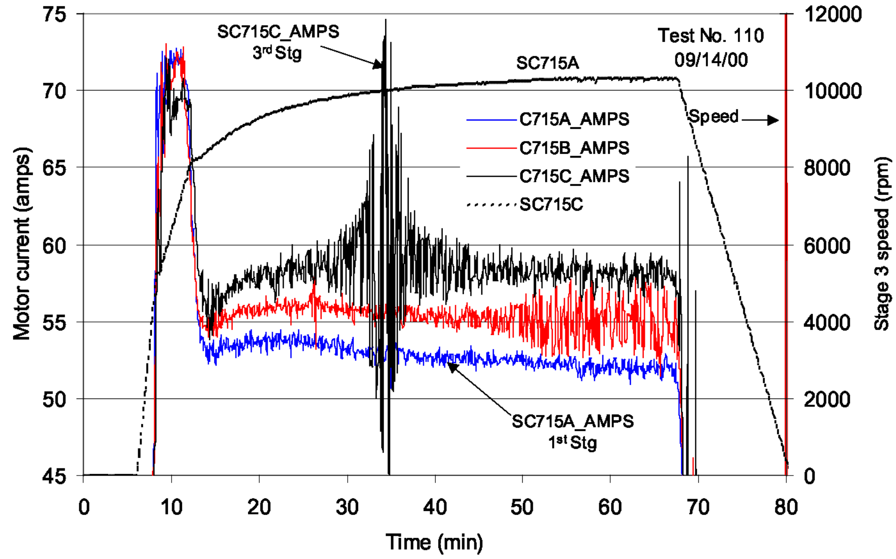


Figure 49. Compressor motor current oscillation vs. speed anomaly.



The troubleshooting activities continued on through several weeks time until GRC engineers corrected or developed "work-arounds" of all issues and finally became satisfied with compressor performance, reliability and operation. As of October 4, 2000 the final set of PLC tuning parameters and compressor control software changes were made and then tested. The test team made the decision that compressor control and performance issues had been satisfactorily corrected during the check-outs. Those issues reconciled included surge avoidance tuning, resolving over-current shutdowns, elimination of nuisance vibration shutdowns and debugging of high drive motor operating temperatures. The modified target goal of 2.8 psia inlet pressure into the first compressor stage were routinely demonstrated during at least ten long duration (> 120 minute) system tests of the GN2 compressor. These particular tests resulted in a controlled system shutdown ("OFF button depressed") and gave performance that closely achieved the LOX PDU production goal of 30 lb_m/sec of LO2 at 120 °R outlet. Results of six representative GN2 compressor check-out tests during this specific Phase of the program, each at a steady-state condition, are tabulated in **Table 7.0**. **Appendix D** contains two complete sets of representative GN2 compressor start-up data plots (Test no. 79, 7/31/00) as the rig was operated both prior to final PLC tuning changes completed on October 4, 2000 and then during the follow-on LN2 and LO2 performance tests (Test no. 144, 10/27/00).

Table 7.0: Gaseous N2 compressor performance check-out test data and steady-state (SS) results.

Tag / ID	*Description – GN2 compressor steady state data* ‡	*No. 73 7/29*	*No.79 7/31*	*No. 82 8/22*	*No. 84 8/23*	*No.110 9/14*	*No.144 10/27*
N/A	GN2 compressor run time, min	61	84	70	88	74	92
SC715A	Stage 1 speed, rpm	10740	9912	10254	10432	9718	9332
SC715B	Stage 2 speed, rpm	11062	10202	10560	10744	10012	9612
SC715C	Stage 3 speed, rpm	10416	10504	10866	11058	10304	9894
FT715	Compressor vent flow, lb/sec	2.06	2.19	2.17	2.09	2.12	2.05
FT715S	Compressor surge flow, lb/sec	2.51	1.80	1.87	1.67	1.91	0.72
FT607	Heat exchanger bath fill, lb/sec	1.40	0.62	1.05	1.17	0.87	1.11
FC1	Stage 1 flow coefficient, Φ_1	0.228	0.256	0.257	0.255	0.249	0.238
FC2	Stage 2 flow coefficient, Φ_2	0.189	0.221	0.220	0.214	0.214	0.213
FC3	Stage 3 flow coefficient, Φ_3	0.176	0.191	0.189	0.180	0.186	0.188
PT715	Stage 2 ht-exer, ullage press, psia	3.09	2.78	2.71	2.70	2.86	3.02
TT703A	Stage 2 ht-exer, ullage temp, ^{o}R	120.5	119.4	120.7	124.1	119.8	122.6
PT715A	Stage 1 inlet pressure, psia	2.39	2.38	2.41	2.02	2.42	2.80
TT715A	Stage 1 inlet temp., ^{o}R	152.1	234.5	143.0	142.2	163.2	139.8
PT715B	Stage 2 inlet pressure, psia	4.94	4.88	4.84	4.50	4.94	5.45
TT715B	Stage 2 inlet temp., ^{o}R	166.9	200.5	167.3	163.2	160.1	167.9
PT715C	Stage 3 inlet pressure, psia	9.05	8.67	8.73	8.39	8.69	9.31
TT715C	Stage 3 inlet temp., ^{o}R	216.4	225.0	220.7	217.8	207.4	219.7
PT715D	Stage 3 outlet pressure, psia	14.62	14.64	14.80	14.66	14.55	14.72
TT715D	Stage 3 outlet temp., ^{o}R	262.4	221.5	282.6	281.5	264.7	269.4
C715A VolQ	Stage 1 outlet volume flow rate, cfm	1601	1662	1725	1742	1580	1450
C715B VolQ	Stage 2 outlet volume flow rate, cfm	1133	1222	1262	1246	1163	1111
C715C VolQ	Stage 3 outlet volume flow rate, cfm	850	930	954	923	886	862
C715A Volt	Stage 1 motor voltage, volts	460.0	433.8	449.1	456.8	425.9	408.9
C715B Volt	Stage 2 motor voltage, volts	460.0	447.0	460.0	460.0	438.6	421.3
C715C Volt	Stage 3 motor voltage, volts	456.3	460.0	460.0	460.0	451.3	433.4
C715A Amps	Stage 1 motor current, amps	66.0	52.7	53.5	51.9	52.3	47.1
C715B Amps	Stage 2 motor current, amps	70.5	55.7	56.5	57.0	54.6	48.5
C715C Amps	Stage 3 motor current, amps	68.7	61.1	63.5	61.8	58.0	48.0
TT715M1A	Stage 1 motor winding "A" temp. ^{o}F	250	235	245	257	217	187
TT715M1B	Stage 1 motor winding "B" temp. ^{o}F	213	201	210	220	185	161
TT715M1C	Stage 1 motor winding "C" temp. ^{o}F	237	225	233	243	207	183
TT715M2A	Stage 2 motor winding "A" temp. ^{o}F	231	222	231	239	209	176
TT715M2B	Stage 2 motor winding "B" temp. ^{o}F	233	224	234	243	206	174
TT715M2C	Stage 2 motor winding "C" temp. ^{o}F	234	237	242	250	225	193
TT715M3A	Stage 3 motor winding "A" temp. ^{o}F	206	233	255	263	224	180
TT715M3B	Stage 3 motor winding "B" temp. ^{o}F	202	228	255	263	222	183
TT715M3C	Stage 3 motor winding "C" temp. ^{o}F	189	214	252	261	222	177
VT715A	Stage 1 vibration sensor, in/sec	0.167	0.120	0.129	0.118	0.135	0.127
VT715B	Stage 2 vibration sensor, in/sec	0.118	0.101	0.132	0.112	0.172	0.083
VT715C	Stage 3 vibration sensor, in/sec	0.099	0.096	0.007	0.007	0.084	0.071
ZT715	Gas bypass control valve FCV715 position transmitter, % closed	16.7	29.8	28.5	28.3	25.2	53.1
N7113	Dewar N-71 LN2 total outflow, gal	1260	530	580	760	510	1180
N7117	Dewar N-71 pressure, psig	17.9	19.8	20.1	23.2	20.1	20.0

Note: ‡ LN2 or LO2 recirculation flow rate at FT535 was zero for all compressor check-out test runs reported above.

6.3 LO2 Pump Performance Tests

A series of LOX pump checkout tests began during the week of 7/23/00 in preparation for the start of the South Forty Propellant Densification planned test matrix. An immediate problem developed, however during initial start-up tests of the skids' LO2 pump while flowing with LN2 at relatively low upstream and downstream pressures. The problem was that a significant leakage problem with the pumps' shaft mechanical seal had apparently occurred.

Replacement of the Barber-Nichols LOX pump seal was initiated. The test team concluded that the seal appeared not to have failed on the very first cryogenic pump flow test attempt with LN2. The pump was removed from the system and a component repair and change-out was accomplished. Repair inspections showed that the LOX pump seal was not physically damaged, out-of-tolerance or worn. Several mechanical changes per BN recommendations were made in the field by SLI technicians despite the intact appearance of the seal. These included hardware surface re-polishing and replacement of the flexible Variseal. The pump was later reinstalled on the LOX propellant densification unit on 7/28/00. A repeat LN2 cryogenic pump flow test was conducted in-parallel with a planned STA loading experiment on 7/30/00 but showed no real improvement to LN2 leaking from the shaft seal of the pump as indicated by the radial pattern of spray emitted seen in **figure 50**. The BN pump was removed from the PDU skid and return shipped to the OEM shop for seal design reassessment, warranty repair and testing. The failed LOX pump remained at the manufacturers shop for about four weeks and then arrived back at GRC on August 26th for retest evaluation. The LOX pump was reinstalled on the densifier skid with checkout tests completed on 09/01/00. These efforts resulted in a second pump seal failure that was worse than the original leakage rate initially observed. The seal design changes were ineffective with the pump rotating and while it was very cold at LN2 temperatures. Pump LN2 performance test data was however obtained, while the BN pump was operated for a short duration with the leaking shaft as shown in **figure 51**.

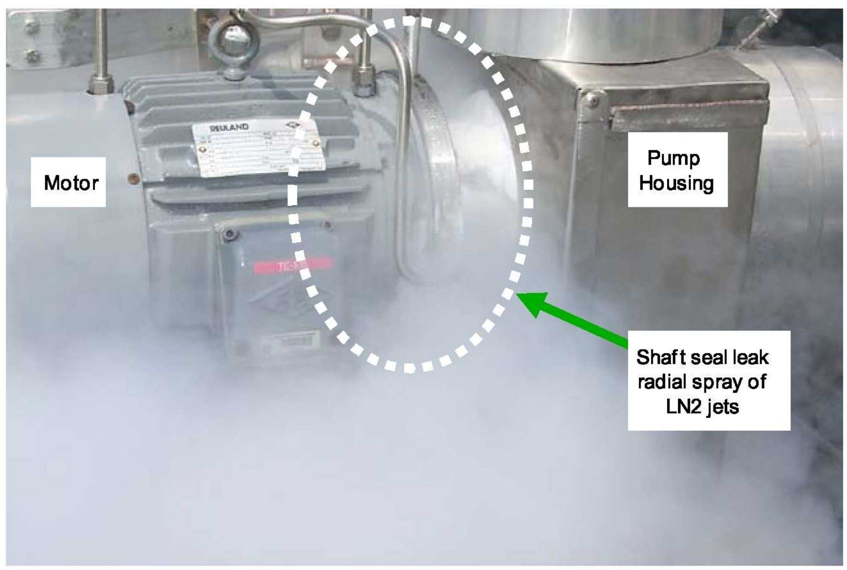
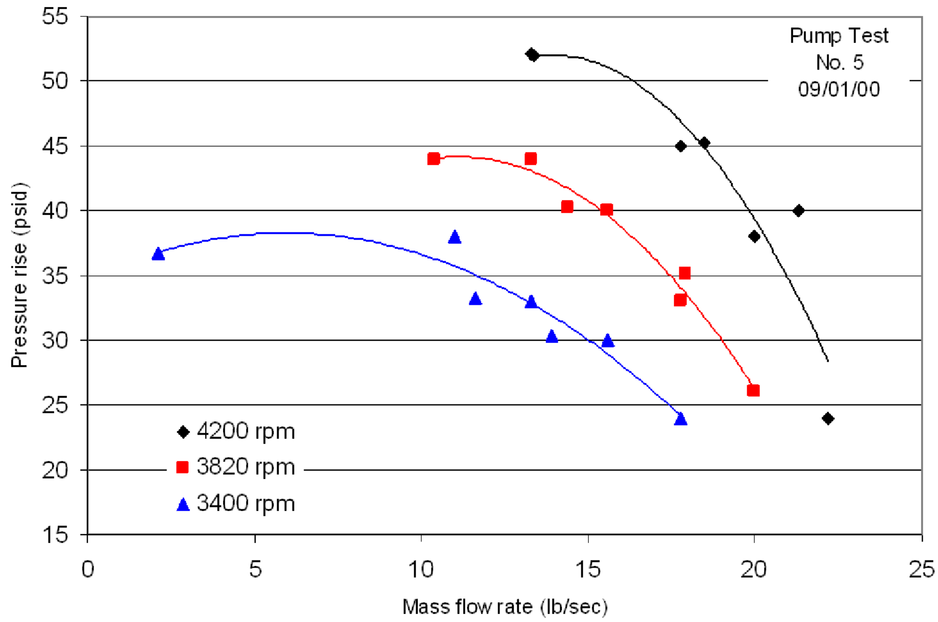


Figure 50. Mechanical shaft seal leakage of LN2 during 9/1/00 BN pump check-out test.

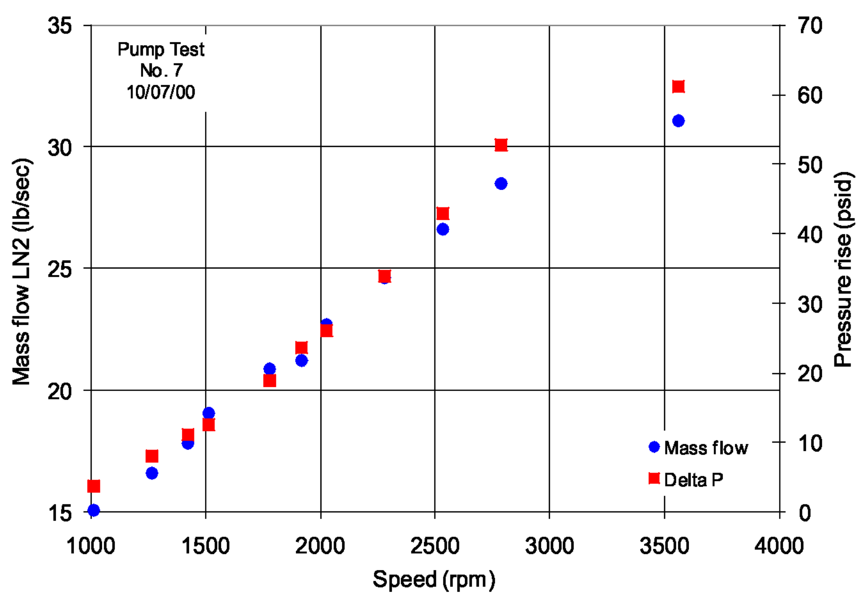
In order to continue on with the S40 densification test program, an alternate pump was required. It was decided that the program would utilize a spare cryogenic LOX transfer pump on the PDU skid that was available and had been procured as a replacement pump for another program, while the BN pump was sent back to the OEM. This spare Cryo-Mach LN2 pump was temporarily installed on the PDU on Sept-29-2000 while the BN pump was at the OEM shop for repairs and in-house check-out test during most of the S40 campaign. The BN pump was not ready for PDU service until the very end of the S40 program and for the very last test conducted with the LOX densification rig.

Figure 51: Barber-Nichols pump performance test results with LN2.



The LN2 test results with the replacement centrifugal pump were encouraging and showed that performance mapping tests based on head and flow with the back-up Cryo-Mach pump (**figure 52**) were very close to meeting the 30 lb_m/sec LO2 recirculation flow rate goal. One minor problem encountered, however, with the Cryo-Mach was that the spare pump's closed-loop mass flow controller could not be made functional by GRC controls engineers. This would in fact cause some operational difficulties later on in the follow-up LO2 tests when trying to maintain a constant mass flow rate (**figure 53**) "manually" through the PDU against a variable system resistance (i.e. changing STA head). Subsequent pump performance tests conducted with liquid oxygen as the test fluid were run with the

Figure 52: Cryo-Mach pump performance with LN2. Flow and ΔP map vs. speed.



Cryo-Mach pump as well in late October. These tests verified the LO2 pump flow rate and head rise as a function of drive speed. Pump performance results were considered nominal and varied from 130 – 195 gpm of LOX at 5 – 37 psid head rise in-between 1000 and 2000 rpm pump speed as presented in the **figure 54** summary mapping data. These test values confirmed the acceptance of the Cryo-Mach pump performance versus requirements for this system component to support the planned LO2 densifier tests with liquid oxygen. Reported in **Appendix E** are two complete data sets of the Cryo-Mach LOX pump performance plots recorded during open-loop pump mapping tests with both LN2 and LO2 as the test fluids.

Figure 53: LN2 mass flow rate by manual pump speed control against increasing STA back pressure due to changing elevation head.

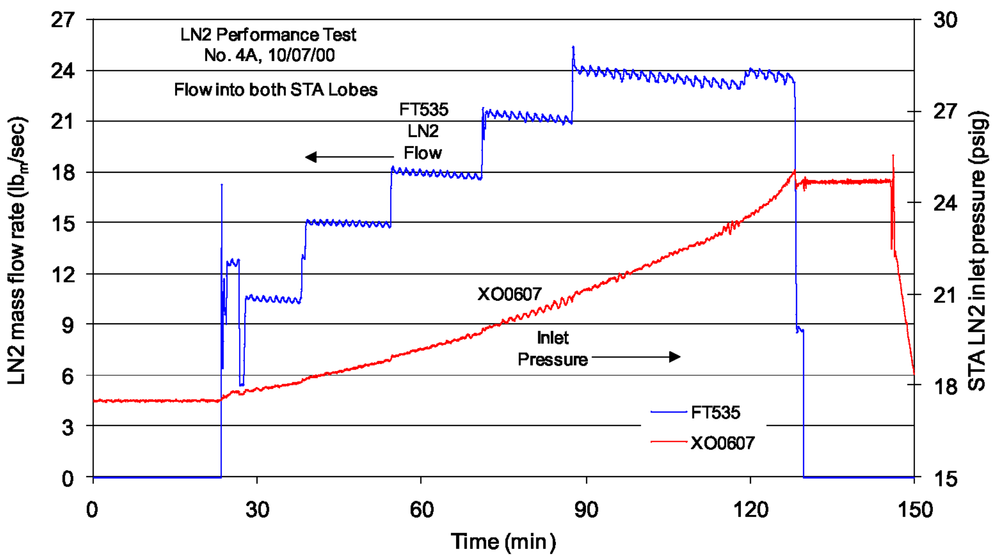
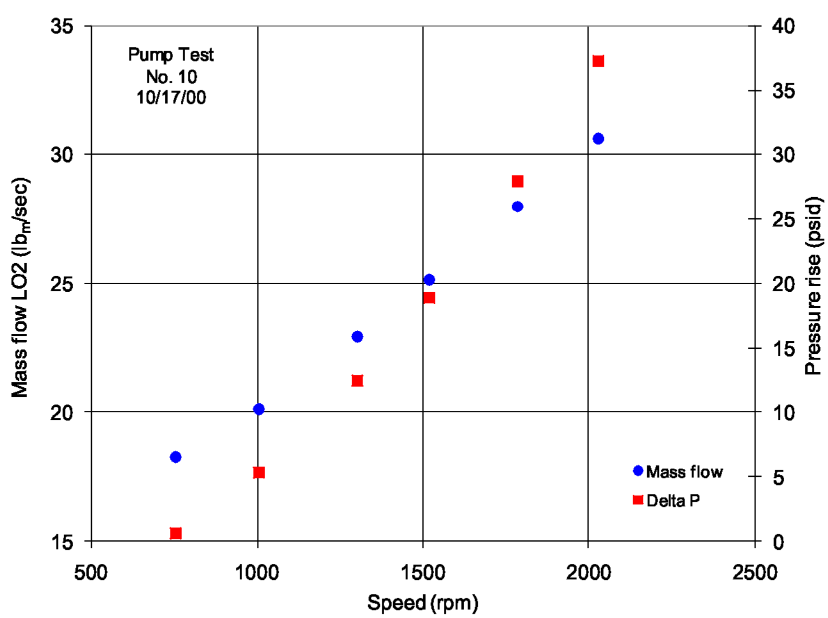


Figure 54: Cryo-Mach pump performance with LO2. Flow and ΔP map vs. speed.



One final remark worthy of mention was that on December 12, 2000, GRC completed a LOX pump performance test with the "re-built" Barber Nichols pump. The totally redesigned pump shaft seal worked perfectly this time with no indication of LO2 leakage observed during a short 30 minute pump mapping test (**Table 8.0**) followed by a lengthy 2.5 hour LO2 loading test of the STA. This pump test was the last and final experiment GRC conducted with the LOX PDU during the test campaign at S40. The test operations team would then begin the lengthy process of removing LOX from the system by allowing it to boil-off from inside the STA. It was estimated that it would require two to three weeks time to get all of the LOX out of the systems during S40 facility clean-up.

Table 8.0: Performance test results with Barber-Nichols LO2 recirculation pump.

Test Description: BN LO2 pump performance¶ mapping, 12/12/00. Test fluid: LO2					
SC535	***FT535***		***PT540 – PT525***	***P535_Amps***	***ZT555***
Pump speed, rpm	***LO2 flow rate***		***Pump ΔP, psid***	***Motor current, amps***	***FCV-555 position, % Open***
	lb_m/sec	gpm			
1960	21.8	137.9	4.2	4.4	100.
2500	24.9	157.5	11.6	5.1	100.
3000	28.3	179.0	19.7	6.1	100.
3500	30.4	192.3	27.5	7.2	100.

¶ Note: Barber-Nichols LO2 pump design point is 190 gpm at 50.0 psid and 4200 rpm

6.4 STA Structural Loading Tests with NBP LN2

The purpose of the STA structural load testing was to verify the load carrying capability and safety of the modified STA support strut configuration. As previously discussed (refer to **Section 3.5**), there were twenty-four (24) original rack-and-pinion cylindrical strut members (**figure 55**) attached to the Test Support Platform (TSP). These were used to support the tank at MSFC during ambient load tests. Based on thermal modeling and stress analysis results by LMMSS, only 7 of the 24 struts were installed by GRC on the STA because the model results indicated that the tank was structurally over-constrained at cryogenic temperatures. This modified support configuration would then first require testing and after validation, could be used to support the cryogenic LN2/LO2 combined loads during densifier runs as shown in the **figure 56** schematic. The STA mass on-board was expected to range from 135,000 to 198,000 pounds of high-density propellant. In order to measure strut static and dynamic load characteristics, each of the seven to eight struts were equipped with a single triaxial strain gage. The strain gage output was monitored in real-time during the first several tanking operations with NBP LN2. The strut strain gage test redline limits defined by LMMSS structural engineers would be 65.7 kips compression (-) and 11.0 kips tension (+) maximum applied stress. If any one strut approached or exceeded the maximum allowable force based on strain gage data, the test would be scrubbed.

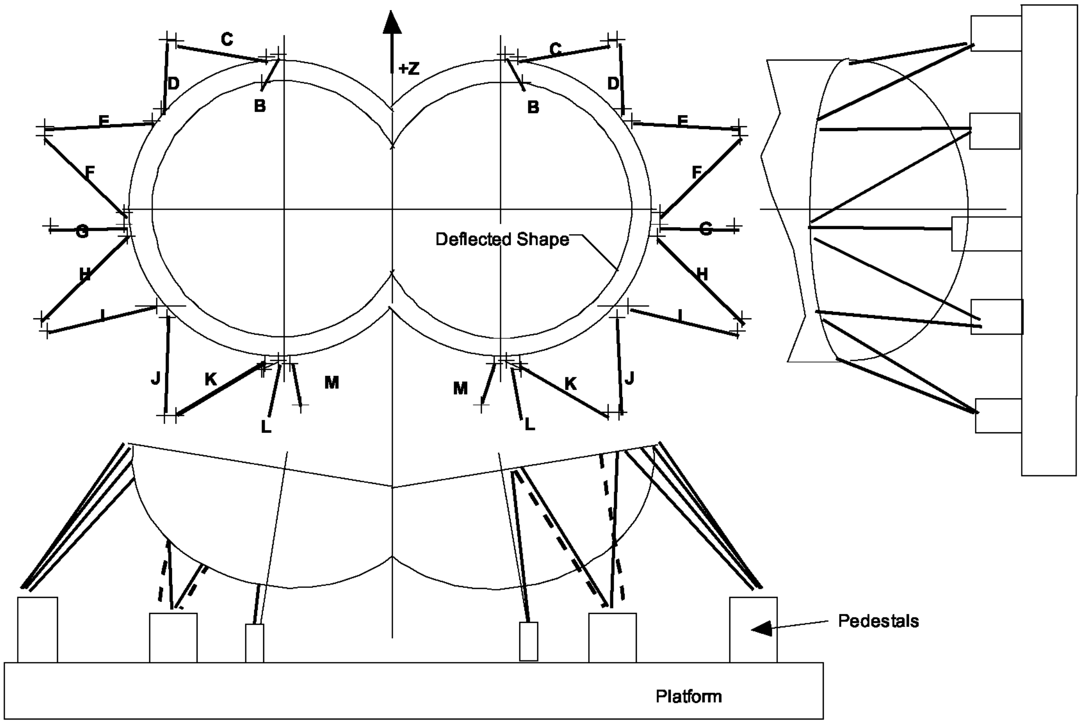


Figure 55. Original STA design twenty-four strut tank support configuration.

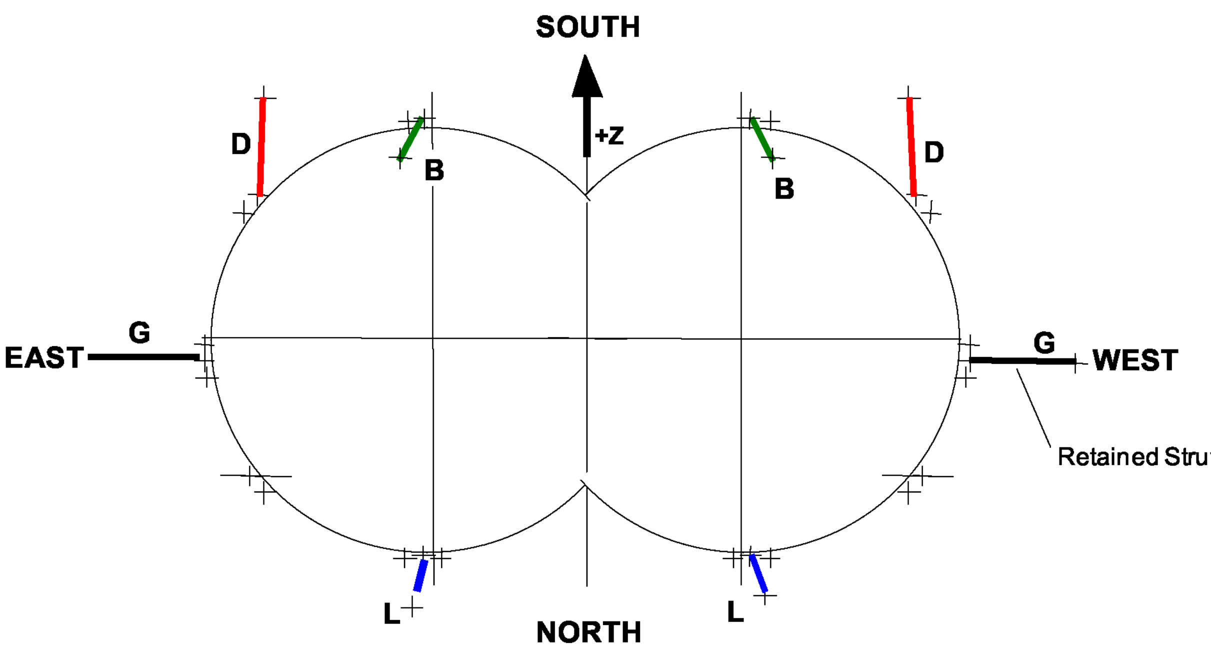


Figure 56: Modified STA support strut configuration on the X-33 LO2 tank for propellant densification testing.

A summary of the structural loading test results conducted in July through August is reported in **Table 9.0**. The first four LN2 loading attempts resulted in run termination before the tank was completely filled. Even though the stress analysis showed that the seven to eight struts would be structurally adequate with margin, the strain gage test results obtained during Tests 1 – 4 gave indications of higher than allowable loads.

Table 9.0: Test summary – STA structural loading tests with NBP liquid nitrogen.

Test ‡ No.	*Date*	*Percent STA filled (%)*	*Approx. propellant loaded mass (lb_m)*	*Qty. of struts*	*Strain gage data for strut loading at end of fill*		*Test Termination / Remarks*
					Strut ID	*Force ¶ (kips)*	
1	7/7/00	58.4	75,250	7	D-east	+ 12.0	High tension, D-east strut
2	7/11/00	96.9	124,790	7	G-west	+ 13.0	High tension, G-west strut
3	7/21/00	30.6	39,350	7	G-west	+ 8.0	G-west strut drifting towards high tension
4	8/4/00	78.5	101,020	8	B-east	+ 10.2	High tension, B-east strut
					B-west	- 55.7	
					D-east	+ 4.4	
					D-west	+ 3.9	
					G-east	- 23.5	
					G-west	+ 6.2	
					L-east	- 28.5	
					L-west	- 4.7	
5	8/25/00	98.8	127,130	8	B-east	- 37.0	All strut forces were below max. redline limit, Tank filled OK to normal operating cap. probe level, LTN2 = 22.7”
					B-west	- 22.1	
					G-east	+ 0.3	
					G-west	+ 0.6	
					J-east	- 3.1	
					J-west	- 8.2	
					L-east	- 20.9	
					L-west	- 30.5	
4B‡	10/24/00	96.9	190,680	8	B-east	- 44.7	LO2 densifier performance test with LO2. STA filled to PVT3 with LO2 inlet temp = 121.3 °R
					B-west	- 41.6	
					G-east	+ 4.9	
					G-west	+ 0.4	
					J-east	- 6.1	
					J-west	- 8.2	
					L-east	- 33.2	
					L-west	- 43.5	

Notes: ‡ Test 4B was a densifier performance test conducted with LO2 and is shown for comparison purposes.
¶ Force conversions: 1 kip = 1,000 lb_f = 4,448 newtons

Following the next two cryogenic load test attempts completed between 7/21/00 and 8/4/00, several issues were worked in parallel by the test operations team in order to help resolve the inconclusive strain gage loading data that was obtained:

- STA strut strain gage recalibration with attached tank support members was completed.

- A redundant set of portable strain gage monitoring equipment was installed on all struts for subsequent LN2 loading tests.
- Additional structural analysis cases were run by LMMSS including input geometry reflecting the actual T153 support platform orientation.
- Strut angles, gaps and alignment, extended length, tank position relative to struts, and TSP configuration relative to STA were all verified and were reset as necessary.
- Field readjustments of the struts were made based on direction from LMMSS test engineers.
- A second "G" strut was added on the STA to increase the total number of support struts from seven to eight for Test no. 4.
- After Test No. 4, the two D-struts were removed from the TSP and replaced with two installed J-struts for Test no. 5 as shown in the **figure 57** modified strut lay-out.

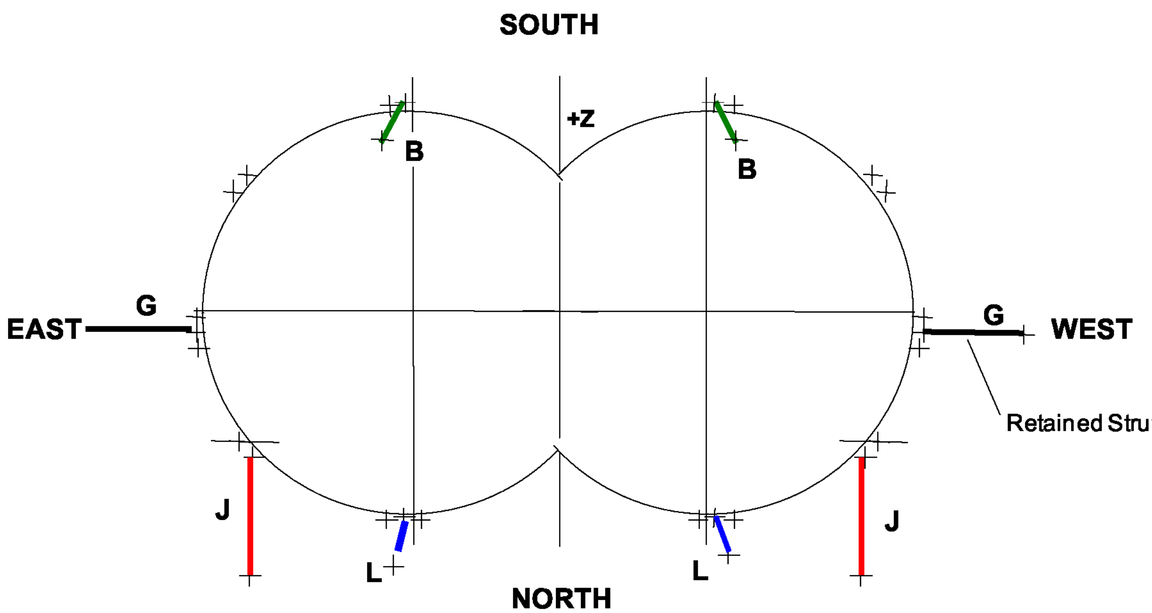


Figure 57: Final as-tested STA eight strut configuration with alternate J-struts installed.

The above rework activities of the STA tank strut support system eventually resulted in a successful tanking and detanking test. Following the J-strut change-over, the LN2 tank loading test conducted at S40 on August 25th showed encouraging results as all eight struts yielded strain gage data that were within the allowable stress limits (-65.7 kips, +11.0 kips) after tank filling to the 98.8 percent level. Two contrasting data plots of STA strut force measurements as they had developed during the 8/25/00 NBP LN2 loading test and a subsequent densified LO2 tanking operation that was performed in late-October are presented in **figures 58** and **59**, respectively.

Figure 58: STA strut test loads during NBP LN2 tank fill.

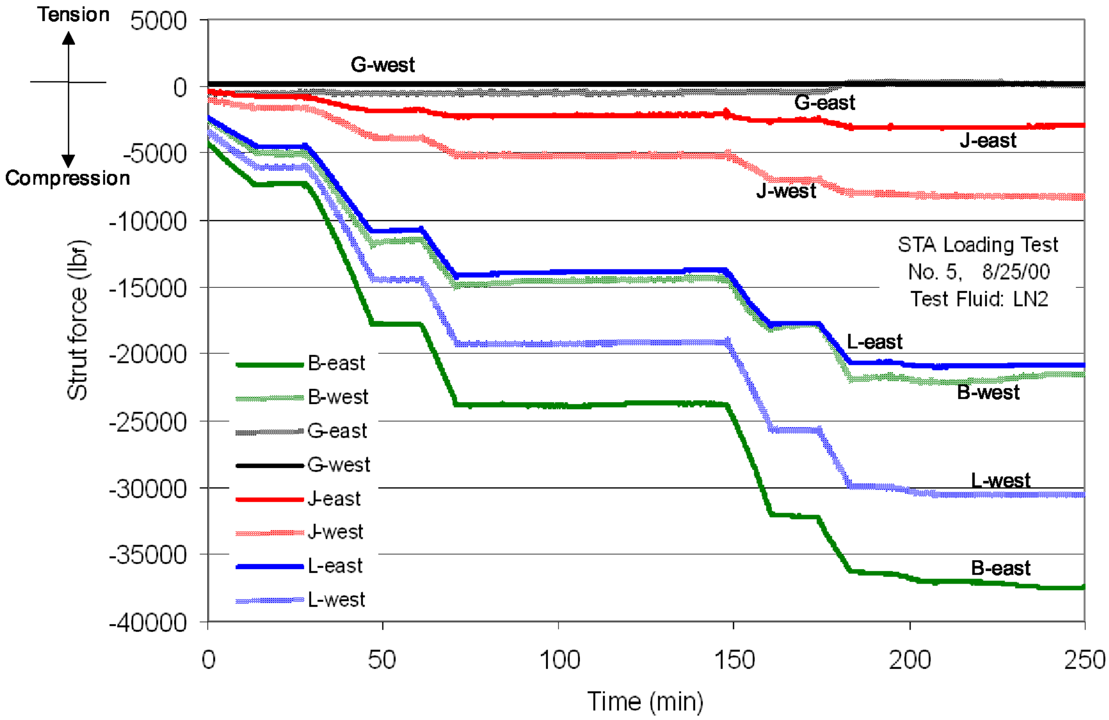
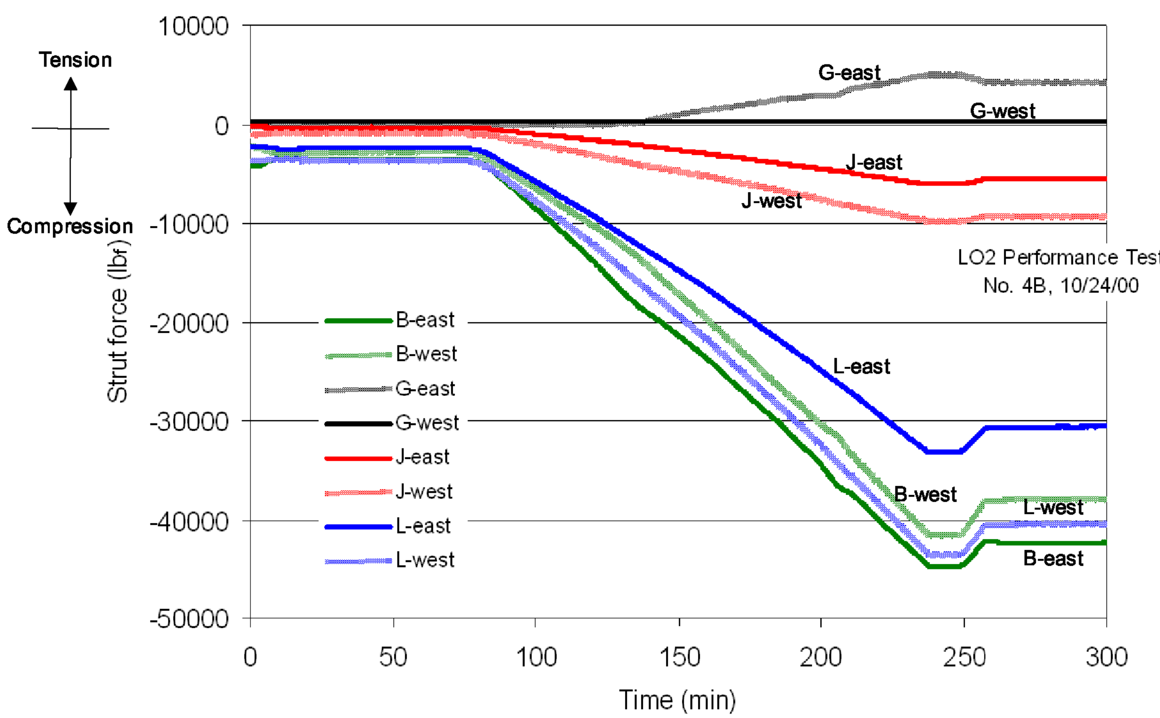


Figure 59: STA strut test loads during densified LO2 tank fill.



6.5 STA Boil-Off Testing

A single boil-off test was run with the STA filled with normal boiling point liquid nitrogen and, then later on in the program while STA was filled with NBP LO2. The hardware and tests were designed to measure the tank's steady-state heat leak and provide LMMSS with an important piece of information required for validation of their tank thermodynamic models. A summary of the key boil-off test results for each fluid is presented in **Table 10.0** below.

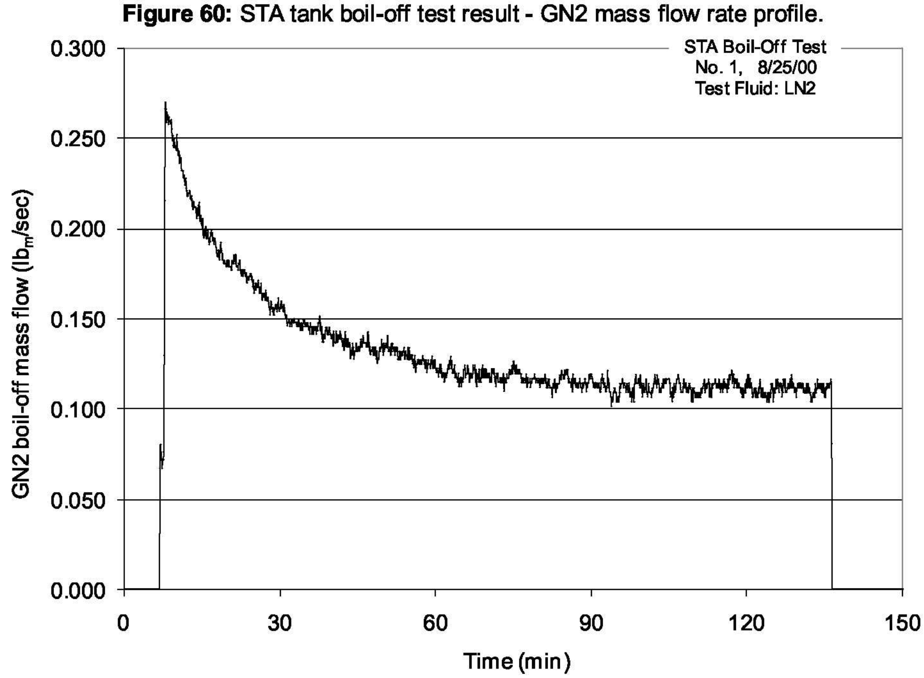
Table 10.0: STA boil-off test results summary.

Boil Off Test No. *Fluid*	*Date*	*Percent STA filled (%)*	*Test duration (min)*	*STA ullage pressure (psia)*	*Liquid temp. @ PVT-3 (°R)*	*Steady state boil-off mass flow rate (lb$_m$/sec)*	*Calc'd steady state heat leak*	
							Btu/hr	*Btu/ hr-ft^2*
1 LN2	8/25/00	98.8	130	14.4	139.8	0.112	34,540	32.6
2 LO2	10/26/00	99.2	204	14.4	162.8	0.140	46,250	43.7

6.5.1 LN2 Boil-Off Result

The LN2 boil-off test conducted with STA on 08/25/00 resulted in an experimental steady state heat leak (Q_{env}) determination of 34,540 Btu/hr. The SS boil-off rate (**figure 60**) during the 130 minute long test averaged 0.112 lb$_m$/sec GN2. As later reported, the STA Q_{env} degraded over time due to spray-on foam insulation (SOFI) age-related problems (**figure 61**) that had developed. These included mechanical breakage, weathering, cracking and moisture penetration, all of which resulted in extensive ice formation on the tanks exterior. When it (Q_{env}) was measured again during a similar LOX boil-off test as described below, the tank environmental heat leak had increased by 33.9 percent.

Figure 60: STA tank boil-off test result - GN2 mass flow rate profile.



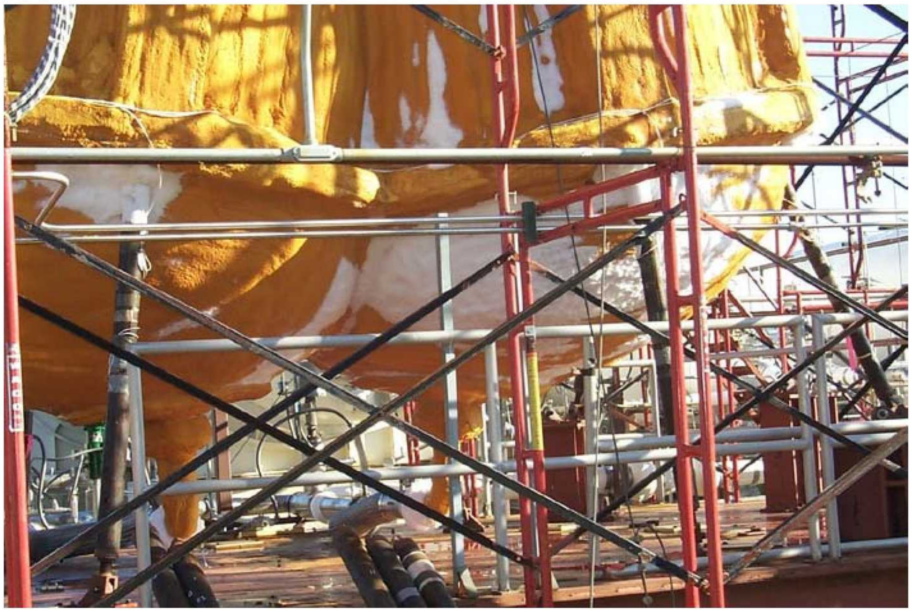
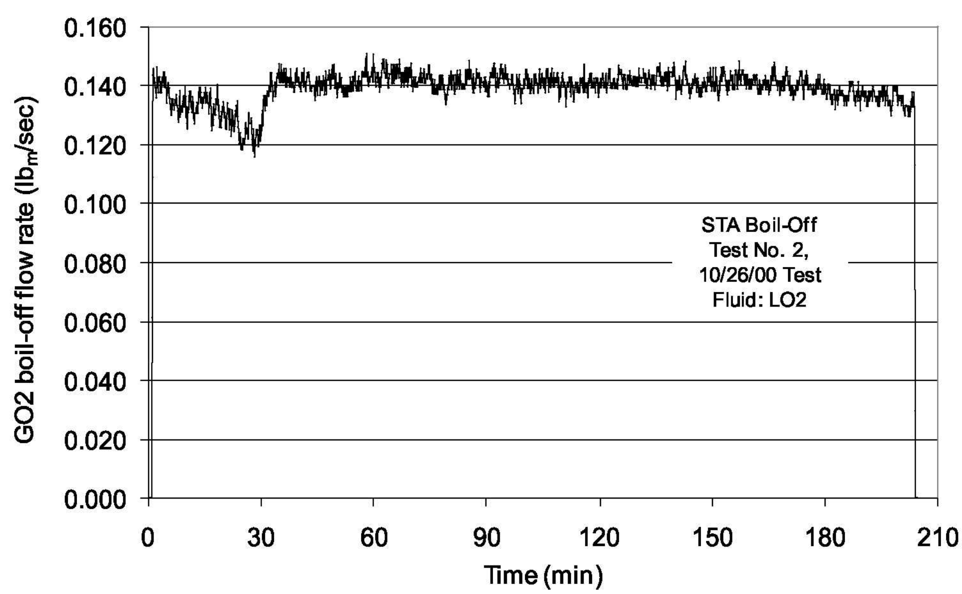


Figure 61: Ice formation and thermal performance loss on the X33 tank SOFI insulation by mechanical breakage, weathering, cracking and moisture penetration.

6.5.2 LO2 Boil-Off Result

The LOX boil off test was conducted on 10/26/00 to reconfirm the experimentally determined heat leak into the STA tank when filled with liquid oxygen in comparison to LN2. On pre-run day (10/25/00), the STA initially contained LO2 at the PVT-10 diode elevation so that it was completely chilled-down before boil-off testing was started. On Run-Day the tank was topped-off from dewar N83 with NBP LO2 to the 28 inch liquid level point based on the BF Goodrich capacitance probe output. The GO2 boil off vent flow rate was measured across a 2.12 inch ID orifice with ΔP transducer XO2111. Tank pressure and gas temperature at the orifice run were steady throughout the test. The tank boil off rate was recorded for approximately 200 minutes. As data was taken, the GO2 flow rate, with the boil-off profile shown in **figure 62**, remained constant indicating a steady-state thermal condition had been

Figure 62: STA tank boil-off test result - GO2 mass flow rate profile.



reached very quickly into the test.

Review of the test data indicated a heat leak much less than the LMMSS predicted value. The original analytically predicted heat leak value was 130,600 Btu/hr for LO2. Based on an average STA tank surface area of 1058 ft^2, the calculated analytical heat flux was 123 Btu/hr-ft^2. The average STA tank boil-off rate measured during the S40 test was 0.140 lbm/sec GO2. Based on saturated LO2 at 14.4 psia, the experimental boil-off rate converts to an average thermal heat leak of 46,250 Btu/hr giving a test surface heat flux of 43.7 Btu/hr-ft^2 which was 35.5% of theoretical but 33.9% larger than the previous LN2 test result.

6.6 LN2 Performance Tests with LOX PDU

As mentioned earlier in the results summary, four PDU performance tests were conducted with LN2 while five *performance* tests with LO2 were run with the X-33 densifier. One closed-loop thermal stratification check-out test was completed with LN2 when the facility was still configured for liquid nitrogen, and then in late-November following facility conversion to LOX, four closed-loop *recirculation* tests were conducted with LO2. Detailed results of the PDU testing with LN2 are provided in the next two sections below. These S40 test results reported on include: 1) Performance testing with LN2 and subsequent loading of STA with DLN2, and, 2) One closed-loop thermal stratification test with recirculating DLN2.

6.6.1 LN2 Performance Test Results – DLN2 Loading of STA

Liquid nitrogen densification check-out testing officially started at the S40 on September 22, 2000 and was completed by the first week of October. **Table 11.0** provides a general run summary of the LN2 performance tests completed during the LO2 PDU system check-out phase of the program. All of the LN2 performance tests shown below went through to planned completion and were without any of the "mid-run" aborts or out-of-limit shut-downs experienced earlier during individual component check-out tests. At the end of each of these tests, the STA was fully loaded with densified LN2 (DLN2). This was achieved in a 1.8 – 2.5 hour time period depending on the DLN2 product outlet mass flow rate established. The STA had a final ullage volume of 2 – 3 percent and contained up to approximately 132,000 pounds of densified and thermally stratified LN2.

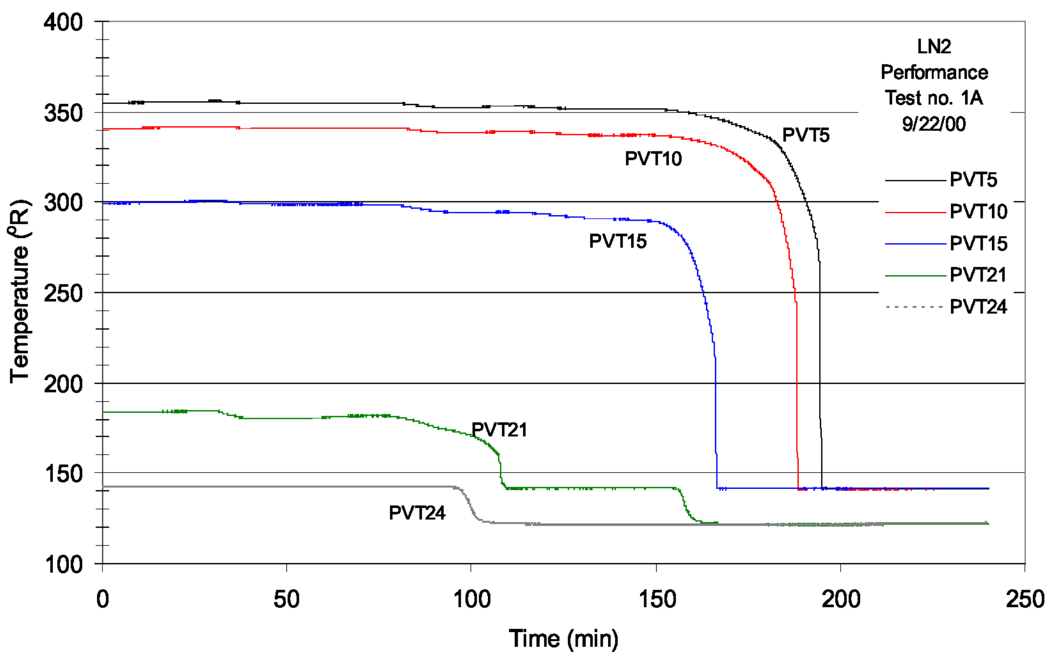
Table 11.0: Test summary – LN2 performance and closed-loop recirculation testing of LO2 PDU.

Test ‡ No.	***Date***	***LN2 Outlet Flow Range (lb_m/sec)***	***GN2 Compressor Set-Point Pressure (psia)***	***LN2 Outlet Temp. from PDU (°R)***	***Test Duration – LN2 Flow (min)***	***Test Description***
1A	9/22	8 – 20	2.2	120	122	LN2 flow into both Lobes.
2A	10/4	10 – 20	5.6	128	144	LN2 flow into both Lobes.
3A	***10/5***	***10 – 20***	***3.6***	***125***	***151***	***LN2 flow into both Lobes.***
4A	10/7	10 – 24	2.8	122	107	LN2 flow into both Lobes.
5A	*10/8*	*9 – 18*	*2.8*	*121*	*198*	*Closed loop LN_2 recirculation flow into both Lobes*

Note: ‡ Tests 1A – 4A were LN2 performance tests while test 5A was a thermal stratification closed-loop test with LN2.

The vertical temperature gradient was very steep in the upper quadrant of the STA tank and typically ranged from 122 °R at the bottom to saturated LN2 at 151 °R and 30 psia near the top liquid surface for runs 2A – 5A. As tank operating pressure was reduced, a lower vertical temperature gradient would develop as shown in **figure 63** for Test 1A which ended up stratified from 121 °R at the STA inlet to 141 °R and 16 psia near the top liquid surface.

Figure 63: STA vertical temperature gradient during DLN2 loading test 1A.



The key objectives of the LN2 densification performance tests were primarily to evaluate the GSE as a total integrated system and to also gain operating experience with the PDU equipment and S40 facility before proceeding with the more hazardous liquid oxygen testing. Although the densifier was designed to process LO2, analysis of the GSE equipment performance specifications resulted in the following "nominal" target run condition ranges for the LN2 densification trials: 10 – 25 lb_m/sec LN2 mass flow rate; 2.4 – 6.0 psia heat exchanger ullage pressure; and 8,000 – 9,500 rpm GN2 compressor operating speed. **Table 12.0** indicates select steady-state experimental performance test conditions run for each of the five LN2 densification runs completed during this LN2 system check-out phase of the program. In all of the LN2 performance tests that were run, the recirculation mass flow rate was "step-change" varied for test mapping purposes, and therefore, the data as reported in **Table 12.0** represents a stable and steady-state set of operating conditions at the reported given mass flow and averaged over a discrete period of operating run-time.

Table 12.0: Steady-state LN2 performance test data measurements with LO2 PDU.

Tag ID	*Description – PDU data*	*Test ‡ 1A*	*Test 2A*	*Test 3A*	*Test 4A*	*Test ¶ 5A*
FT535	LN2 recirc mass flow, lb/sec	16.19	19.83	10.31	23.64	14.13
TT530	Pump inlet temp, °R	141.6	143.6	143.7	143.3	140.8
PT525	Pump inlet pressure, psia	67.5	34.1	47.8	28.7	34.3
TT545	Pump outlet temp, °R	141.6	144.7	144.9	144.1	141.5
PT540	Pump outlet pressure, psia	57.7	92.4	109.5	65.1	51.7
TT550	Stage 1 ht-exer, outlet temp, °R	140.1	140.4	140.0	140.7	139.4
PT550	Stage 1 ht-exer, outlet press, psia	57.4	91.8	109.3	64.4	51.7
TT565	Stage 2 ht-exer, outlet temp, °R	118.9	127.4	122.3	121.5	120.3
PT560	Stage 2 ht-exer, outlet press, psia	56.3	90.2	109.1	62.4	51.1
FT607	Heat exchanger bath fill, lb/sec	2.47	1.78	1.45	3.02	1.92
PT715	Stage 2 ht-exer, ullage press, psia	2.80	5.82	3.74	3.34	3.10
TT602A	Stage 1 ht-exer, bath temp, °R	139.7	140.0	139.9	140.3	139.0
TT603A	Stage 2 ht-exer, bath temp, °R	119.2	127.9	123.0	121.8	120.9
TT703A	Stage 2 ht-exer, ullage temp, °R	119.1	128.0	123.0	121.1	120.3
TT574	PDU skid outlet LN2 temp, °R	120.0	128.5	124.9	121.9	121.1
FT715	Compressor vent flow, lb/sec	2.85	2.52	2.11	2.93	2.27
FT715S	Compressor surge flow, lb/sec	0.63	0.81	0.73	0.0	0.35
SC715A	Stage 1 speed, rpm	10,200	6,610	8,360	8,920	9,090
SC715B	Stage 2 speed, rpm	10,510	6,800	8,610	9,190	9,370
SC715C	Stage 3 speed, rpm	10,810	7,000	8,860	9,450	9,640
FC1	Stage 1 flow coefficient, Φ_1	0.285	0.258	0.235	0.325	0.260
FC2	Stage 2 flow coefficient, Φ_2	0.245	0.262	0.220	0.281	0.228
FC3	Stage 3 flow coefficient, Φ_3	0.198	0.249	0.198	0.238	0.197
PT715A	Stage 1 inlet pressure, psia	2.21	5.60	3.59	2.78	2.80
TT715A	Stage 1 inlet temp., °R	129.1	151.3	138.2	131.4	133.8
PT715B	Stage 2 inlet pressure, psia	4.72	7.96	6.11	5.16	5.30
TT715B	Stage 2 inlet temp., °R	158.9	153.2	161.9	145.6	157.0
PT715C	Stage 3 inlet pressure, psia	8.48	10.87	9.67	9.08	9.18
TT715C	Stage 3 inlet temp., °R	209.6	181.7	204.9	189.1	203.8
PT715D	Stage 3 outlet pressure, psia	14.85	14.68	14.53	14.87	14.71
TT715D	Stage 3 outlet temp., °R	260.7	204.5	244.4	230.7	248.2
N7113	Dewar N-71 LN2 total outflow, gal	2,533	2,485	3,038	2,808	6,150
XO8309	Dewar N-83 LN2 total outflow, gal	13,445	16,610	17,610	16,817	1,790
N/A	GN2 compressor run time, min	184	193	205	155	321
N/A	LN2 mass flow duration, min	122	144	151	107	198
N7117	Dewar N-71 pressure, psig	30.0	20.0	20.0	20.0	30.0
XO8311	Dewar N-83 pressure, psig	60.0	35.0	35.0	35.0	35.0
XO2103	STA ullage pressure, psia	16.0	30.0	30.0	30.0	31.0
N/A	Approx. STA liquid fill volume, %	96.9	96.9	96.9	98.5	98.9
N/A	STA uppermost diode wetted	PVT3	PVT3	PVT3	PVT2	PVT2

Notes: ‡ LO2 pump was not operated due to shaft seal problem. LN2 flow during Test 1A was by ΔP transfer.
¶ Test 5A was the only closed-loop thermal stratification test conducted with LN2. Refer to Section 6.6.2.

Typical start-up transients and the resulting steady-state performance of the LO2 PDU while operating with and producing densified LN2 (DLN2) are represented by the data given in **figures 64** through **67** for LN2 check-out Test No. 4A conducted on October 7, 2000. The compressor start-up transient illustrated in **figure 64** shows how the compressor speed would spin-up, with each of the three stages accelerating at 900 rpm per minute. The rig then would transition into an active pressure PID control mode at which point the speeds were regulated by the PLC until the set-point inlet pressure was established as illustrated in the **figure 65** interstage compressor pressure profile. **Figure 66** shows five characteristic constant LN2 mass flow rates that were run during this particular test at 10, 15, 18, 21 and 24 lb_m/sec of LN2. After completion of the 1.8 hour STA loading process with 122 ^oR densified LN2 exiting the PDU, the initial warmer fluid layer in the bottom of the tank was displaced upwards by the colder and more dense inlet LN2 as illustrated by the vertical STA thermal temperature distribution measurements (**figure 67**) at the point in time when the LN2 flow was stopped at end-of-run. Reported in **Appendix F** is one complete data set showing all graphical test results for LN2 PDU performance test no. 3A completed on October 5, 2000, this in addition to STA LN2 loading data and post-test LN2 resaturation time-lines indicating the warm-up rate of propellant during a 24hr ground-hold.

Figure 64:GN2 compressor speed vs. time profile during LN2 performance test 4A.

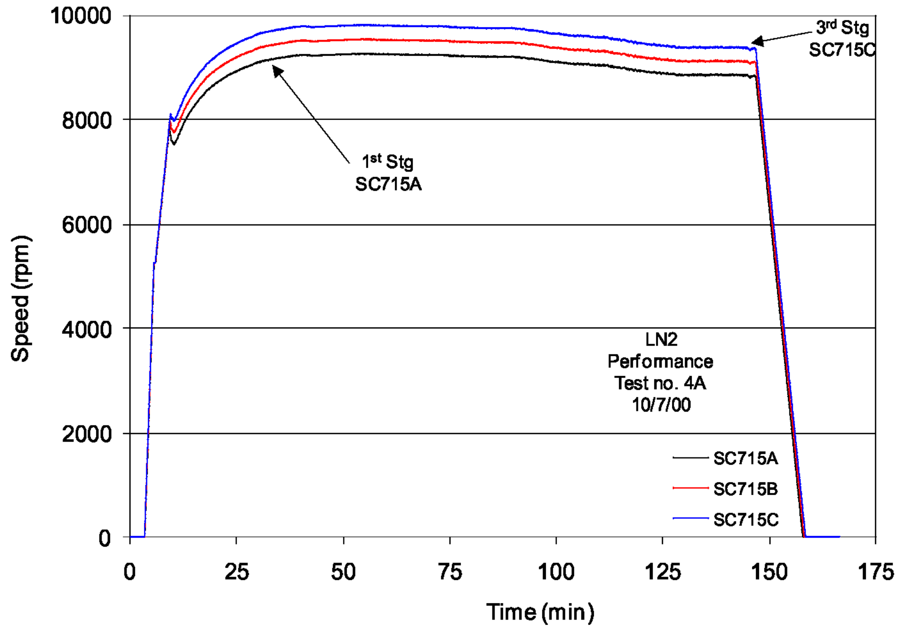


Figure 65:GN2 compressor interstage pressures during LN2 performance test 4A.

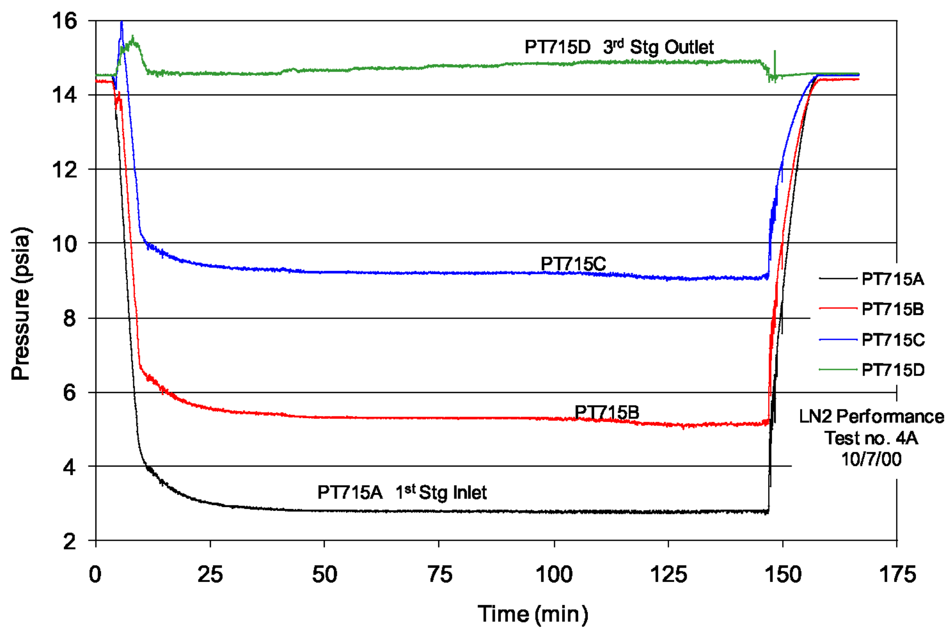


Figure 66: LN2 mass flow rate data for LN2 performance test 4A.

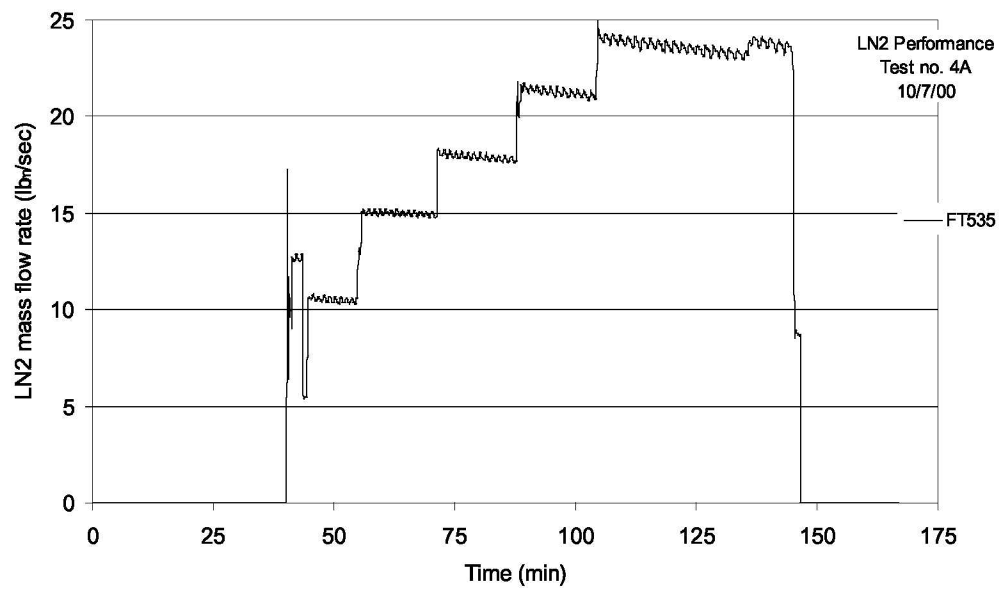
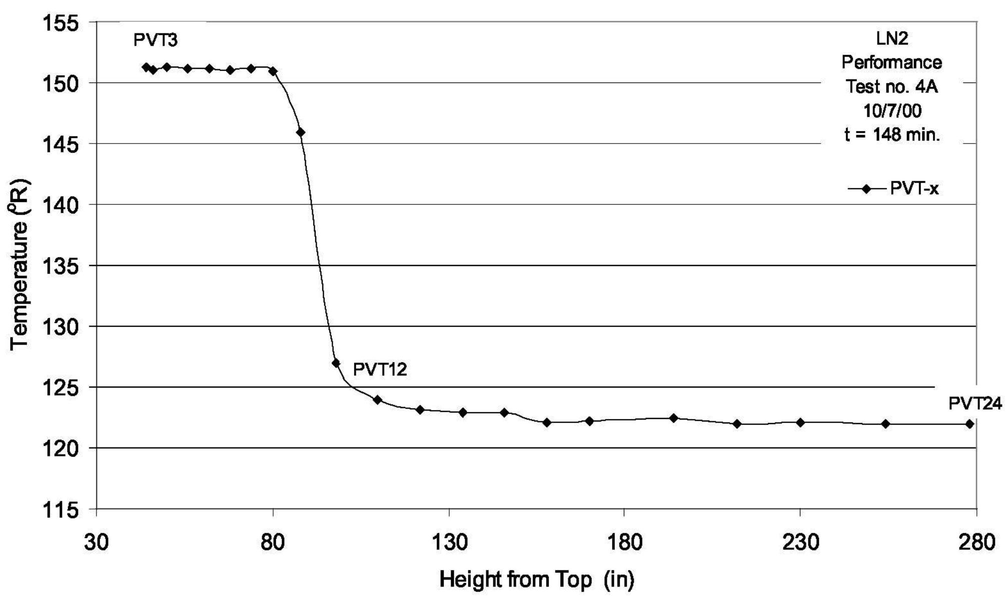


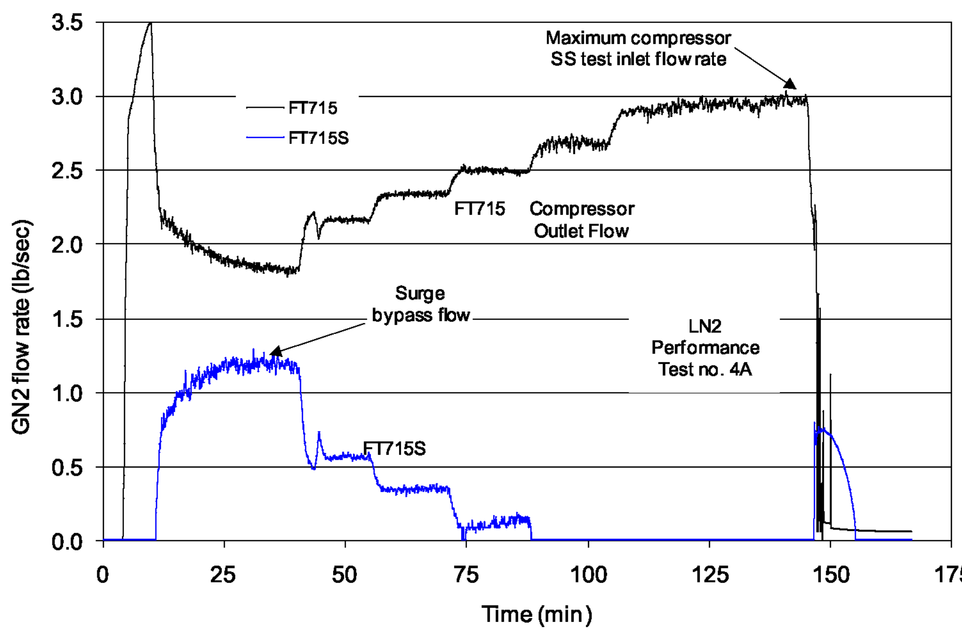
Figure 67:STA LN2 vertical temperature gradient at end of DLN2 loading test 4A



The most *significant results and conclusions* based on the LN2 performance check-out tests with respect to anticipated densifier unit performance with LO2 in the follow-on test series are summarized by the following remarks and test result observations.

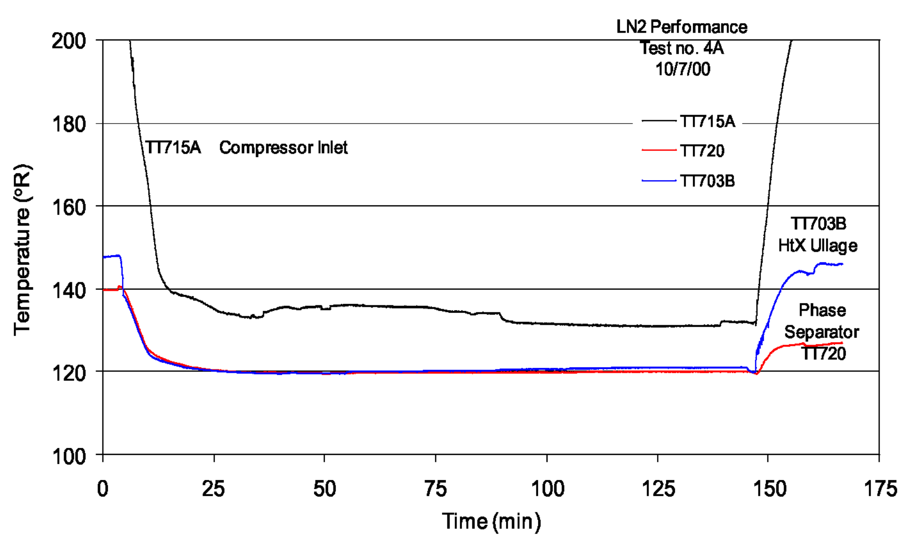
The 3.3 lb_m/sec design point compressor GN2 mass flow rate could not be simulated or achieved during either the previous GN2 compressor checkout tests or the LN2 performance testing. **Figure 68** indicates the "best" or maximum compressor outlet flow rate developed during any single test to date which was approximately 3.0 lb_m/sec. The three primary contributing causes for this 9.0 % mass flow performance reduction from the intended design point were: 1) the high motor winding temperature issues alluded to above in Section 6.2; 2) the inability of the Cryo-Mach spare pump to deliver 25 lb_m/sec or more of LN2 which drives the boil-off rate; and, 3) the higher than expected GN2 temperatures at the inlet of the 1st compressor stage. The inlet gas temperature situation would be attributed to a combination of primarily higher than desired SS thermal heat leak through compressor piping and the phase separator, and, to a lesser extent, the very long duration thermal transient that would be required to reduce all the upstream metal mass temperatures to lower values approaching the saturation temperature in the Stage 2 exchanger.

Figure 68: Compressor outlet GN2 mass flow rate during LN_2 performance test 4A.



The compressor did exhibit start-up variation tendencies depending on upstream hardware and metal wall starting temperatures. **Figure 69** illustrates a typical GN2 inlet temperature transient with a final SS plateau of 132 °R in comparison to the BN aerodynamic inlet design value of 118 °R entering the 1st compressor stage. It's further noted that in order to "thermally" simulate the 2nd stage heat exchanger boil-off rate for LOX service and jointly satisfy the real compressor

Figure 69: Gaseous nitrogen temperature change from 2nd stage heat exchanger ullage to GN2 compressor first stage suction inlet during LN2 performance test 4A.



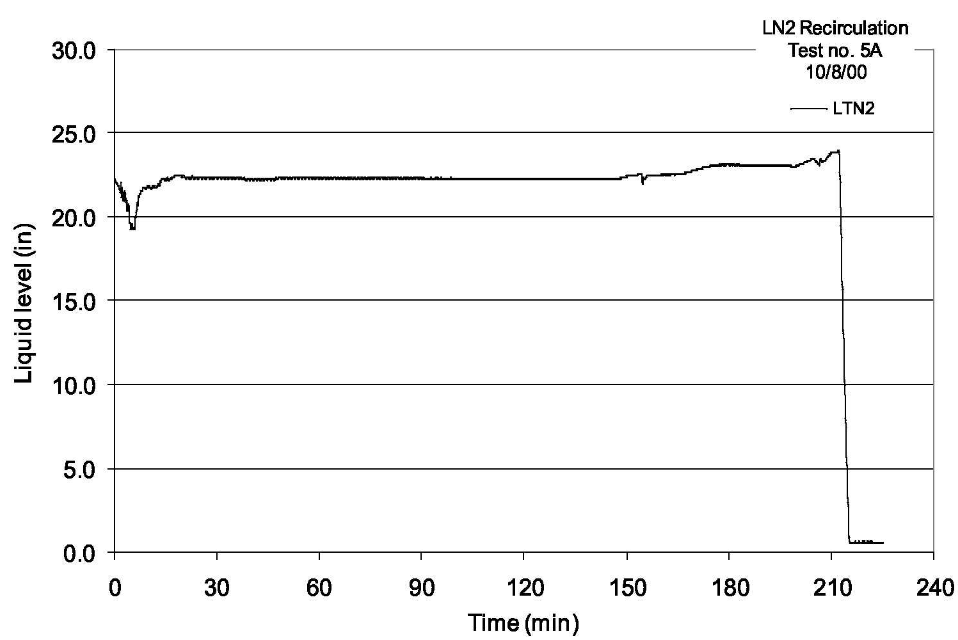
design point inlet conditions with LN2 flowing through the exchanger tube-side, the required LN2 mass flow would be 25 lb_m/sec with a necessary ΔT across the exchanger of 22 ^oR. These conditions were never achievable with the Cryo-Mach Pump and the BN GN2 compressor operating together as a system in tandem.

In summary, as an outcome of the LN2 check-out tests, the maximum densifier performance achievable was nominally 20 lb_m/sec LN2 flow rate at a minimum compressor inlet pressure set-point of 2.8 psia. The upper limit on LN2 flow rate was fixed by the maximum flow rate capability delivered by the Cryo-Mach pump while the lower limit on compressor stage 1 inlet pressure was the lowest stable pressure that could be operated at without overloading the drive motors, causing a VFD fault or shutting down on a surge instability event like the one previously shown in **figure 45**. Scaled from the LO2:LN2 fluid density ratio, the corresponding maximum LO2 flow rate expected would be 28 lb_m/sec based on the resultant Cryo-Mach pump performance assuming the same head requirement. These "as-tested" performance conditions, specifically on the GN2 compressor and LO2 pump established the baseline conditions for the subsequent runs to be performed with LOX.

6.6.2 LN2 Closed-Loop Thermal Stratification Test 5A Results

This section describes X-33 tanking results and the ensuing STA data obtained during the single densified LN2 closed-loop thermal stratification test 5A that was run at the S40 on October 8, 2000. The main objectives of the test were to evaluate densifier system performance and verify the yet "un-tested" GRC developed operational procedures for densifying an 18,830 gallon batch of pre-loaded NBP LN2 inside the STA in a closed-loop recirculating mode.

Figure 70: STA LN2 liquid level during recirculation test 5A.



Initially the STA was pre-filled with NBP LN2 to a nominal capacitance probe liquid level of 22 inches. This corresponded to an approximate starting mass of 127,400 lb_m of LN2 while the level operating point would be located in-between diodes PVT1 and PVT2. Tank level control (**figure 70**) with LN2 replenishment flow control set-up and maintained by skid control valve LCV-500 was satisfactory through-out the test. The STA ullage pressurization and back-pressure control systems operated as designed and without control-related issues like overshoot or oscillation as the pressure was held at the desired nominal 30 psia set-point. The GN2 compressor was started at an inlet pressure set-point of 2.8 psia and zero thermal load on the exchanger tube-side (i.e. no LN2 mass flow). The total time required for compressor spin-up, stage 2 heat exchanger ullage pump down to 3.1 psia and attainment of stable compressor operation was at around 45 minutes following the start. The compressor stage speeds leveled out at 9,090, 9,370 and 9,640 rpm for stages one through three, respectively. It's noted that for pressure balance control purposes, the speed ratios for the two down-stream stages were scaled off the first stage at 1.03 and 1.06 times the first stage speed which was designated the "control stage" in terms of inlet pressure and flow coefficient (Φ) management.

The fluid outlet syphon line was chilled and primed with LN2 and then the closed-loop LN2 flow was initiated from STA thru the LOX densifier and back into STA. The Cryo-Mach pump was set to run at a constant preset speed of 1,550 rpm and the head rise it provided was 18.0 psid. The LN2 outlet flow rate from the skid (**figure 71**) was held approximately constant during the test. It was nominally 14 lb_m/sec while the flow was directed into both STA bottom lobes. The LN2 replenishment flow rate (FT515) downstream of LCV-500 was constant at about 1.0 lb_m/sec over a period of 146 minutes for STA make-up and level control. The recirculation flow rate was stopped after about 200 minutes of LN2 flow time by shutting down the pump when STA had reached thermal equilibrium per SS indications from silicon diode sensor XO2305 found downstream from the 4 inch VJ outlet siphon of the tank. Facility LN2 temperature data in the primary LN2 recirculation flow loop including the inlet to STA (XO2402), the outlet from STA (XO2305) and the return inlet temperature to the LOX skid (XO0107) are indicated in **figure 72**. The vertical thermal stratification profile measurements inside the STA during the complete recirculation and densification process are as shown in **figure 73**. Additional data sets including tank lateral temperatures (**figure 74**) at three elevations indicated that no radial thermal gradients in excess of 1.0 ^{o}R ΔT had developed during the process. Based on an approximate end-of-run final bulk average temperature of 123 ^{o}R, this depicted in **figure 75** when the recirculating flow was stopped, indicated that the final STA loaded mass was 133,700 pounds LN2, representing a 4.9 percent mass increase. Recirculation test #5A represented the completion of the planned LN2 performance check-out testing to allow for facility conversion activities over to LOX test service.

Figure 71: LN2 recirculation and replenishment flow rate profile during test 5A.

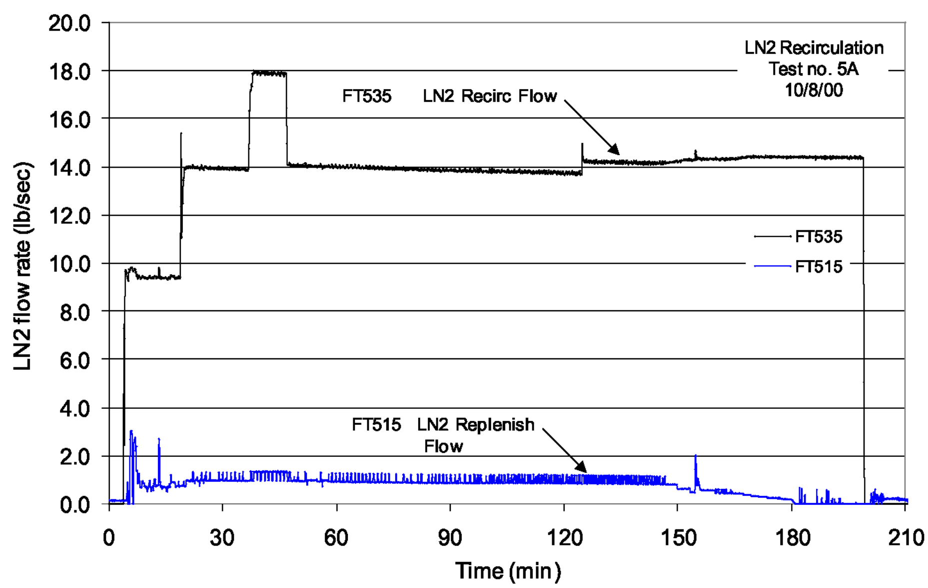


Figure 72: Facility LN2 primary recirculation flow loop temperatures for test 5A.

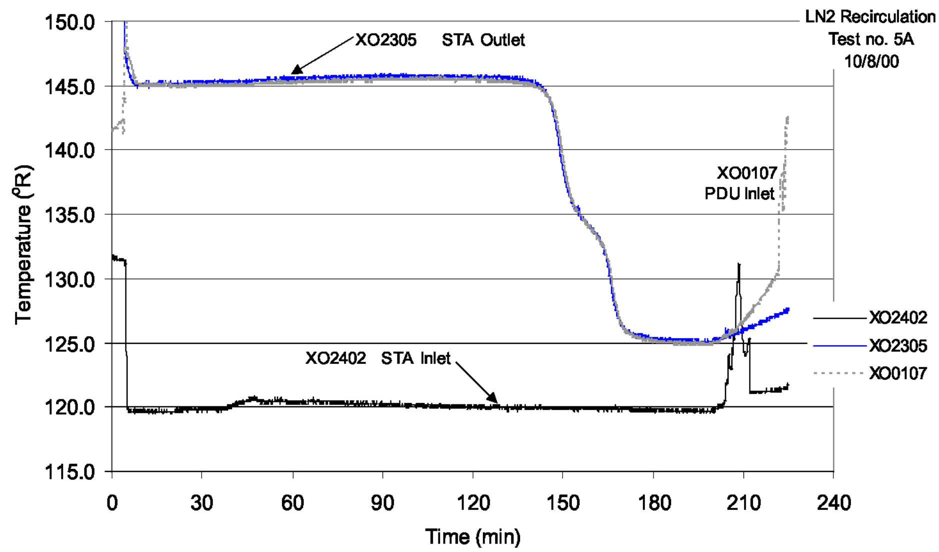


Figure 73: STA vertical diode temperture profile during DLN2 recirculation test 5A.

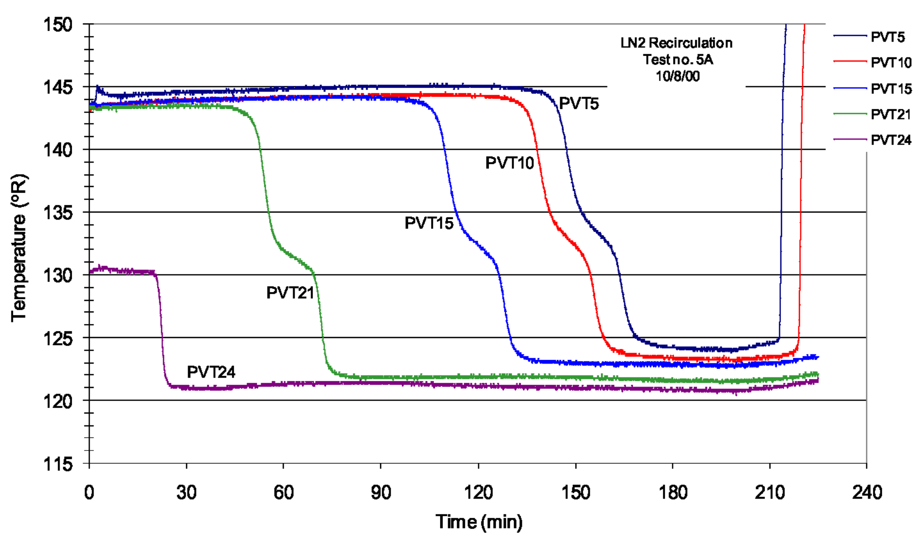


Figure 74: STA lateral diode temperatures at end of DLN2 recirculation test 5A.

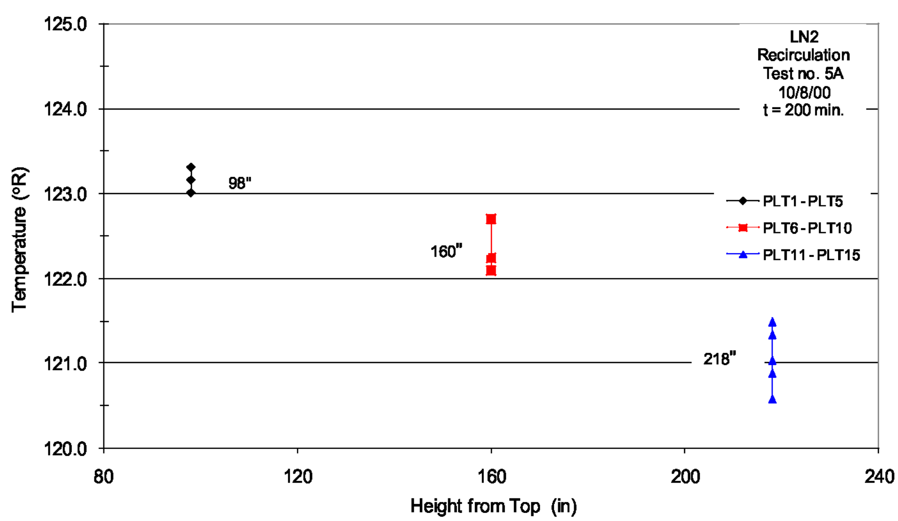
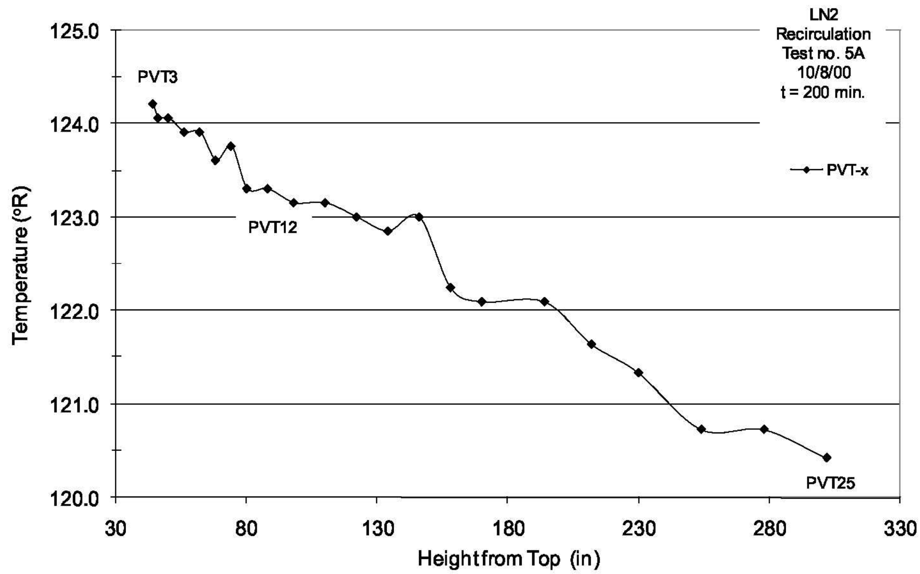


Figure 75:STA LN2 vertical temperature gradient at end of DLN2 recirculation test 5A indicating a thermally stratified tank at end of run.



6.7 LO2 Performance Tests with LOX PDU

Following the LN2 system check-out tests of the PDU and S40 facility conversion from LN2-to-LO2 which was completed on October 14th, liquid oxygen densification performance testing began in mid-October 2000 and was finished by mid-November.

A total of five LO2 densification performance tests were executed at GRCs' S40. **Table 13.0** provides a general run summary of the experimental conditions for the five LOX densifier performance tests carried out during this phase of the program. A closer review of the test results summary table shows that of the five tests conducted, only ***Test 4B*** was completed as originally planned in that the STA was fully loaded with densified LO2 by the end of run. Four LO2 PDU performance tests with associated STA loading resulted in the following early terminations: Tests 1B and 2B – run abort for anomalous high facility filter ΔP downstream of the LO2 PDU; Test 3B – automatic abort of GN2 compressor VFD by a fault shutdown due to a thermal relay overload; Test 5B – intermittent LOX recirculation pump high over-current VFD fault shutdowns.

Table 13.0: Test results summary – LO2 performance testing of LO2 PDU.

Test No.	*Date*	*LO2 Outlet Flow Range (lb_m/sec)*	*GN2 Compressor Set-Point Pressure (psia)*	*LO2 Outlet Temp. from PDU (°R)*	*Test Duration* *LO2 Flow (min)*	*Test Description*
1B	10/14	10 – 14	2.8	121	96	LO2 flow into both Lobes.
2B	10/17	12	2.8	121	72	LO2 flow into both Lobes.
3B	10/20	10 – 16	2.8	121	138	LO2 flow into both Lobes.
4B	***10/24***	***16 – 22***	***2.8***	***121***	***167***	***LO2 flow into both Lobes***
5B	11/15	24 – 30	2.8	121	84	LO2 flow into both Lobes.

It's noted that the dew point of the STA system was verified prior to introducing LO2 flow for the first time. The results of the dew point test conducted on the STA tank was 31 ppm_v of moisture over a 1 hour test. This corresponded to a 398.8 °R (–61.2 °F) dew point which was considered acceptable.

Table 14.0 shown below indicates select steady-state experimental performance conditions for four of the five LO2 densification tests made during the LO2 system performance phase of the program. In each of the LO2 performance tests conducted, the LOX recirculation mass flow rate was varied for test mapping purposes, and therefore, the data as reported in **Table 14.0** represents a stable and steady-state set of densifier operating conditions at the given mass flow and were averaged over a discrete period of operating run-time. Even though four of five tests reported herein resulted in early shutdown, valuable PDU performance operating data was obtained at LO2 mass flows from 10 – 20 lb_m/sec. In addition, certain newly experienced problems associated with the start of processing and producing densified LO2 were corrected prior to the final phase of the test program with the LMMSS VentureStar tank involving closed-loop thermal stratification tests with the STA using LOX. A discussion of significant points of interest for LO2 performance Tests 1B – 4B are provided in the next four subsections below.

Table 14.0: Steady-state LO2 performance test data measurements with LO2 PDU.

Tag ID	Description – PDU data	Test 1B	Test 2B	Test 3B	Test 4B
FT535	LO2 recirc mass flow, lb/sec	10.10	11.94	14.15	20.05
TT530	Pump inlet temp, °R	148.8	158.5	165.5	165.3
PT525	Pump inlet pressure, psia	50.5	49.7	48.6	43.3
TT545	Pump outlet temp, °R	149.1	158.7	165.7	165.5
PT540	Pump outlet pressure, psia	77.6	76.8	73.3	66.2
TT550	Stage 1 ht-exer, outlet temp, °R	140.0	140.3	140.4	140.9
PT550	Stage 1 ht-exer, outlet press, psia	77.6	76.8	73.2	65.9
TT565	Stage 2 ht-exer, outlet temp, °R	119.7	119.8	119.7	120.3
PT560	Stage 2 ht-exer, outlet press, psia	77.3	76.2	72.5	64.6
FT607	Heat exchanger bath fill, lb/sec	1.41	1.56	1.75	2.08
PT715	Stage 2 ht-exer, ullage press, psia	2.99	3.01	2.98	3.10
TT602A	Stage 1 ht-exer, bath temp, °R	139.8	139.8	140.0	140.4
TT603A	Stage 2 ht-exer, bath temp, °R	120.5	120.4	120.3	120.8
TT703A	Stage 2 ht-exer, ullage temp, °R	120.8	121.0	120.0	120.5
TT574	PDU skid outlet LO2 temp, °R	121.0	121.0	120.8	121.1
FT715	Compressor vent flow, lb/sec	2.13	2.12	2.24	2.43
FT715S	Compressor surge flow, lb/sec	0.71	0.59	0.55	0.21
SC715A	Stage 1 speed, rpm	9,290	9,290	9,350	9,230
SC715B	Stage 2 speed, rpm	9,570	9,570	9,630	9,510
SC715C	Stage 3 speed, rpm	9,850	9,850	9,910	9,780
FC1	Stage 1 flow coefficient, Φ_1	0.242	0.243	0.253	0.272
FC2	Stage 2 flow coefficient, Φ_2	0.218	0.220	0.227	0.243
FC3	Stage 3 flow coefficient, Φ_3	0.189	0.192	0.196	0.208
PT715A	Stage 1 inlet pressure, psia	2.82	2.80	2.80	2.79

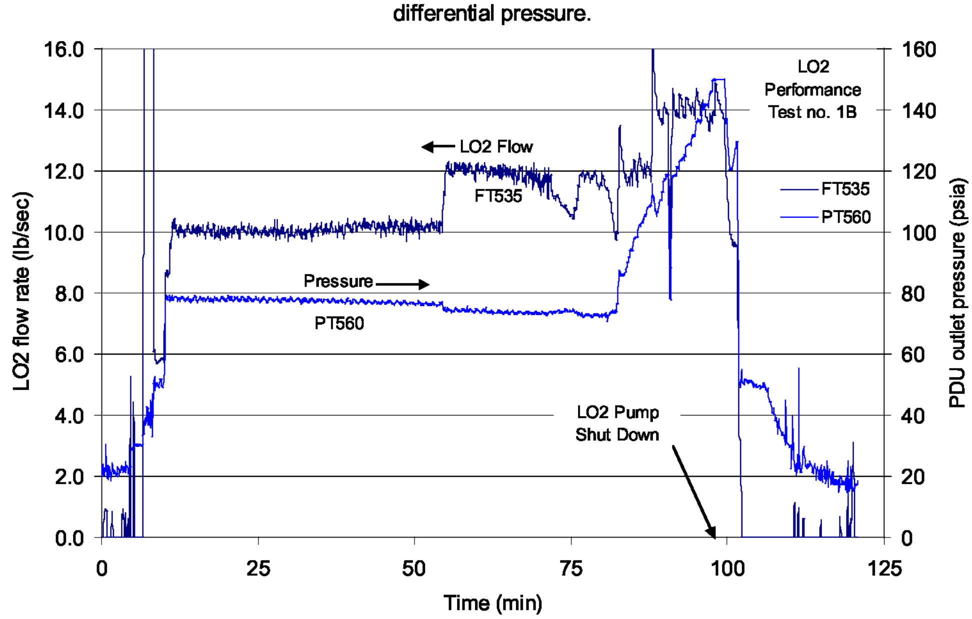
Table 14: Steady-state LO2 performance test data measurements with LO2 PDU. **(continued)**

Tag ID	Description – PDU data	Test 1B	Test 2B	Test 3B	Test 4B
TT715A	Stage 1 inlet temp., °R	132.2	138.7	133.3	140.0
PT715B	Stage 2 inlet pressure, psia	5.44	5.44	5.43	5.45
TT715B	Stage 2 inlet temp., °R	163.5	165.4	163.3	160.3
PT715C	Stage 3 inlet pressure, psia	9.26	9.27	9.29	9.33
TT715C	Stage 3 inlet temp., °R	214.1	217.0	214.6	209.2
PT715D	Stage 3 outlet pressure, psia	14.74	14.75	14.91	15.08
TT715D	Stage 3 outlet temp., °R	262.2	264.8	261.2	254.7
N7113	Dewar N-71 LN2 total outflow, gal	2,390	1,890	3,930	4,580
XO8309	Dewar N-83 LO2 total outflow, gal	6,150	4,620	9,450	17,920
N/A	GN2 compressor run time, min	150	129	192	245
N/A	LO2 mass flow duration, min	96	72	138	167
N7117	Dewar N-71 pressure, psia	44.7	44.7	44.7	44.7
XO8311	Dewar N-83 pressure, psia	49.7	49.7	49.7	49.7
XO2103	STA ullage pressure, psia	30.0	30.0	30.0	30.0
N/A	Approx. STA liquid fill volume, %	30.6	39.2	47.7	96.9
N/A	STA uppermost diode wetted	PVT22	PVT21	PVT20	PVT3

6.7.1 LO2 PDU Performance Test 1B

The plans for this performance test were to initially run at an LO2 slow-fill flow rate of 10 lb_m/sec and then incrementally increase to a fast-fill rate of 20 lb_m/sec. During the course of the test, the LO2 pump was manually shut down early after only 96 minutes into the slow-fill flow portion of the STA loading. A problem occurred due to an anomalous high ΔP across the facility filter element XO-0602 located down stream of the PDU and upstream of the STA inlet in a 4 inch section of VJ transfer line. An excessively high back-pressure at PT560 (skid outlet P) resulted (**figure 76**) due to a plugged or clogged facility filter element in the LOX transfer line between

Figure 76: LO2 flow rate and skid outlet pressure - test abort high facility filter differential pressure.

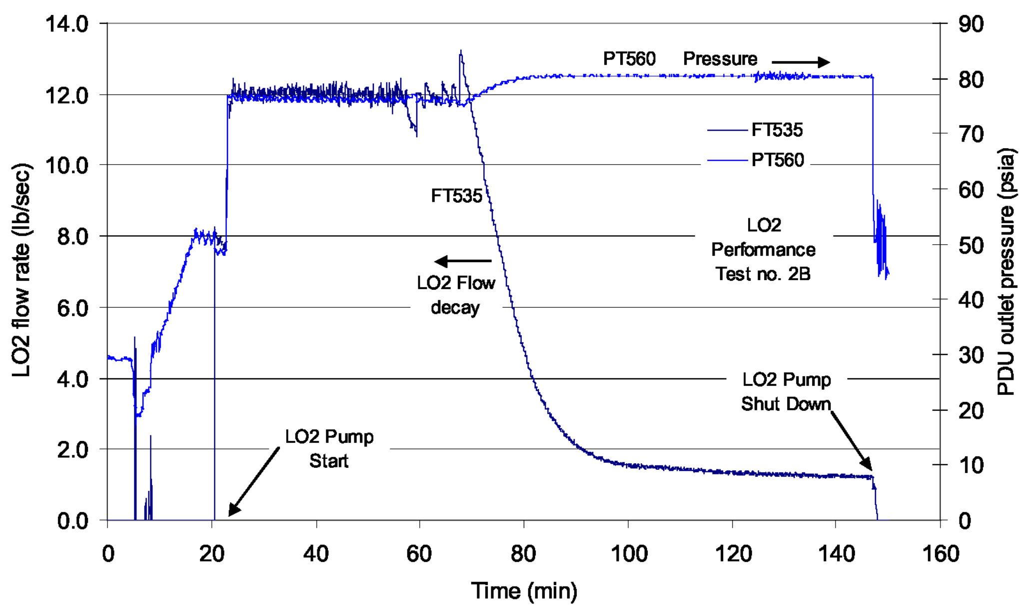


the skid and STA. This began to restrict the free flow of LOX from the PDU into the STA tank. The abort shutdown occurred after DLO2 crossed the STA vertical diode PVT22 resulting in a final STA loading of only approximately 5,800 gallons of LOX in the tank.

6.7.2 LO2 PDU Performance Test 2B

Liquid oxygen performance Test no. 2B had also resulted in an abort, early into the run due to the same anomalous high ΔP condition causing loss of DLO2 flow (**figure 77**) across the facility filter element. This occurred after only 72 minutes of DLO2 flowing time. GRC research engineers began an investigation into the cause of these two recent early and un-explainable run aborts by what appeared to be "filter clogging". It was hypothesized that the apparent viscosity of DLO2 was significantly increased at the lower 120 ^{o}R subcooled outlet temperature and this was causing the high filter element differential pressure. This was compounded by the fact that the filter element specified by LMMSS had a very small pore size distribution. To resolve the problem and continue on with testing, the 10 μm filter element on XO-0602 was removed and replaced with a 300 μm (50 mesh) SS in-line basket strainer inside of the original VJ filter element housing. This facility modification effectively solved the problem as the operating ΔP across the course strainer was reduced to a more normal range of 2 – 3 psid during subsequent DLO2 performance tests as discussed below. This hardware fix allowed test operations to proceed, but it did not provide any further insight into the true reasons behind these high ΔP events across the filter.

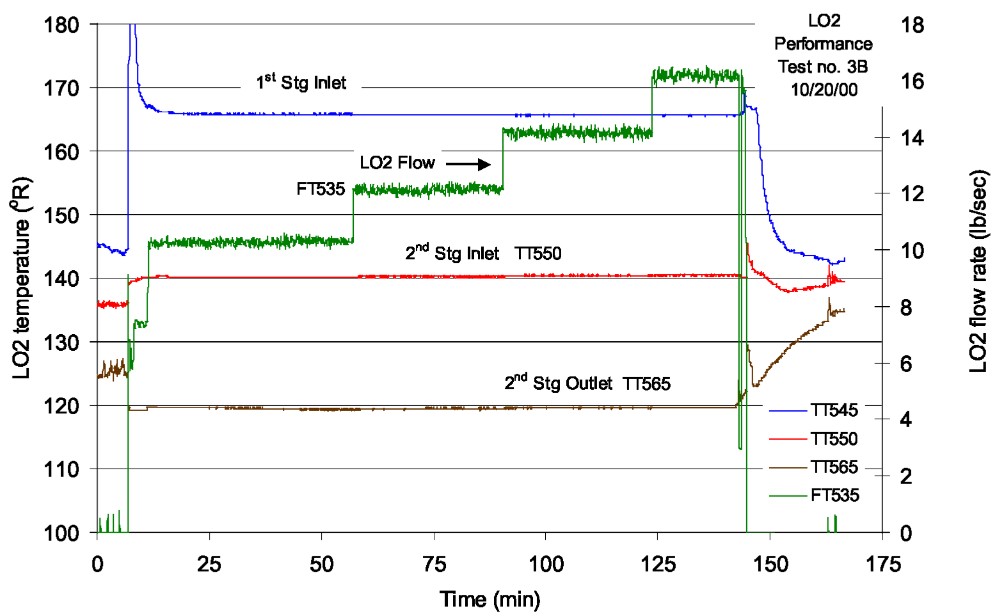
Figure 77: LO2 flow rate and skid outlet pressure - test abort high facility filter differential pressure - Test 2B.



6.7.3 LO2 PDU Performance Test 3B

The LO2 performance Test #3B conducted on October 20th began very well, as stable operating conditions were maintained through the first three test mass flows. The plan was to conduct an STA fast-fill loading test with both the LOX pump running and compressor operating at a set-point of 2.8 psia ullage pressure. The LOX flow rate would be incrementally increased from 10 – 20 lb_m/sec with each mass flow rate time continued for a time increment of about 30 minutes. **Figure 78** indicates the "flatness" of the LO2 temperature profile as it flowed through the PDU heat exchanger train and became densified. After 19 minutes of operating time at the 16 lb_m/sec LO2 flow rate point, an unexpected fault shut-down occurred on the stage-two compressor VFD resulting in an early termination of the test. A restart was not possible, so after the S40 facility was secured, a site entry was made and the problem was diagnosed as a previously un-experienced thermal relay overload with a VFD stage-two fault. This problem was subsequently corrected by a simple adjustment of the cabinet set-point temperature on the VFDs' electrical enclosure air-conditioning unit designed to maintain the enclosure temperature normal.

Figure 78: LO2 stream temperatures across two-stage heat exchanger system.



6.7.4 LO2 PDU Performance Test 4B

Near total success was finally realized during LO2 PDU performance ***Test 4B*** run with LO2 mass flows ranging from 16 – 22 lb_m/sec. In this test and for the first time during the program the STA was fully loaded with DLO2 as testing went through the full planned duration. During LO2 performance ***Test No. 4B*** conducted on October 24, 2000, some of the key measured start-up transients and resulting steady-state performance of the LO2 PDU while operating with and producing densified LO2 are presented in **figures 79** through **84**.

The GN2 compressor start-up and operating speed transient (**figure 79**) resulted in final stage steady-state speeds cruising in-between 9,230 and 9,780 rpm. Given the now very well refined compressor start-up process, the resulting interstage pressure pump-down transient (see **figure 80**) to go from an atmospheric pressure ullage to 2.8 psia required 38 minutes of run time and the overall performance compression ratio was 5.4:1. Motor stator winding temperatures on the rig leveled out at 200 – 210 °F and showed no further sign of increase while motor currents varied from 45 – 55 amps during test. The compressor flow coefficient (Φ) history given in **figure 81** illustrated the complexity of the dynamics for both the compressor start-up and normal operation. The authors point-out two interesting features of the flow coefficient data-set: 1) the surge avoidance controller was very reactive during the first 95 minutes of the run, this necessary to maintain the Stage 1 inlet

Φ_1 above the controllers set-point value of 0.18 to prevent a surge shut-down at 0.12; and 2) the discrete step-changes seen with each of the stages Φ as the LO2 mass flows were changed, thereby reflected the gradual increase in compressor mass flow through-put that varied from 1.8 – 2.5 lb_m/sec GN2 vent rate over the test range of LOX flows.

As in previous tests the LO2 test mass flow rates as shown in **figure 82** were manually controlled, in this case by running the Cryo-Mach LO2 pump at a constant speed of 1,540 rpm and then throttling the LO2 skid control valve (FCV-555) from 67 – 84 percent open at maximum flow. During this test, DLO2 was produced at constant and steady outlet conditions of 121 ^{o}R and 65 psia exiting the skid. The consumables transferred from LN2 dewar N-71 and the LO2 supply dewar N-83 are provided in **figure 83**. Approximately 4,600 gallons of LN2 were consumed during the thermodynamic venting process to subcool nearly 171,000 pounds of DLO2. The STA vertical temperature profile changes that took place and the ultimate thermally stratified condition of the LOX during the course of the densification and loading process is indicated in **figure 84**.

Figure 79: Compressor stage speeds during LO2 performance test 4B.

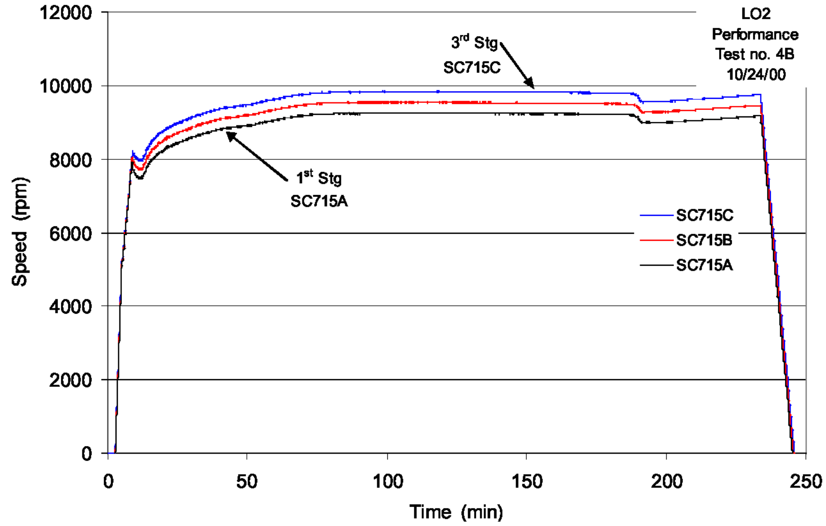


Figure 80: Compressor interstage pressure profile - LO2 performance test 4B.

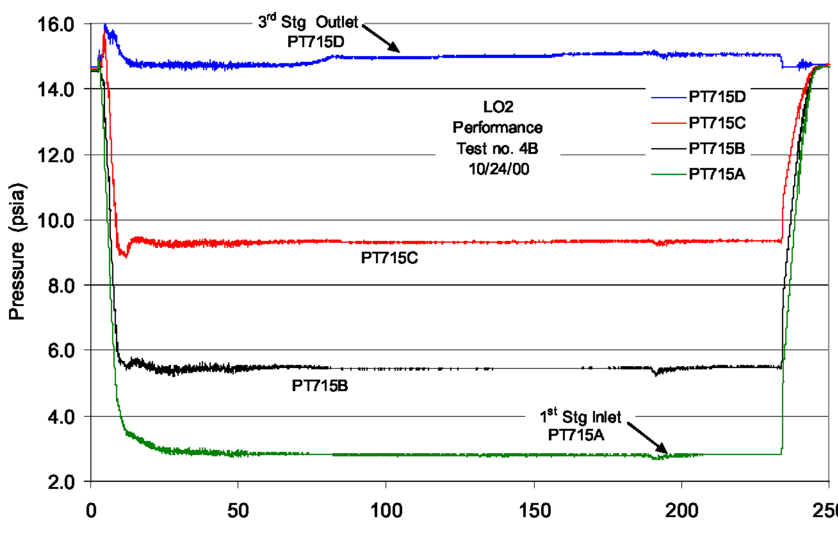


Figure 81: Compressor flow coefficient profile during LO2 performance test 4B.

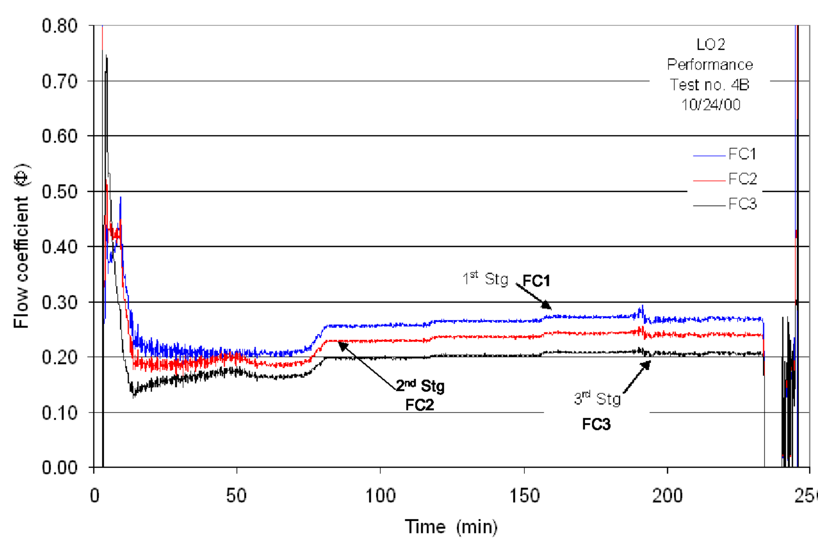


Figure 82: Densified LOX flow rate - LO2 performance test 4B.

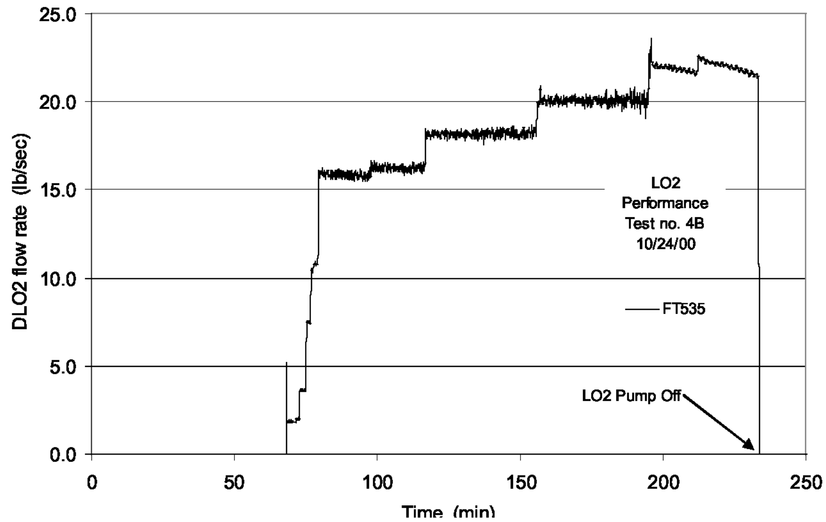


Figure 83: Dewars N83 and N71 volume change during LO2 performance test 4B.

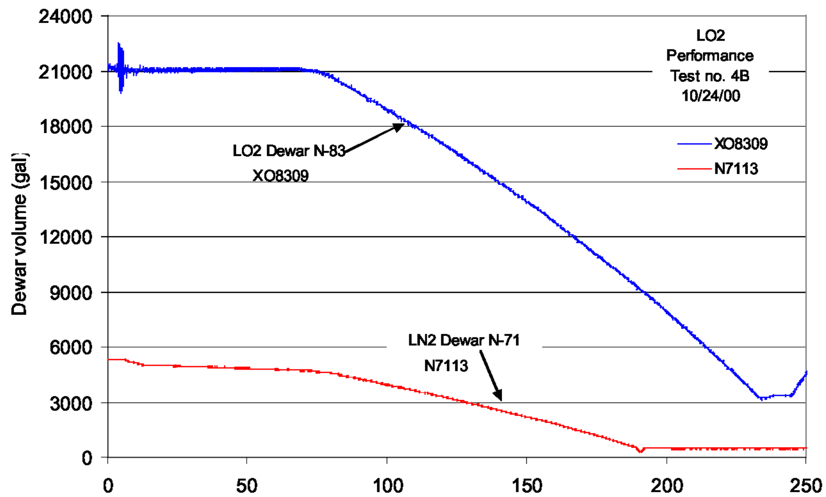
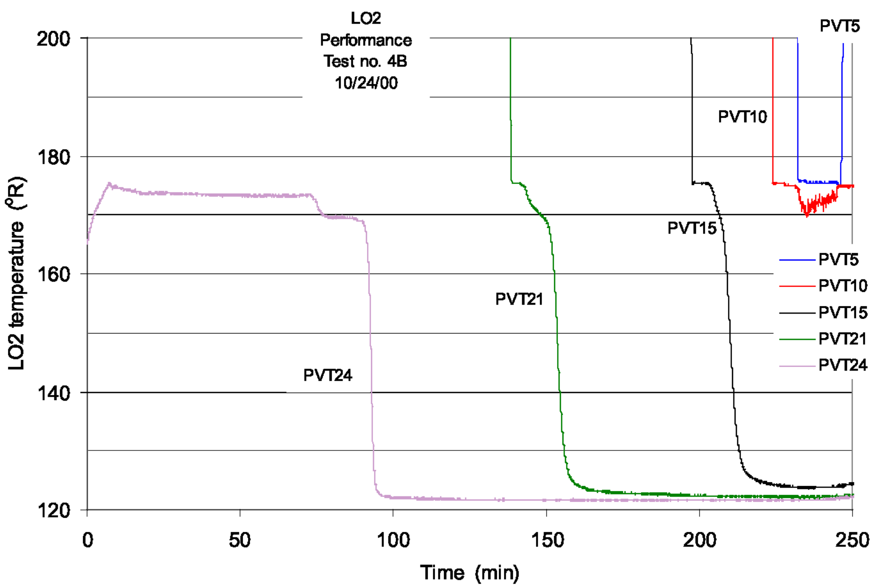


Figure 84: STA vertical diode temperature profiles - LO2 performance test 4B.



6.8 STA Closed-Loop Thermal Stratification Testing with LO2

The last Phase of the S40 program was started in late-November and culminated with four closed-loop LOX thermal stratification tests completed by December 5, 2000. These particular tests and the corresponding test matrix were conducted under a collaboration with GRC and the LMMSS. **Table 15.0** indicates the general PDU performance results summary for each of the test conditions that were run. With respect to specific LO2 densification unit performance, all of these tests, with the exception of ***Test # 4C*** that was run at the nominal LO2 design flow rate of the rig, were very similar in performance to the previously discussed LO2 ***Test 4B*** at the 20 lb_m/sec operating point. Some mention will however be made of the densifier performance findings while conducting ***Test 4C*** which was very close to the nominal GSE design point value of 30 pounds per second of DLO2 production. Additional test data obtained during these runs are reported in **Appendix G**.

Table 15.0: Test results summary – LO2 closed-loop thermal stratification testing of LO2 PDU.

Test No. ‡	***Date***	***LO2 Outlet Flow (lb_m/sec)***	***GN2 Compressor Set-Point Pressure (psia)***	***LO2 Outlet Temp. from PDU (°R)***	***Test Duration — LO2 Flow (min)***	***Test Description***
1C	11/18	20	2.8	121	230	Closed loop LO2 recirculation flowing into both Lobes
2C	11/22	21 - 22	2.8	121	231	Closed loop LO2 recirculation flow in un-instrumented Lobe
3C	11/30	21	2.8	120	230	Closed loop LO2 recirculation flow into instrumented Lobe
4C	***12/5***	***28 – 30***	***2.8***	***121 - 122***	***190***	*Closed loop LO2 recirculation flow into both Lobes.*

Note: ‡ Cryo-Mach LO2 back-up pump was used for all four LOX thermal stratification tests.

For all the test matrix runs per **Table 15.0**, densified fluid inlet temperature to the STA from the LO2 PDU was controlled between 120 – 122 °R. This inlet LO2 temperature corresponded to a second stage heat exchanger ullage pressure of 2.8 psia. **Table 16.0** shown below indicates select steady-state experimental performance conditions for each of the LO2 closed-loop thermal stratification tests made during this final phase of the program.

6.8.1 STA LO2 Closed Loop Thermal Stratification – Test 1C

A closed loop thermal stratification test with LO2 was conducted on the morning of 11/18/00. The STA was first loaded with NBP LO2 and then the tank was topped off to its normal operating liquid level on the capacitance probe. The GN2 compressor was started-up at 08:42 with no heat load on the LO2 heat exchangers. The compressor was operated at an inlet pressure set-point of 2.8 psia. After stabilization of the GN2 compressor suction/discharge operating conditions, the LO2 pump was started at 09:55. The LO2 pump was set-up to run at 1500 rpm with skid control valve FCV-555 adjusted to about 87% open which provided a nominal LO2 mass flow rate of 20 lb/sec into the STA.

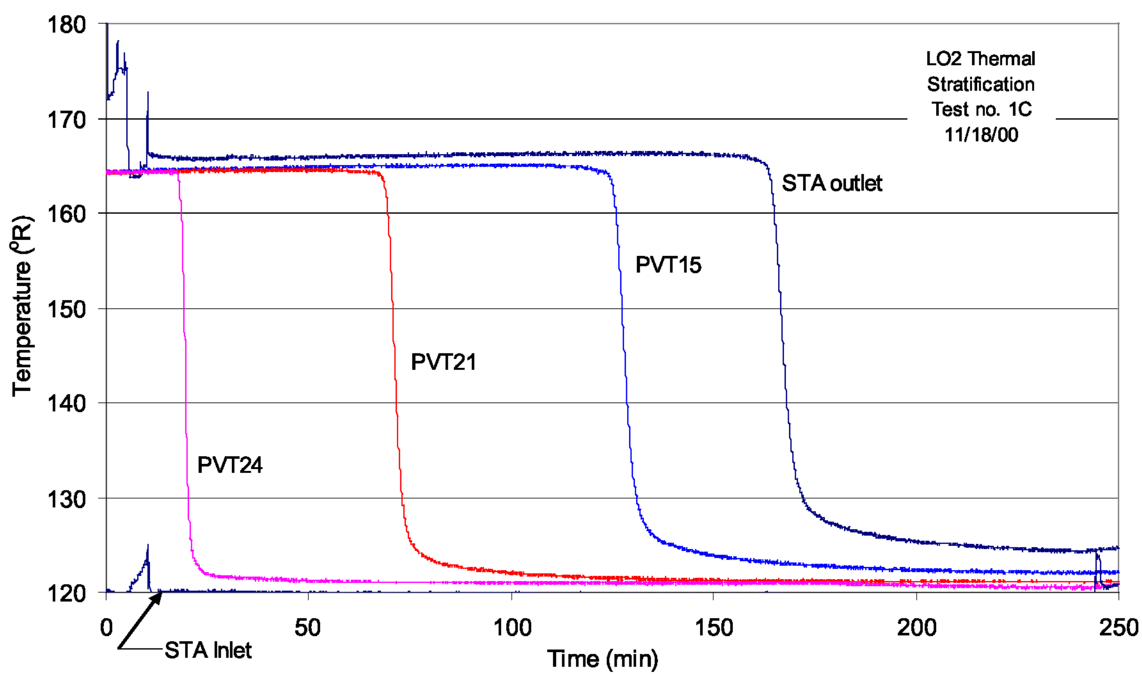
Table 16.0: Steady-state LO2 performance test data measurements with LO2 PDU during closed loop thermal stratification testing.

Tag / *ID*	*Description – PDU data*	*Test 1C*	*Test 2C*	*Test 3C*	*Test 4C*
FT535	LO2 recirc mass flow, lb/sec	20.1	22.0	21.5	28.4
TT530	Pump inlet temp, °R	126.7	126.3	126.5	127.1
PT525	Pump inlet pressure, psia	35.4	35.9	35.6	30.4
TT545	Pump outlet temp, °R	127.0	126.4	126.7	127.3
PT540	Pump outlet pressure, psia	60.7	60.4	60.6	59.3
SC535	LOX pump speed, rpm	1516	1516	1516	1704
TT550	Stage 1 ht-exer, outlet temp, °R	131.5	131.1	131.3	131.2
PT550	Stage 1 ht-exer, outlet press, psia	60.3	60.1	60.2	58.4
TT565	Stage 2 ht-exer, outlet temp, °R	120.1	120.1	120.3	121.1
PT560	Stage 2 ht-exer, outlet press, psia	59.2	58.5	58.9	56.2
PT709	Stage 2 ht-exer, ullage press, psia	3.20	3.22	3.21	3.42
TT602A	Stage 1 ht-exer, bath temp, °R	132.1	131.7	131.9	132.1
TT603A	Stage 2 ht-exer, bath temp, °R	120.5	120.7	120.6	121.4
TT574	PDU skid outlet LO2 temp, °R	120.7	120.9	120.8	121.5
FT715	Compressor vent flow, lb/sec	2.06	2.02	2.04	2.31
PT715A	Stage 1 inlet pressure, psia	2.81	2.81	2.80	2.77
TT715A	Stage 1 inlet temp., °R	133.7	135.7	134.7	131.0
PT715D	Stage 3 outlet pressure, psia	14.55	14.56	14.57	14.48
XO2103	STA ullage pressure, psia	29.9	29.9	29.9	30.1
LT02	STA capacitance probe level, inch	24.1	25.9	23.2	25.9
XO2102	STA vent gas temp., °R	446.4	423.9	345.8	405.5
XO2302	STA siphon outlet pressure, psig	12.7	12.5	12.6	11.5
XO2305	STA siphon outlet temp., °R	125.4	125.1	125.1	126.3
PLT1	STA internal temp. lateral, 98", °R	123.2	123.0	123.0	124.2
PLT5	STA internal temp. lateral, 98", °R	123.0	123.0	123.0	124.2
PLT6	STA internal temp. lateral, 160", °R	122.3	122.1	122.2	123.6
PLT10	STA internal temp. lateral, 160", °R	121.8	121.8	121.8	123.0
PLT11	STA internal temp. lateral, 218", °R	121.2	121.2	121.3	122.5
PLT15	STA internal temp. lateral, 218", °R	121.2	121.2	121.3	122.5
PVT1	STA internal temp. vert., 14", °R	292.3	283.3	258.0	270.5
PVT2	STA internal temp. vert., 28", °R	168.8	167.4	168.8	167.8
PVT3	STA internal temp. vert., 44", °R	124.4	124.4	124.1	125.3
PVT5	STA internal temp. vert., 50", °R	124.4	124.2	124.1	125.1
PVT10	STA internal temp. vert., 80", °R	123.5	123.3	123.2	124.2
PVT15	STA internal temp. vert., 134", °R	122.6	122.4	122.4	123.6
PVT18	STA internal temp. vert., 170", °R	121.8	121.6	121.9	123.2
PVT21	STA internal temp. vert., 212", °R	121.2	121.3	121.5	122.7
PVT24	STA internal temp. vert., 278", °R	120.9	121.2	120.7	122.1
N/A	GN2 compressor run time, min	314	286	288	245
N/A	LO2 mass flow duration, min	230	228	230	190
N/A	Approx. STA liquid fill volume, %	98.8	98.6	98.8	98.6
N/A	STA uppermost diode wetted	PVT2	PVT2	PVT2	PVT2

Test 1C: Steady state data points @ t = 200 minutes, 1:05 pm, row 4982
Test 2C: Steady state data points @ t = 200 minutes, 3:00 pm, row 2702
Test 3C: Steady state data points @ t = 200 minutes, 6:25 pm, row n/a
Test 4C: Steady state data points @ t = 150 minutes, 12:30 pm, row 902

Recirculation of densified LO2 continued during Test 1C until steady state temperatures were achieved. Steady-state was defined to occur when the STA siphon outlet temperature at diode XO2305 stabilized with respect to fluid inlet temperature at diodes XO2402/XO2502 and this ΔT reached a minimum and steady condition. The LO2 inlet temperature entering the STA through both lobes was a constant 120 ^oR. A steady-state stratification condition (**figure 85**) was eventually attained within STA after approximately 200 minutes (3.3 hrs) of closed-loop LO2 recirculation. During the test the following pressure conditions were maintained: 30 psia STA; 45 psia N-71; and 50 psia N-83. Upon completion of the test, the STA was drained back to diode PVT-10 and the remaining sub-cooled LO2 was held in STA to allow the fluid to re-saturate to original NBP conditions by natural heat-leak into the system. This operational scenario was typical for all subsequent LO2 recirculation tests performed with STA for these runs.

Figure 85: STA thermal stratification temperature profiles with circulating LOX - Test 1C.



6.8.2 STA LO2 Closed Loop Thermal Stratification – Test 2C

The second closed loop thermal stratification test with LO2 was conducted on the morning of 11/22/00. The conditions for this test were the same as Test No. 1C with the exception of the STA inlet flow path. Densified oxygen was directed to flow into STA through the un-instrumented lobe which is across valve XO-2403. Total time of LO2 recirculation flow (**figure 86**) at 20 lb/sec during this test was 223 minutes with LO2 entering the STA nominally at 121 ^oR. A steady-state thermal condition (**figure 87**) was observed within STA after approximately 200 minutes (3.3 hrs) of closed-loop LO2 run time.

Figure 86: STA inlet DLO2 flow rate and STA tank LOX make-up rate.

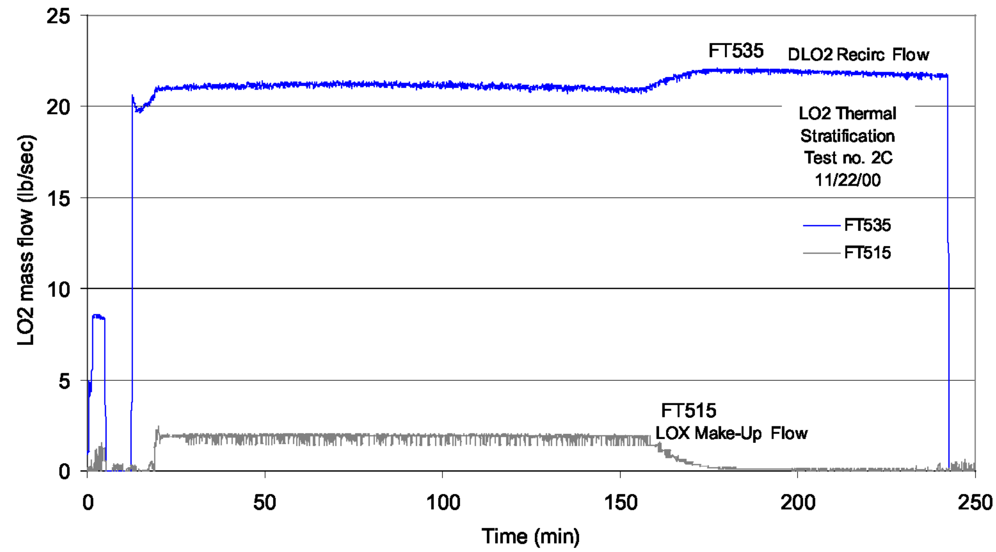
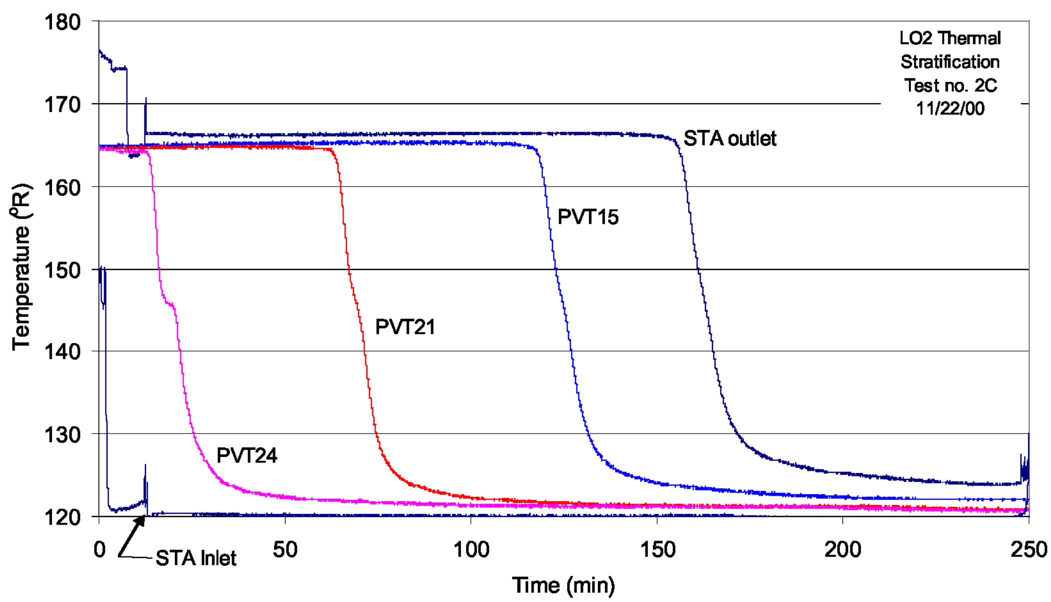


Figure 87: STA thermal stratification temperature profiles with circulating LOX - Test 2C.



6.8.3 STA LO2 Closed Loop Thermal Stratification – Test 3C

This LO2 closed-loop recirculation test began late in the day of 11/30/00. The GN2 compressor was first brought on-line at 14:18 and it ran smoothly on the very first start-up attempt. Liquid oxygen recirculation flow was started at 15:18 at a 20.5 lb/sec mass rate. The flow was through the STA inlet valve XO-2503 which was on the instrumented side of the tank. The STA liquid level controller had very accurately maintained liquid level at typically a 24.6 inch set-point for this test (**figure 88**) as well as during previous runs. The LO2 inventory in N83 was however marginal, and the test was continued as planned until N-83, that was used for providing make-up LO2, was drained empty. When this occurred, the LOX make-up supply valve (LCV-500) was closed at 17:29 and the test proceeded, allowing STA liquid level to slightly drop by 2 inches below its set point. The GN2 compressor was shutdown at 19:05 and the LO2 pump was stopped at 19:06. The final test operation was a drain-back of STA to just below diode PVT-10 and the S40 facility was secured. End-of run temperature conditions (**figure 89**) for this test were similar to the previous two runs.

Figure 88: STA liquid level capacitance probe data with recirculating LOX - Test 3C.

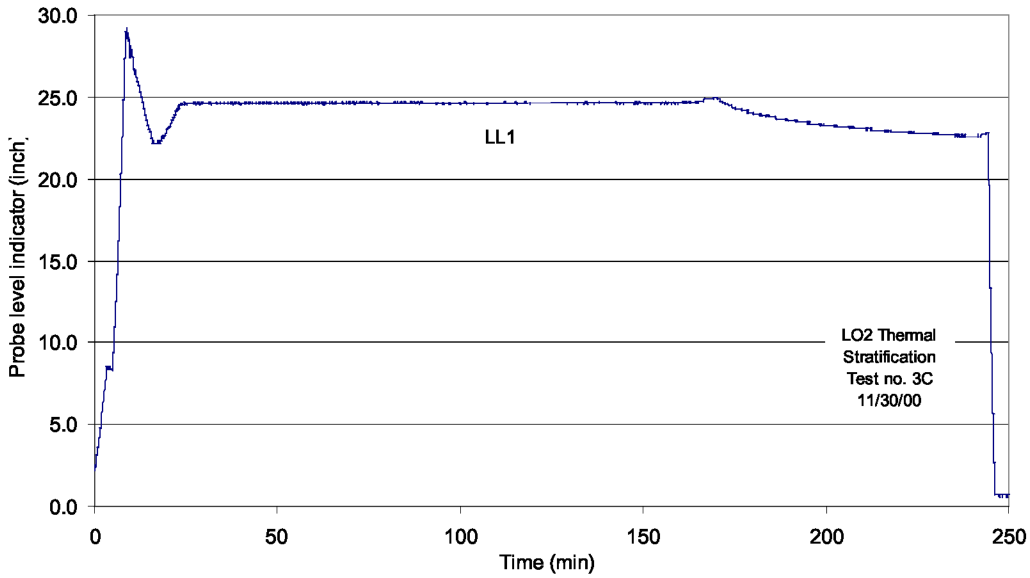
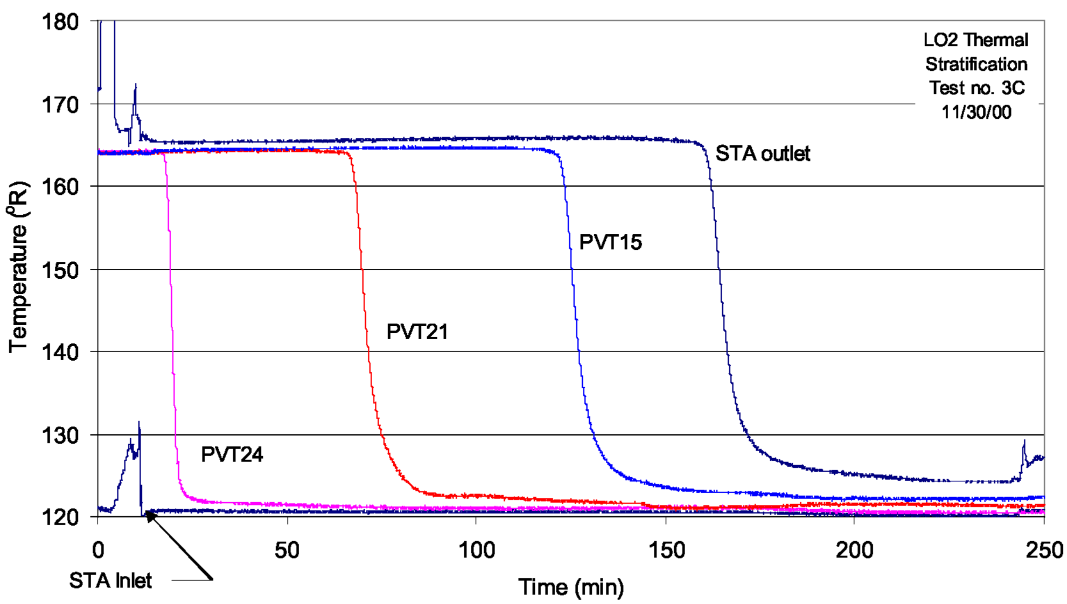


Figure 89: STA thermal stratification temperature profiles with circulating LOX - Test 3C.



6.8.4 STA LO2 Closed Loop Thermal Stratification – Test 4C

On 12/5/00 the GRC Propellant Densification Test Operations Team completed the final test of the matrix with a 30 lb_m/sec closed-loop LO2 recirculation run. The GN2 compressor was successfully ramped-up at 09:16 with no heat load on the LO2 heat exchangers. At approximately 09:50, the pressure at the inlet to the compressor had stabilized and reached 2.8 psia. The Cryo-

Mach LO2 pump was started at 10:08 and was operated between 1750 – 2000 rpm with skid outlet LOX control valve FCV-555 100% wide open to achieve the target 30 lb_m/sec test flow rate. Due to high current loads at the increased mass flow rate, the LO2 pump was incapable of sustained operation at 2000 rpm (30 lb_m/sec), and so, the recirculation flow rate was slightly reduced to 28 lb_m/sec to avoid a nuisance over-current shutdown. The facility dewar systems, the LO2 densification skid and the STA ullage pressures (**figure 90**) were all controllable and remained steady throughout the test. A steady-state thermal condition (**figure 91**) was achieved within STA after approximately 160 minutes (2.7 hrs) of closed-loop LO2 recirculation. A controlled shutdown of the LO2 pump and GN2 compressor occurred at 13:18 to conclude the run. The facility was then secured and the STA was drained back to from diode PVT2 to PVT10 to allow the subcooled LO2 to recondition to its NBP. **Figure 92** shows a typical LOX re-saturation temperature profile as the densified propellant warmed up to 162 ^oR inside the STA over a 44 hour period.

Figure 90: STA ullage pressure during LO2 thermal stratification test 4C.

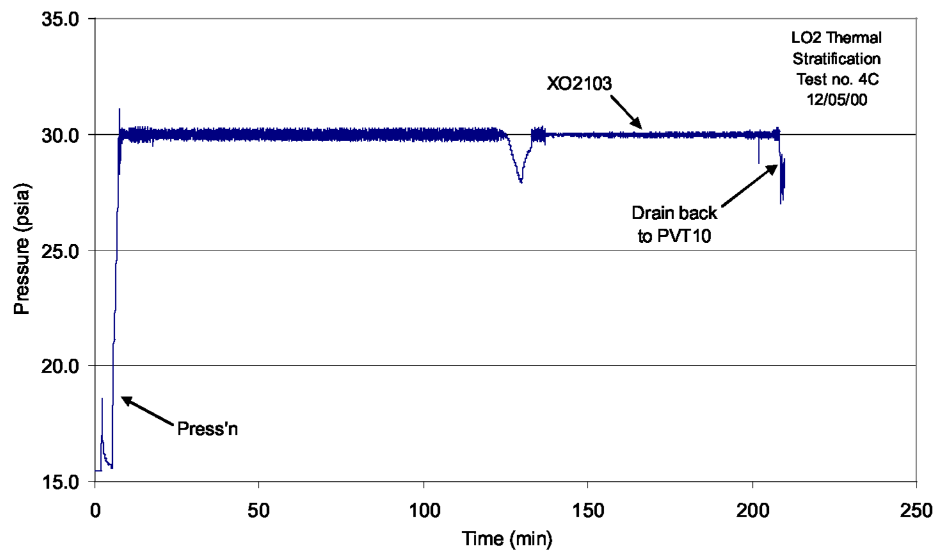


Figure 91: STA thermal stratification temperature profiles with circulating LOX - Test 4C.

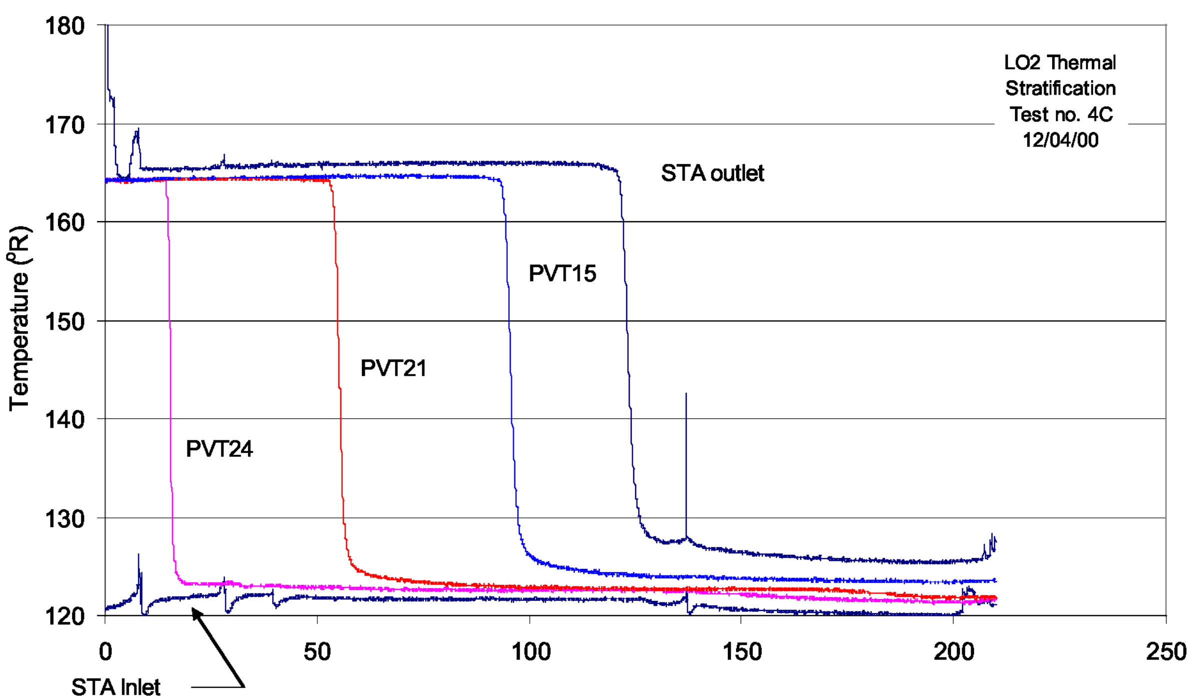
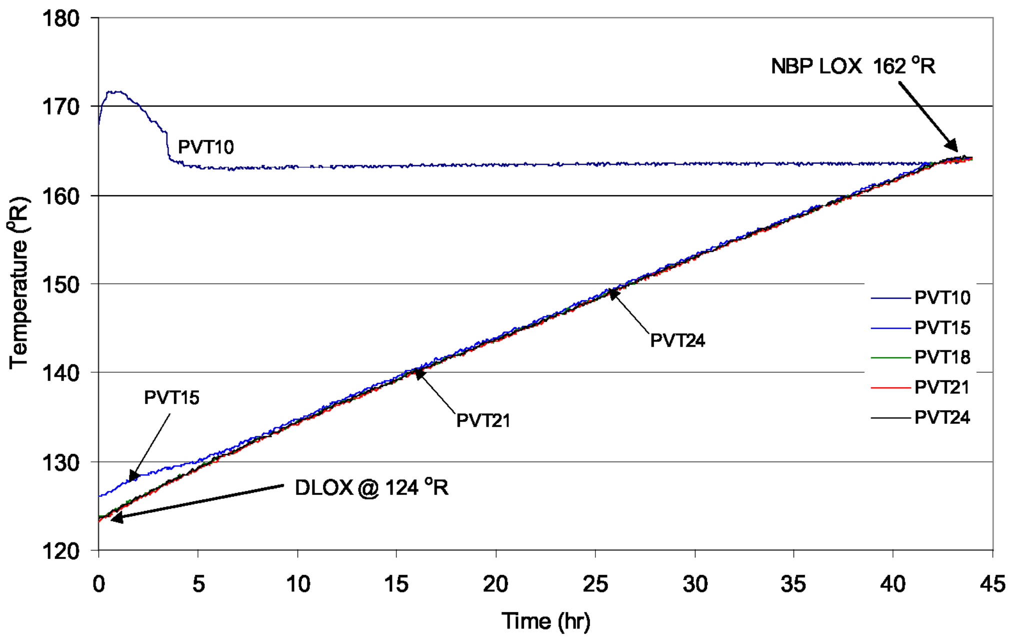


Figure 92:STA LO2 resaturation temperature vs time - densified propellant heat-up.



7. CONCLUDING REMARKS

A liquid oxygen propellant densification unit was designed, built and tested at the NASA Glenn Research Center (GRC). The steady state demonstration and performance test series was conducted with the densifier to simulate LO2 propellant tank loading, recirculation and thermal stratification of the liquid oxygen loaded inside of a flight weight tank. The X33 scale LO2 densification unit was designed to process subcooled cryogen at a nominal rate of 30 pounds per second. The densification process subcools NBP LO2, thereby effectively lowering the temperature of the fluid from 168 °R down to an outlet product temperature of 120 °R.

Test operational and performance goals with the 30 lb_m/sec LO2 densifier were successfully demonstrated during the course of the program. With the STA tank volume at around 20,000 gallons, the initial loaded mass of NBP LO2 inside of STA at the onset of the densification process was approximately 180,200 pounds. Following completion of the 20 – 30 lb_m/sec densification flow testing, experimental results indicated that by the end of the process and based on an average bulk measured temperature of 123 °R, the final loaded mass of LO2 was approximately 196,300 pounds. This additional loaded mass of 16,100 pounds represented on average an 8.9 percent increase in on-board LO2 propellant. Test results confirmed the presence of thermally stratified oxygen layers inside the tank. These layers varied in the vertical direction from 122 °R for the colder, denser fluid at the bottom to 166 °R for the warmer less dense liquid oxygen near the top outlet of the STA tank.

Other significant conclusions and lessons learned resulting from these tests were the following:

- The design-point temperature of the LO2 densification unit was demonstrated at the 20 lb/sec LO2 outlet mass flow rate. The outlet temperature at the higher flow test of 28 – 30 lb/sec was below the target but within +2 °R of the 120 °R design outlet temperature of the rig.
- The temperature performance condition noted above was correctable. With appropriate GN2 compressor coolant-system modifications, the compressor could have the capability to run at slightly lower inlet pressure settings than GRC was able to operate during the LMMSS tests.
- STA densification times to reach steady state were 190 – 210 minutes for the first three closed-loop thermal stratification tests run at 20 lb/sec LO2 mass flow rate. For the higher flow rate test at 28 lb/sec, the densification time-line was proportionately reduced to approximately 160 minutes.
- Based on a known tank volume and level, the initial loaded mass of NBP LO2 inside of STA at the onset of the densification process was approximately 180,200 pounds for all tests. At the end of run using an average measured test bulk temperature of 123 °R, the final calculated loaded mass was around 196,300 pounds. This loaded mass differential becomes 16,100 pounds which represented an 8.9% increase in on-board LO2 propellant.
- The densified LO2 inlet flow-path into the STA lobes had no noticeable affect on fluid thermal conditions inside the tank. No radial temperature gradients were evident from the STA test data.
- The experimental goals of the test program were satisfactorily achieved. The liquid oxygen closed-loop recirculation testing had demonstrated three very key technologies:
    - The feasibility of high-volume LOX densification production operations.
    - Establishing the syphon line outlet flow and top-to-bottom recirculation of LO2 during test operations was successful.
    - Thermal stratification conditions were achievable in a flight-weight LO2 propellant tank using this unique processing method.

Throughout the course of the test program, GRC had produced in excess of 150,000 gallons of 120 °R densified LO2. This included the combined GRC LO2 densifier performance testing and the closed-loop recirculation tests that would typify an on-the-pad loading operation. During LN2 performance checkout tests of the LO2 densifier systems, over 200,000 gallons of densified LN2 at 120 °R was produced as well.

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APPENDIX A

LO2 PDU TEST ARTICLE INSTRUMENTATION

APPENDIX A – LO2 PDU TEST ARTICLE INSTRUMENTATION

Channel Type	ID ID Number	Description	Range Limits	Units	Location Facility	Densifier	STA
ET	**C715A_Volt**	Stage 1 Compressor Motor Voltage	0 - 500	volt		X	
ET	**C715B_Volt**	Stage 2 Compressor Motor Voltage	0 - 500	volt		X	
ET	**C715C_Volt**	Stage 3 Compressor Motor Voltage	0 - 500	volt		X	
FT	**FT515**	Replenish LO2 Mass Flow Rate	0 - 3.1	lb/sec		X	
FT	**FT535**	LO2 Pump Discharge Mass Flow Rate	0 - 30	lb/sec		X	
FT	**FT607**	Stage 2 Exchanger LN2 Make-Up Flow Rate	0 - 5.6	lb/sec		X	
FT	**FT715**	gN2 Compressor Vent Mass Flow Rate	0 - 3.3	lb/sec		X	
FT	**FT715S**	gN2 Surge Mass Flow Rate to Stage 2 Exchanger	0 - 1.8	lb/sec		X	
FXQ	**C715A_VolQ**	Stage 1 Compressor Outlet Volume Flow Rate	0 - 3000	cfm		X	
FXQ	**C715B_VolQ**	Stage 2 Compressor Outlet Volume Flow Rate	0 - 3000	cfm		X	
FXQ	**C715C_VolQ**	Stage 3 Compressor Outlet Volume Flow Rate	0 - 3000	cfm		X	
IT	**C715A_Amps**	Stage 1 Compressor Motor Current	0 - 150	amp		X	
IT	**C715B_Amps**	Stage 2 Compressor Motor Current	0 - 150	amp		X	
IT	**C715C_Amps**	Stage 3 Compressor Motor Current	0 - 150	amp		X	
LT	**LT615**	Stage 2 Heat Exchanger LN2 Bath Level	0 - 51	inch		X	
LT	**LT620**	Stage 1 Heat Exchanger LN2 Bath Level	0 - 60	inch		X	
PDT	**PDT502**	Differential Pressure across LO2 Filter F-502	0 - 5	psid		X	
PDT	**PDT522**	Differential Pressure across LO2 Filter F-522	0 - 5	psid		X	
PDT	**PDT630**	Differential Pressure across LN2 Filter F-630	0 - 5	psid		X	
PT	**PT505**	Facility LO2 Make-Up Pressure to Densifier	0 - 115	psia		X	
PT	**PT525**	LO2 Pump Inlet Pressure	0 - 115	psia		X	
PT	**PT540**	LO2 Pump Outlet Pressure	0 - 115	psia		X	
PT	**PT550**	Stage 1 Heat Exchanger Outlet Pressure	0 - 115	psia		X	
PT	**PT560**	Stage 2 Heat Exchanger Outlet Pressure	0 - 115	psia		X	
PT	**PT605**	Facility LN2 Pressure at Densifier Inlet	0 - 165	psia		X	
PT	**PT707**	Stage 1 Heat Exchanger Ullage Pressure	0 - 65	psia		X	
PT	**PT709**	Stage 2 Heat Exchanger Ullage Pressure	0 - 65	psia		X	
PT	**PT715**	Stage 2 Heat Exchanger Ullage Pressure	0 - 5	psia		X	
PT	**PT715A**	Inlet Pressure to Compressor First Stage	0 - 50	psia		X	
PT	**PT715B**	Inlet Pressure to Compressor Second Stage	0 - 50	psia		X	
PT	**PT715C**	Inlet Pressure to Compressor Third Stage	0 - 50	psia		X	
PT	**PT715D**	Discharge Pressure at Compressor Third Stage	0 - 50	psia		X	
PT	**PT715S**	Pressure at Compressor Surge Line Flow Meter	0 - 50	psia		X	
PT	**PT755**	Local Atmospheric Pressure in LO2 Skid Area	0 - 20	psia		X	
PT	**PT800**	500 psig Helium Supply Pressure to Skid	0 - 600	psig		X	
PT	**PT805**	100 psig Helium System Pressure	0 - 150	psig		X	
PT	**PT807**	25 psig Helium System Pressure	0 - 50	psig		X	
PT	**PT815**	Helium Pressure in Compressor Enclosure	0 - 40	psia		X	
PT	**PT850**	500 psig Nitrogen Supply Pressure to Skid	0 - 600	psig		X	

APPENDIX A – LO2 PDU TEST ARTICLE INSTRUMENTATION (cont'd)

Channel Type	ID ID Number	Description	Range Limits	Range Units	Location Facility	Location Densifier	Location STA
PT	**PT855**	125 psig Nitrogen System Pressure	0 - 150	psig		X	
PT	**PT857**	40 psig Nitrogen System Pressure	0 - 50	psig		X	
SI	**SC535**	LO2 Pump Speed	0 - 5000	rpm		X	
SI	**SC715A**	Stage 1 Compressor Speed	0 - 12000	rpm		X	
SI	**SC715B**	Stage 2 Compressor Speed	0 - 12000	rpm		X	
SI	**SC715C**	Stage 3 Compressor Speed	0 - 12000	rpm		X	
TE	**TT510**	LO2 Makeup Inlet Temperature	2.5 - 855	^oR		X	
TE	**TT530**	LO2 Pump Inlet Temperature (1 of 2)	2.5 - 855	^oR		X	
TE	**TT532**	LO2 Pump Inlet Temperature (2 of 2)	2.5 - 855	^oR		X	
TE	**TT535A**	LO2 Pump Motor Winding "A" Temperature	-100- 400	^oF		X	
TE	**TT535B**	LO2 Pump Motor Winding "B" Temperature	-100-400	^oF		X	
TE	**TT535C**	LO2 Pump Motor Winding "C" Temperature	-100-400	^oF		X	
TE	**TT545**	LO2 Pump Outlet Temperature	2.5 - 855	^oR		X	
TE	**TT550**	Stage 1 Heat Exchanger Outlet Temperature	2.5 - 855	^oR		X	
TE	**TT565**	Stage 2 Heat Exchanger Outlet Temperature	2.5 - 855	^oR		X	
TE	**TT574**	Densifier Skid Exit LO2 Temperature	2.5 - 855	^oR		X	
TE	**TT592**	LO2 Pond Vent Temperature	2.5 - 855	^oR		X	
TE	**TT602A**	Stage 1 Heat Exchanger LN2 Bath Temperature	2.5 - 855	^oR		X	
TE	**TT602B**	Stage 1 Heat Exchanger LN2 Bath Temperature	2.5 - 855	^oR		X	
TE	**TT603A**	Stage 2 Heat Exchanger LN2 Bath Temperature	2.5 - 855	^oR		X	
TE	**TT603B**	Stage 2 Heat Exchanger LN2 Bath Temperature	2.5 - 855	^oR		X	
TE	**TT610**	Facility LN2 Supply Temperature to Densifier	2.5 - 855	^oR		X	
TE	**TT680**	Heat Exchanger LN2 Drain Line Temperature	2.5 - 855	^oR		X	
TE	**TT702A**	Stage 1 Heat Exchanger Ullage Temperature	2.5 - 855	^oR		X	
TE	**TT702B**	Stage 1 Heat Exchanger Ullage Temperature	2.5 - 855	^oR		X	
TE	**TT703A**	Stage 2 Heat Exchanger Ullage Temperature	2.5 - 855	^oR		X	
TE	**TT703B**	Stage 2 Heat Exchanger Ullage Temperature	2.5 - 855	^oR		X	
TE	**TT715A**	Inlet Temperature to Compressor First Stage	2.5 - 855	^oR		X	
TE	**TT715B**	Inlet Temperature to Compressor Second Stage	2.5 - 855	^oR		X	
TE	**TT715C**	Inlet Temperature to Compressor Third Stage	2.5 - 855	^oR		X	
TE	**TT715D**	Discharge Temperature at Compressor Stage 3	2.5 - 855	^oR		X	
TE	**TT715E**	Vent Gas Temperature at FT715 Flow Meter	2.5 - 855	^oR		X	
TE	**TT715M1A**	Stage 1 Compressor Motor Winding "A" Temp.	-100-400	^oF		X	
TE	**TT715M1B**	Stage 1 Compressor Motor Winding "B" Temp.	-100-400	^oF		X	
TE	**TT715M1C**	Stage 1 Compressor Motor Winding "C" Temp.	-100-400	^oF		X	
TE	**TT715M2A**	Stage 2 Compressor Motor Winding "A" Temp.	-100-400	^oF		X	
TE	**TT715M2B**	Stage 2 Compressor Motor Winding "B" Temp.	-100-400	^oF		X	
TE	**TT715M2C**	Stage 2 Compressor Motor Winding "C" Temp.	-100-400	^oF		X	
TE	**TT715M3A**	Stage 3 Compressor Motor Winding "A" Temp.	-100-400	^oF		X	
TE	**TT715M3B**	Stage 3 Compressor Motor Winding "B" Temp.	-100-400	^oF		X	
TE	**TT715M3C**	Stage 3 Compressor Motor Winding "C" Temp.	-100-400	^oF		X	
TE	**TT715S**	Temp. at Compressor Surge Line Flow Meter	2.5 - 855	^oR		X	

APPENDIX A – LO2 PDU TEST ARTICLE INSTRUMENTATION (cont'd)

Channel Type	ID ID Number	Description	Range Limits	Units	Location Facility	Densifier	STA
TE	**TT720**	Gas Temperature in Phase Separator	2.5 - 855	°R		X	
TE	**TT861A**	PLC Cabinet Temperature	0 - 120	°F		X	
TE	**TT861B**	208V Cabinet Temperature	0 - 120	°F		X	
TE	**TT861C**	480V Cabinet Temperature	0 - 120	°F		X	
TE	**TT862**	Instrumentation Cabinet Temperature	0 - 120	°F		X	
VE	**VT535**	LO2 Pump Vibration Sensor	0 - 1.0	in/sec		X	
VE	**VT715A**	Compressor First Stage Vibration Sensor	0 - 1.0	in/sec		X	
VE	**VT715B**	Compressor Second Stage Vibration Sensor	0 - 1.0	in/sec		X	
VE	**VT715C**	Compressor Third Stage Vibration Sensor	0 - 1.0	in/sec		X	
XFC	**FC1**	Flow Coefficient at Compressor First Stage	0 - 1.0	d-less		X	
XFC	**FC2**	Flow Coefficient at Compressor Second Stage	0 - 1.0	d-less		X	
XFC	**FC3**	Flow Coefficient at Compressor Third Stage	0 - 1.0	d-less		X	
ZT	**ZT715**	Gas Bypass Valve FCV715 Position Transmitter	0 - 100	% close		X	

Instrumentation Legend:

ET	voltage transducer
FT	mass flow transducer
FXQ	volumetric flow rate (calculated)
IT	current transducer
LT	level transducer
PDT	differential pressure transducer
PT	pressure transducer
SI	speed indicator
TE	temperature element
VE	vibration element
XFC	flow coefficient, Φ (calculated)
ZT	position transmitter

APPENDIX B

STA TANKING TABLE

APPENDIX B – STA TANKING TABLE

Table B.1: STA test bed tanking and cryogenic loading data.

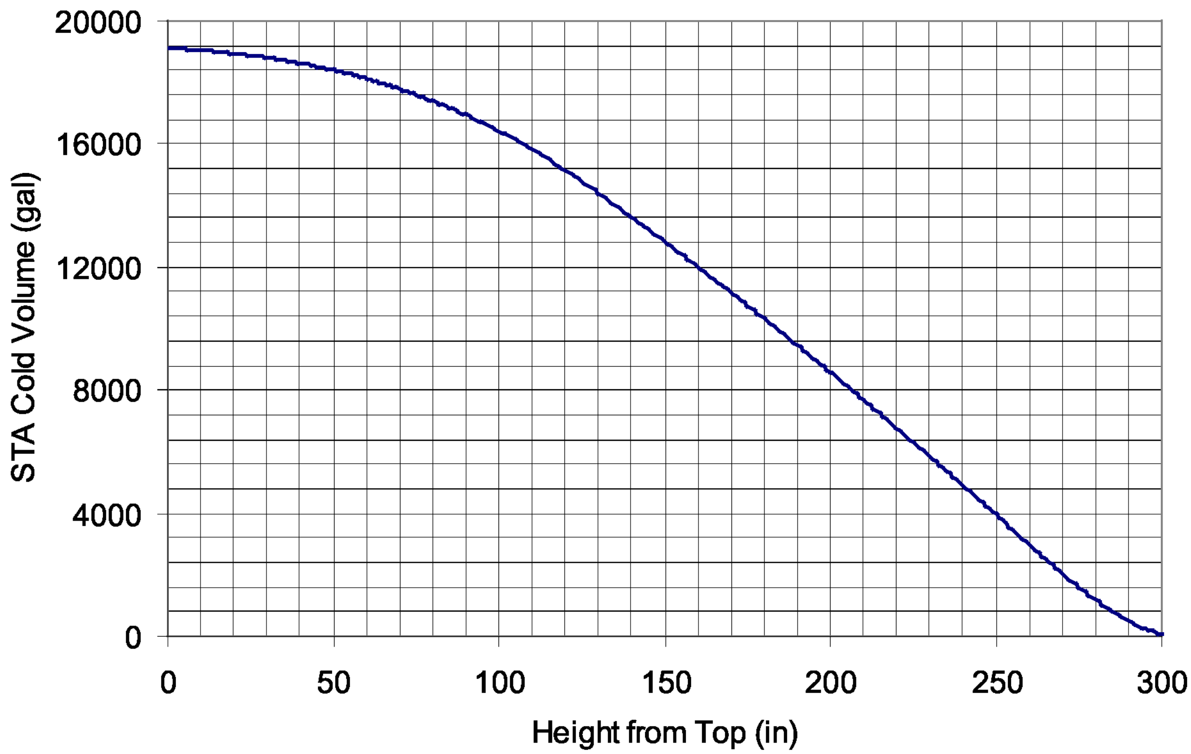
Total STA Tank Volume = 2556.68 ft^3

LN2 NBP Density = 50.36 lb/ft^3 LO2 NBP Density = 71.23 lb/ft^3

Height from Top (inch)	STA Vertical Diode ID PVT-X	Cold Volume in Tank (gal)	Cold Volume in Tank (ft^3)	Percent Ullage Volume (%)	NBP Liquid Nitrogen Mass (lb_m)	NBP Liquid Oxygen Mass (lb_m)
0	-	19126	2556.7	0.0	128754	182112
14	1	19012	2541.4	0.6	127984	181023
28	2	18835	2517.7	1.5	126791	179335
44	3	18538	2478.0	3.1	124790	176506
46	4	18493	2471.9	3.3	124486	176076
50	5	18396	2459.1	3.8	123839	175161
56	6	18237	2437.8	4.6	122768	173645
62	7	18059	2414.0	5.6	121569	171949
68	8	17861	2387.5	6.6	120235	170062
74	9	17642	2358.2	7.8	118759	167975
80	10	17401	2326.0	9.0	117135	165678
88	11	17043	2278.1	10.9	114726	162271
98	12	16534	2210.1	13.6	111301	157426
110	13	15827	2115.6	17.3	106540	150691
122	14	15006	2005.9	21.5	101017	142880
134	15	14096	1884.2	26.3	94889	134213
146	16	13148	1757.5	31.3	88508	125188
158	17	12175	1627.5	36.3	81960	115926
170	18	11178	1494.2	41.6	75248	106432
182	19	10157	1357.7	46.9	68376	96712
194	20	9113	1218.1	52.4	61346	86769
212	21	7503	1002.9	60.8	50508	71439
230	22	5845	781.3	69.4	39346	55652
254	23	3562	476.2	81.4	23980	33918
278	24	1343	179.6	93.0	9044	12791
302	25	28	3.8	99.9	191	271
306	-	0	0.0	100.0	0	0

APPENDIX B – STA TANKING TABLE (cont'd)

Figure B.1: STA cold fluid volume vs. height profile.



APPENDIX C

S40 FACILITY INSTRUMENTATION

APPENDIX C – S40 FACILITY INSTRUMENTATION

Channel Type	ID ID Number	Description	Range Limits	Range Units	Location Facility	Location Densifier	Location STA
LT	**LTO2**	STA Liquid Level Capacitance Probe for LO2	0 - 32	inch			X
LT	**LTN2**	STA Liquid Level Capacitance Probe for LN2	0 - 32	inch			X
PDT	**N7113**	N-71 Liquid Level ΔP Transducer (LN2 Volume)	0 - 13000	gallons	X		
PDT	**XO0602**	Densifier Product Outlet ΔP across Filter	0 - 5	psid	X		
PDT	**XO2111**	STA Boiloff Rifice Meter ΔP Transducer	0 - 5	psid			X
PDT	**XO8309**	N-83 Liquid Level ΔP Transducer (LO2 Volume)	0 - 28000	gallons	X		
PT	**H1102**	GHe Tuber Manifold Pressure	0 - 3000	psig	X		
PT	**H1110**	GHe Pressure to LO2 Densifier	0 - 550	psig	X		
PT	**H1208**	GHe Purge Pressure at 30 psig	0 - 40	psig	X		
PT	**H1508**	GHe Purge Pressure to STA Tank	0 - 40	psig	X		
PT	**N1102**	GN2 Tuber Manifold Pressure	0 - 3000	psig	X		
PT	**N1110**	GN2 Pressure to LO2 Densifier	0 - 600	psig	X		
PT	**N1208**	GN2 Pressure to Purge	0 - 40	psig	X		
PT	**N1508**	GN2 Pressure to Valve Actuators	0 - 150	psig	X		
PT	**N1513**	GN2 Pressurant Gas to Dewar N-71	0 - 75	psig	X		
PT	**N7117**	N-71 Dewar Internal Pressure	0 - 50	psig	X		
PT	**XO0104**	LO2 Densifier Skid Inlet Pressure	0 - 50	psig	X		
PT	**XO0607**	STA Tank Liquid Inlet Pressure	0 - 50	psig	X		
PT	**XO2103**	STA Tank Internal Ullage Pressure	0 - 60	psia			X
PT	**XO2302**	STA Syphon Line Outlet Pressure	0 - 50	psig			X
PT	**XO8311**	N-83 Dewar Internal Ullage Pressure	0 - 75	psig	X		
TE	**N7105**	N-71 Dewar Liquid Nitrogen Temperature	2.5 - 855	°R	X		
TE	**N7107**	N-71 Dewar Ullage Temperature	2.5 - 855	°R	X		
TE	**N7109**	N-71 Dewar Liquid Nitrogen Temperature	2.5 - 855	°R	X		
TE	**PLT1**	STA Internal Temperature, Lateral Rake, 98" level	2.5 - 855	°R			X
TE	**PLT2**	STA Internal Temperature, Lateral Rake, 98" level	2.5 - 855	°R			X
TE	**PLT3**	STA Internal Temperature, Lateral Rake, 98" level	2.5 - 855	°R			X
TE	**PLT4**	STA Internal Temperature, Lateral Rake, 98" level	2.5 - 855	°R			X
TE	**PLT5**	STA Internal Temperature, Lateral Rake, 98" level	2.5 - 855	°R			X
TE	**PLT6**	STA Internal Temperature, Lateral Rake, 160" level	2.5 - 855	°R			X
TE	**PLT7**	STA Internal Temperature, Lateral Rake, 160" level	2.5 - 855	°R			X
TE	**PLT8**	STA Internal Temperature, Lateral Rake, 160" level	2.5 - 855	°R			X
TE	**PLT9**	STA Internal Temperature, Lateral Rake, 160" level	2.5 - 855	°R			X
TE	**PLT10**	STA Internal Temperature, Lateral Rake, 160" level	2.5 - 855	°R			X
TE	**PLT11**	STA Internal Temperature, Lateral Rake, 218" level	2.5 - 855	°R			X
TE	**PLT12**	STA Internal Temperature, Lateral Rake, 218" level	2.5 - 855	°R			X
TE	**PLT13**	STA Internal Temperature, Lateral Rake, 218" level	2.5 - 855	°R			X
TE	**PLT14**	STA Internal Temperature, Lateral Rake, 218" level	2.5 - 855	°R			X
TE	**PLT15**	STA Internal Temperature, Lateral Rake, 218" level	2.5 - 855	°R			X

APPENDIX C – S40 FACILITY INSTRUMENTATION (cont'd)

Channel	ID	Description	Range		Location		
Type	ID Number		Limits	Units	Facility	Densifier	STA
TE	**PVT1**	STA Internal Temperature, Vertical Rake, 14" level	2.5 - 855	°R			X
TE	**PVT2**	STA Internal Temperature, Vertical Rake, 28" level	2.5 - 855	°R			X
TE	**PVT3**	STA Internal Temperature, Vertical Rake, 44" level	2.5 - 855	°R			X
TE	**PVT4**	STA Internal Temperature, Vertical Rake, 46" level	2.5 - 855	°R			X
TE	**PVT5**	STA Internal Temperature, Vertical Rake, 50" level	2.5 - 855	°R			X
TE	**PVT6**	STA Internal Temperature, Vertical Rake, 56" level	2.5 - 855	°R			X
TE	**PVT7**	STA Internal Temperature, Vertical Rake, 62" level	2.5 - 855	°R			X
TE	**PVT8**	STA Internal Temperature, Vertical Rake, 68" level	2.5 - 855	°R			X
TE	**PVT9**	STA Internal Temperature, Vertical Rake, 74" level	2.5 - 855	°R			X
TE	**PVT10**	STA Internal Temperature, Vertical Rake, 80" level	2.5 - 855	°R			X
TE	**PVT11**	STA Internal Temperature, Vertical Rake, 88" level	2.5 - 855	°R			X
TE	**PVT12**	STA Internal Temperature, Vertical Rake, 98" level	2.5 - 855	°R			X
TE	**PVT13**	STA Internal Temperature, Vertical Rake, 110" level	2.5 - 855	°R			X
TE	**PVT14**	STA Internal Temperature, Vertical Rake, 122" level	2.5 - 855	°R			X
TE	**PVT15**	STA Internal Temperature, Vertical Rake, 134" level	2.5 - 855	°R			X
TE	**PVT16**	STA Internal Temperature, Vertical Rake, 146" level	2.5 - 855	°R			X
TE	**PVT17**	STA Internal Temperature, Vertical Rake, 158" level	2.5 - 855	°R			X
TE	**PVT18**	STA Internal Temperature, Vertical Rake, 170" level	2.5 - 855	°R			X
TE	**PVT19**	STA Internal Temperature, Vertical Rake, 182" level	2.5 - 855	°R			X
TE	**PVT20**	STA Internal Temperature, Vertical Rake, 194" level	2.5 - 855	°R			X
TE	**PVT21**	STA Internal Temperature, Vertical Rake, 212" level	2.5 - 855	°R			X
TE	**PVT22**	STA Internal Temperature, Vertical Rake, 230" level	2.5 - 855	°R			X
TE	**PVT23**	STA Internal Temperature, Vertical Rake, 254" level	2.5 - 855	°R			X
TE	**PVT24**	STA Internal Temperature, Vertical Rake, 278" level	2.5 - 855	°R			X
TE	**PVT25**	STA Internal Temperature, Vertical Rake, 302" level	2.5 - 855	°R			X
TE	**XO0107**	Densifier Skid Liquid Inlet Temperature	2.5 - 855	°R	X		
TE	**XO0606**	STA Facility Liquid Inlet Temperature	2.5 - 855	°R	X		
TE	**XO2102**	STA Vent Gas Temperature	2.5 - 855	°R			X
TE	**XO2122**	STA Boil-Off Gas Temperature	2.5 - 855	°R			X
TE	**XO2305**	Syphon Line Outlet Temperature	2.5 - 855	°R			X
TE	**XO2402**	STA Lobe 1 Fill Temperature	2.5 - 855	°R			X
TE	**XO2502**	STA Lobe 2 Fill Temperature	2.5 - 855	°R			X
TE	**XO8304**	N-83 Dewar Liquid Temperature	2.5 - 855	°R	X		
TE	**XO8306**	N-83 Dewar Ullage Temperature	2.5 - 855	°R	X		
TE	**XO8308**	N-83 Dewar Liquid Temperature	2.5 - 855	°R	X		

Instrumentation Legend:

LT level transducer
PDT differential pressure transducer
PT pressure transducer
TE temperature element

APPENDIX D

GN2 COMPRESSOR TEST DATA

APPENDIX D – GN2 COMPRESSOR TEST DATA

Figure D.1: GN2 compressor speed vs. time.

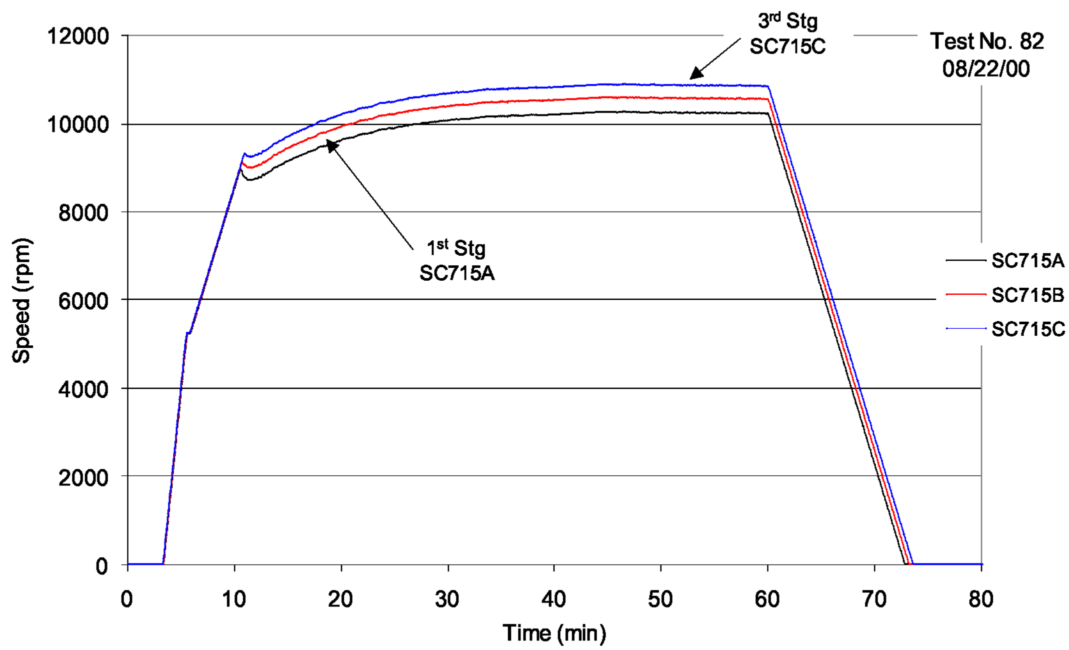


Figure D.2: Compressor interstage pressure profile.

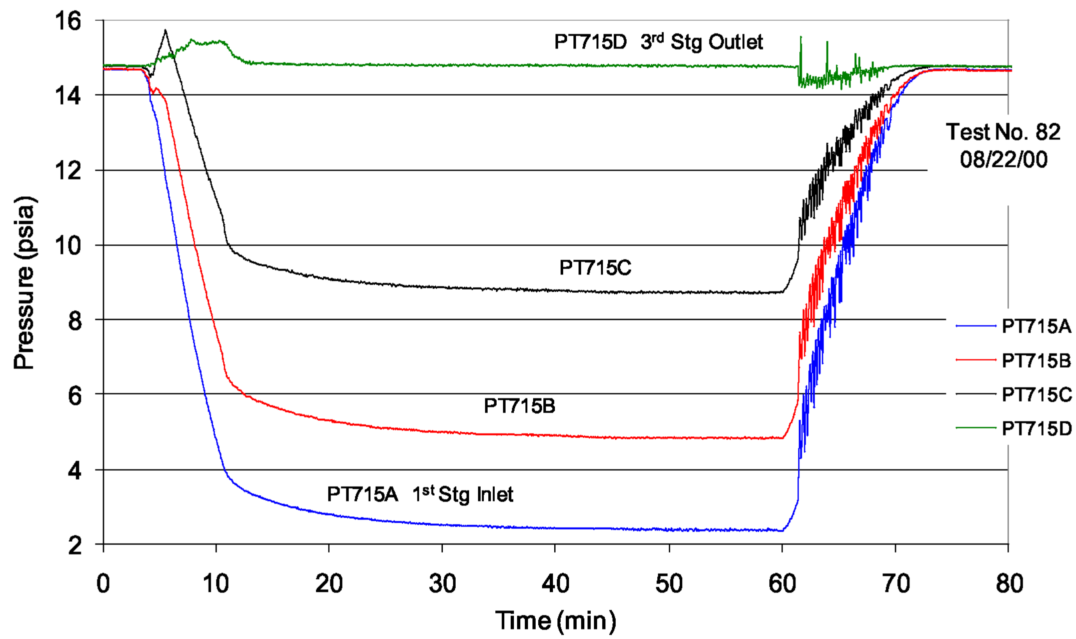


Figure D.3: Compressor interstage gas temperature vs. time.

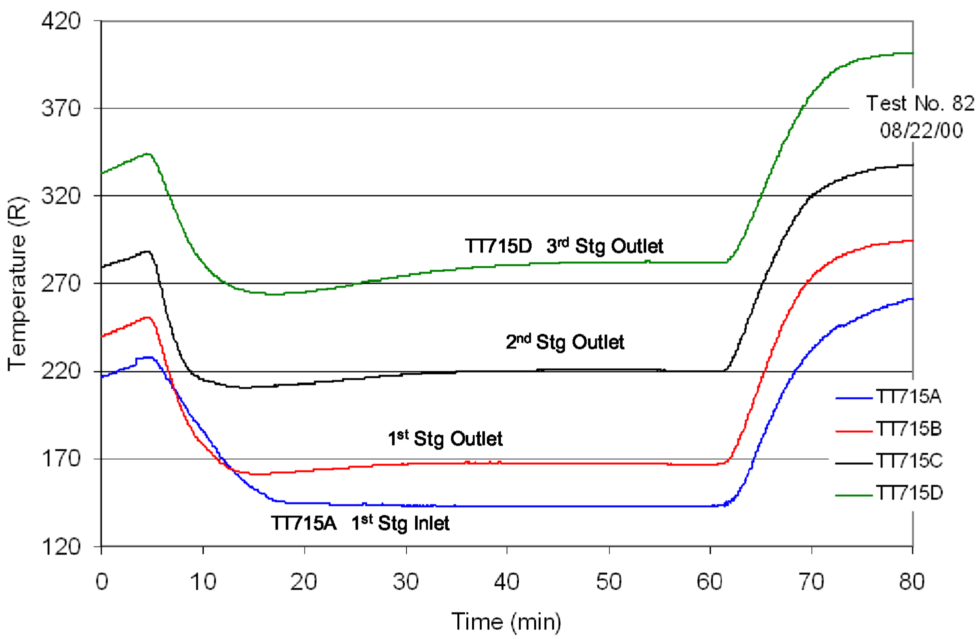


Figure D.4: Compressor mass flow rate and gas bypass flow vs. time.

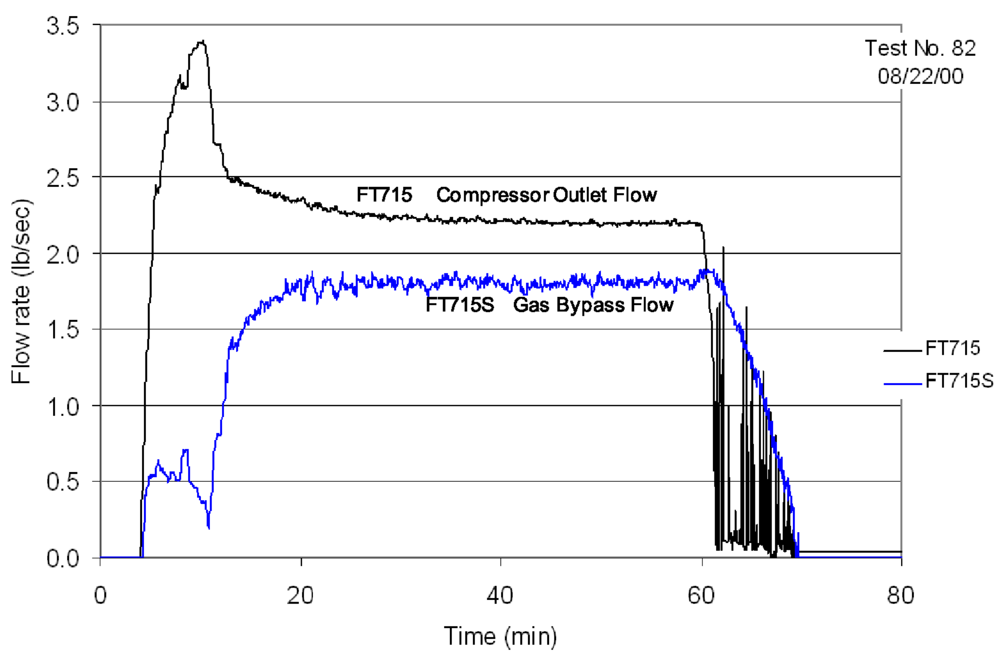


Figure D.5: Compressor stage discharge volume flow rates vs. time.

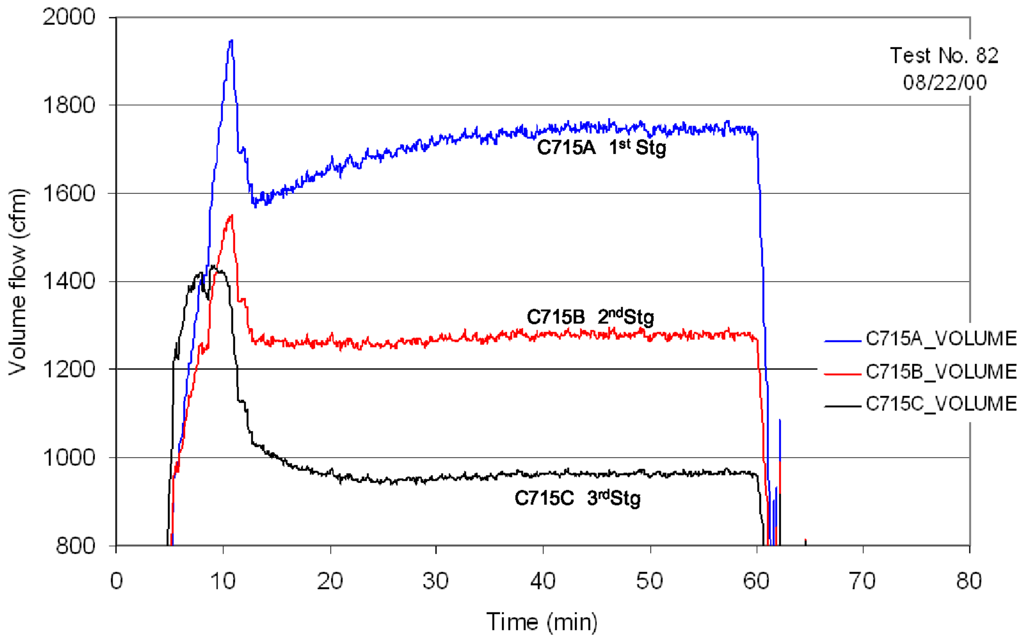


Figure D.6: Compressor flow coefficient vs. time.

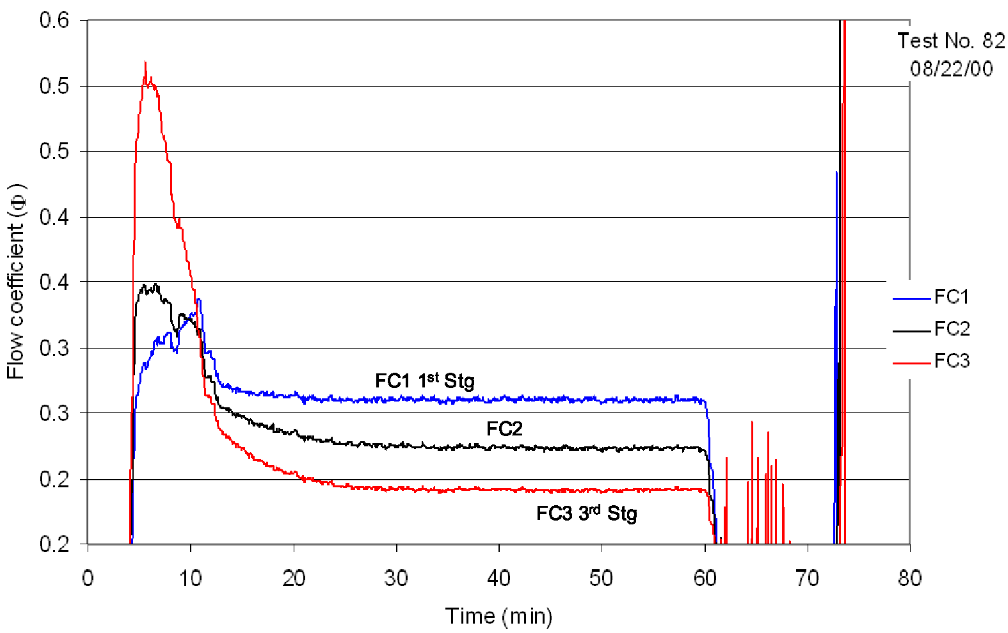


Figure D.7: Compressor surge bypass valve position vs. time.

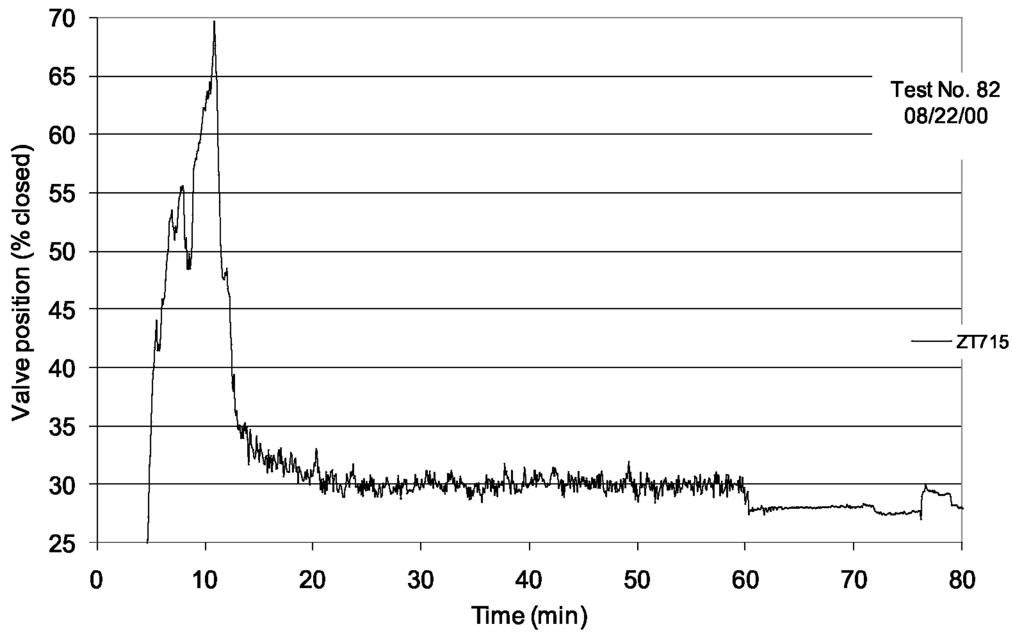
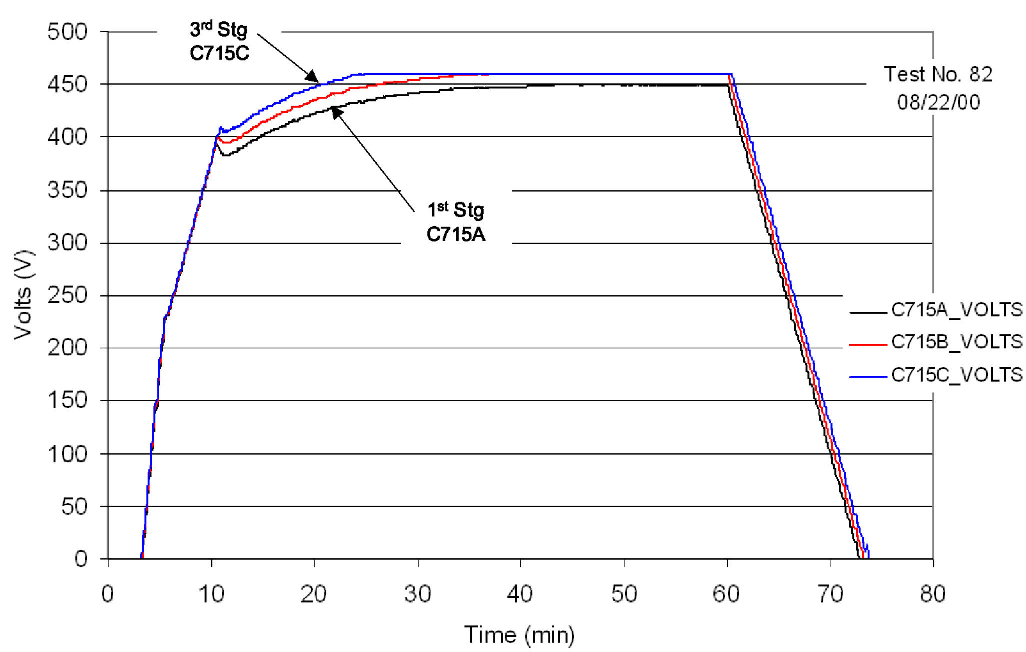


Figure D.8: Compressor motor voltage vs. time.



APPENDIX D – GN2 COMPRESSOR TEST DATA (cont'd)

Figure D.9: Compressor motor current vs. time.

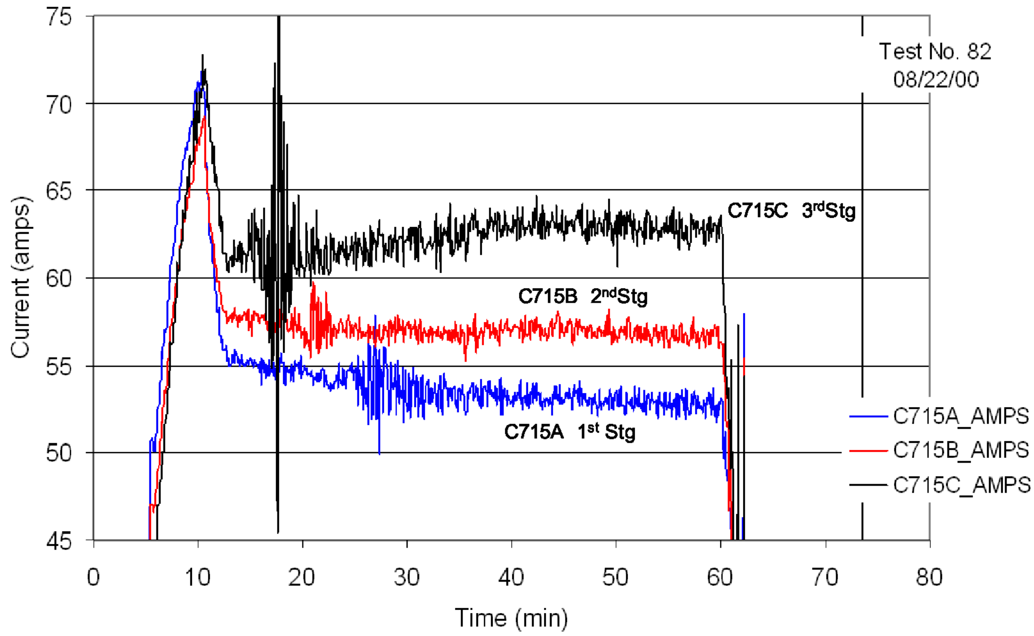
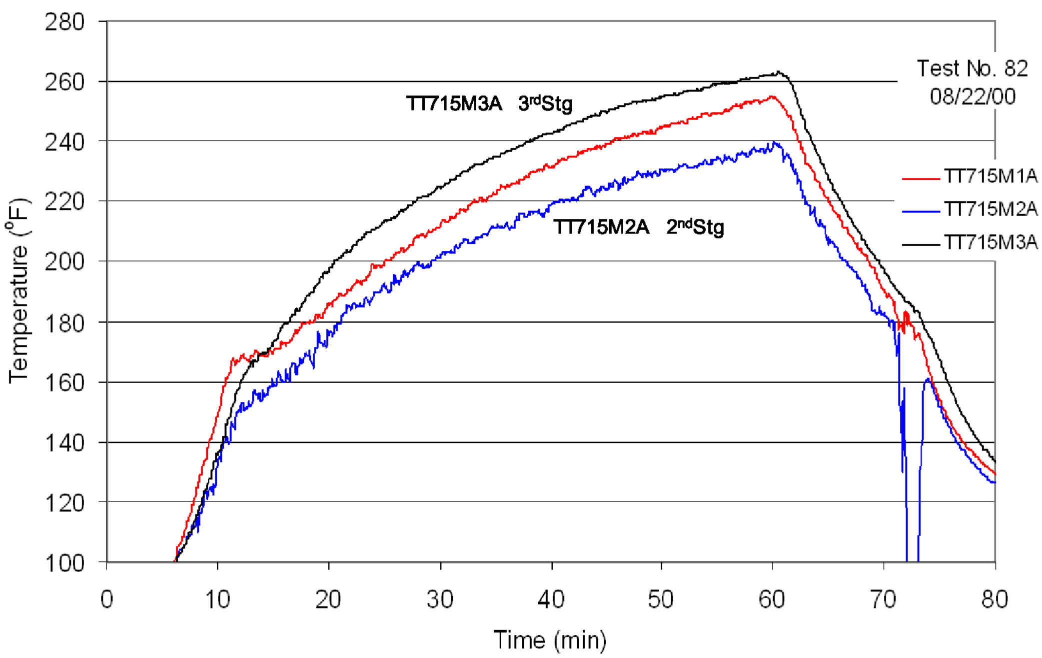


Figure D.10: Compressor stage motor winding temperature profiles.



APPENDIX D – GN2 COMPRESSOR TEST DATA (cont'd)

Figure D.11: Compressor motor vibration history.

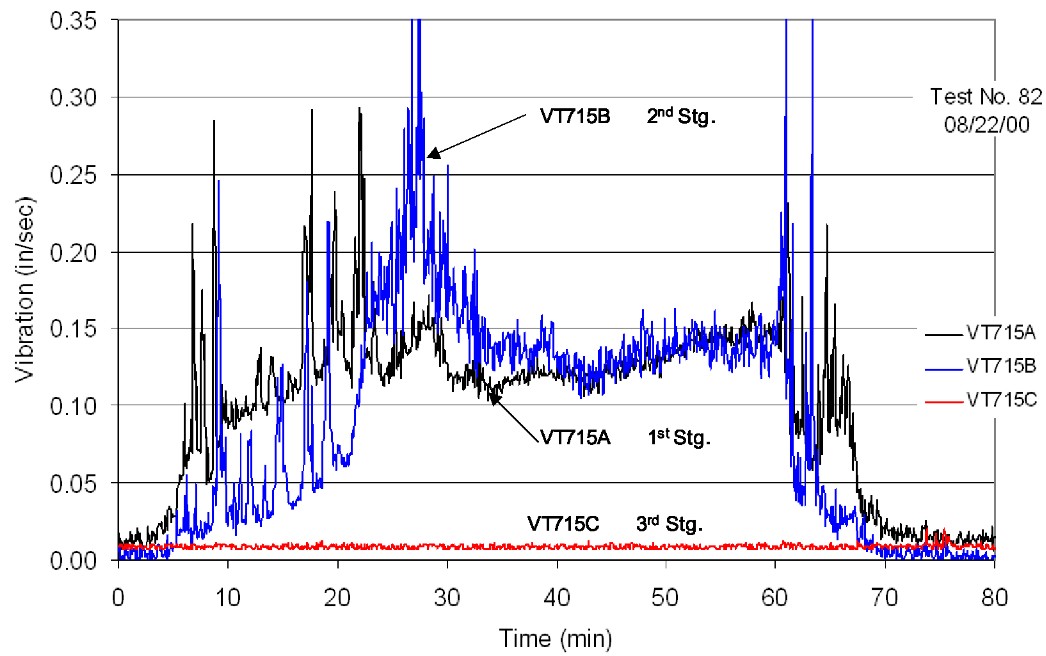


Figure D.12: GN2 compressor speed vs. time.

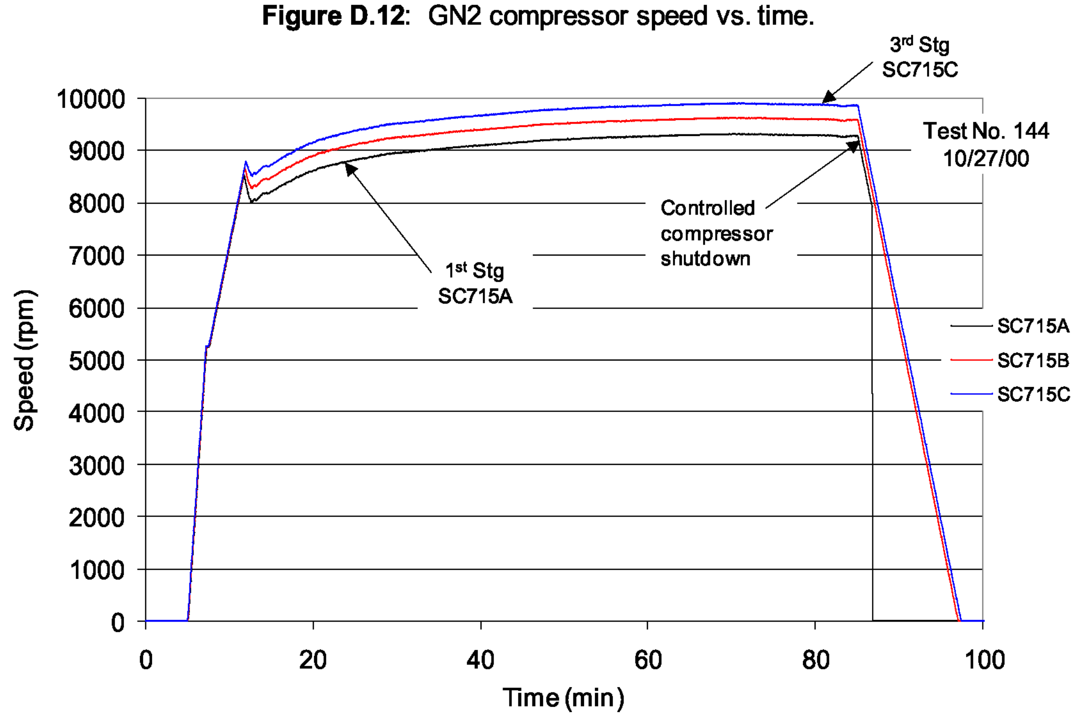


Figure D.13: Compressor interstage pressure profile.

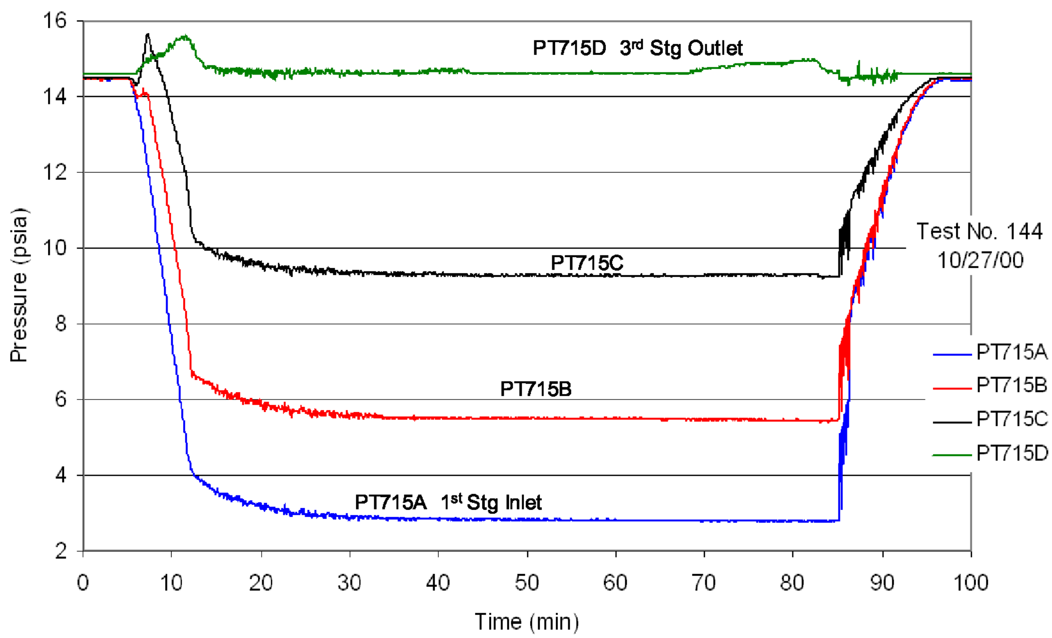


Figure D.14: Compressor interstage gas temperature vs. time.

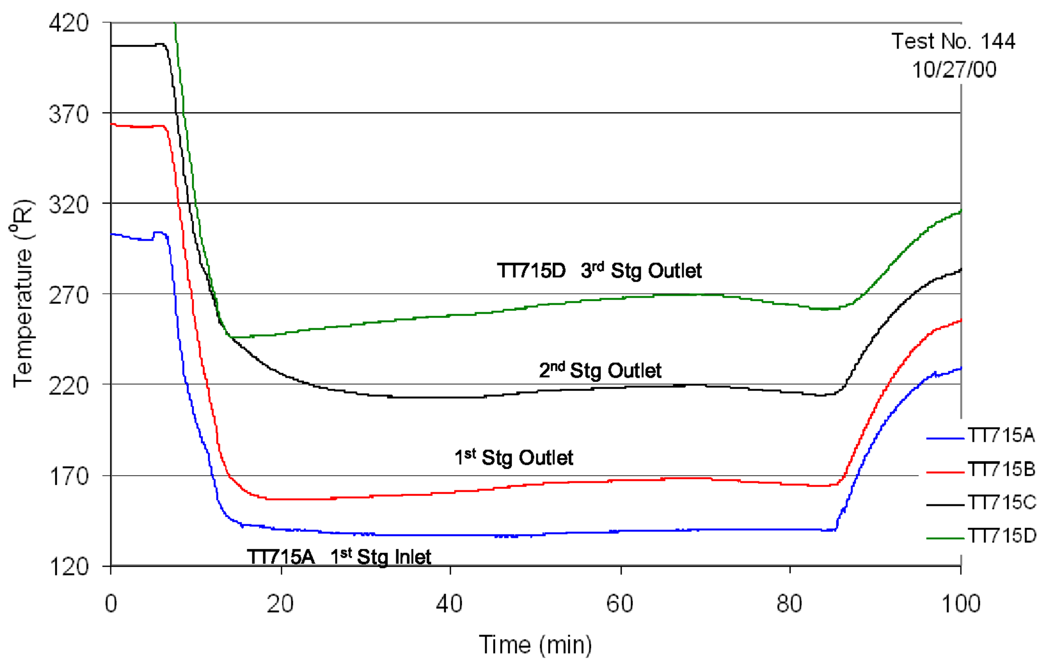


Figure D.15: Compressor mass flow rate and gas bypass flow vs. time.

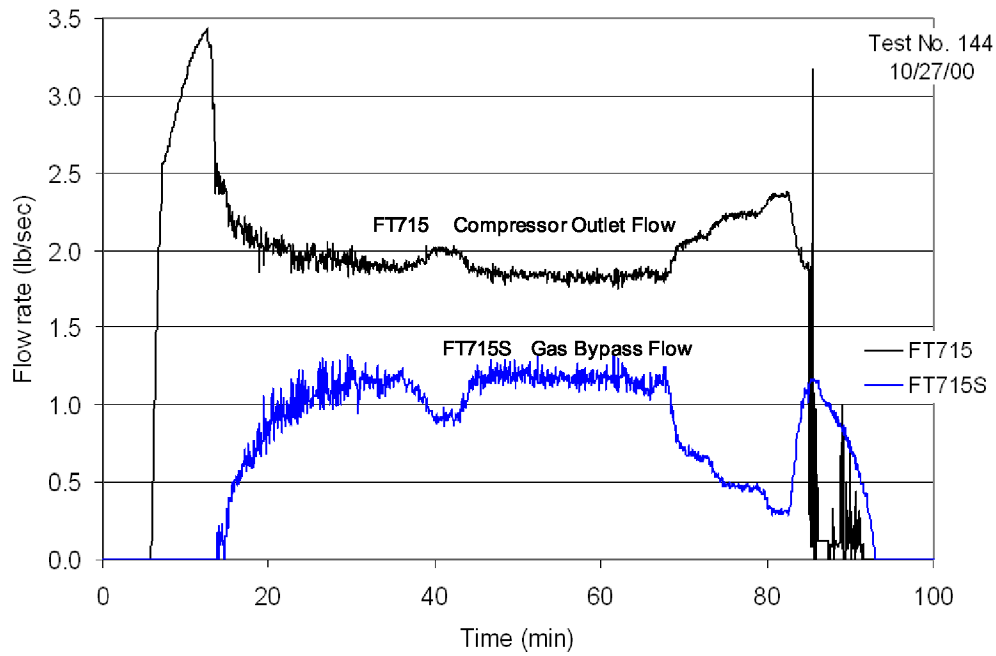


Figure D.16: Compressor stage discharge volume flow rates vs. time.

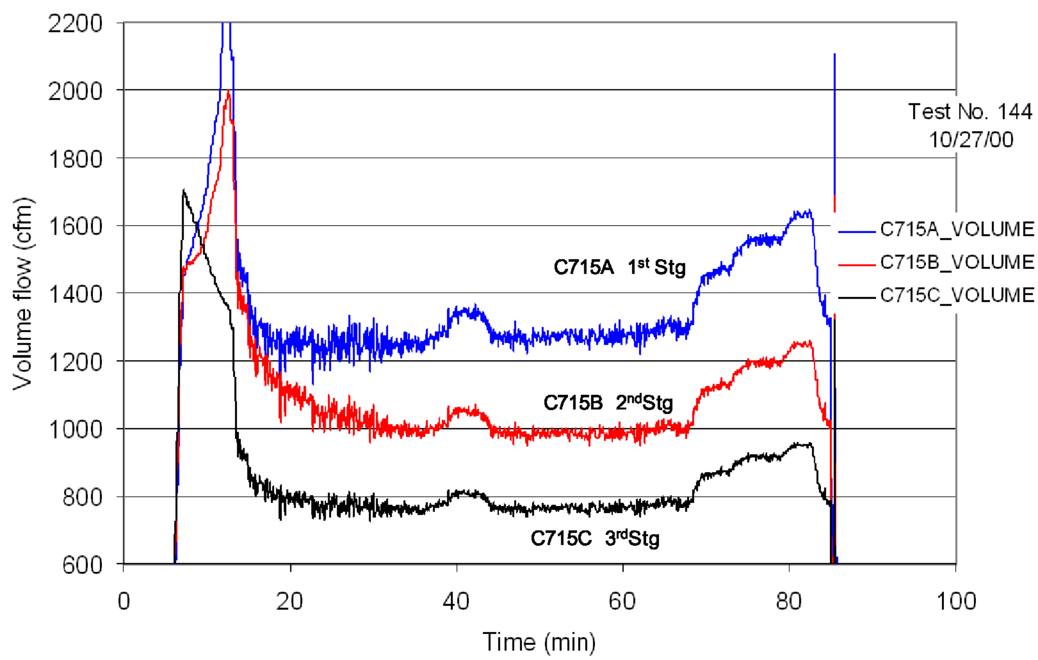


Figure D.17: Compressor flow coefficient vs. time.

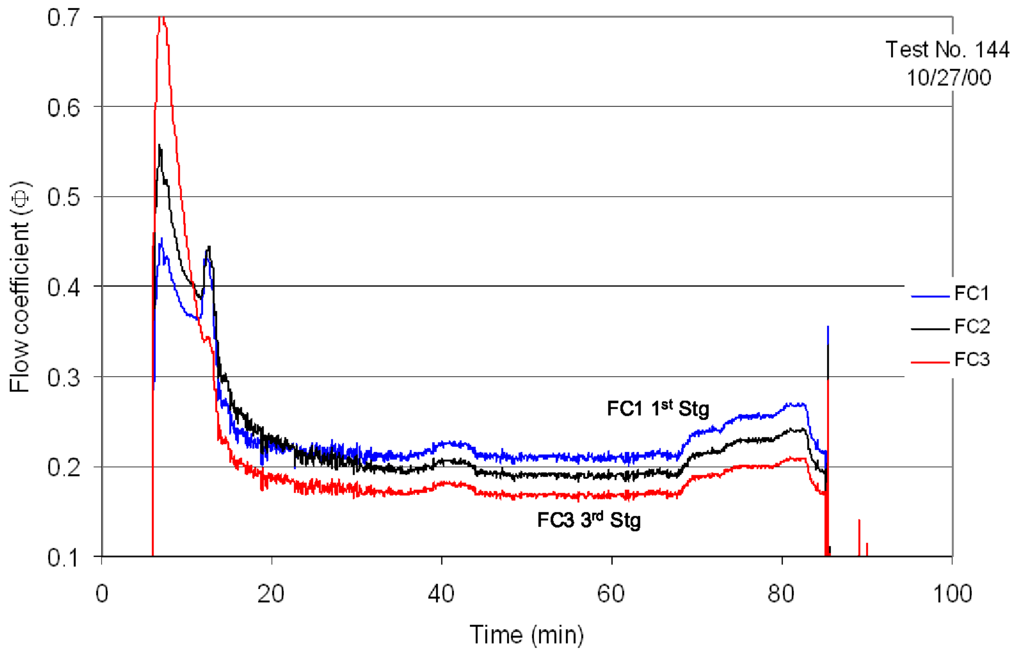
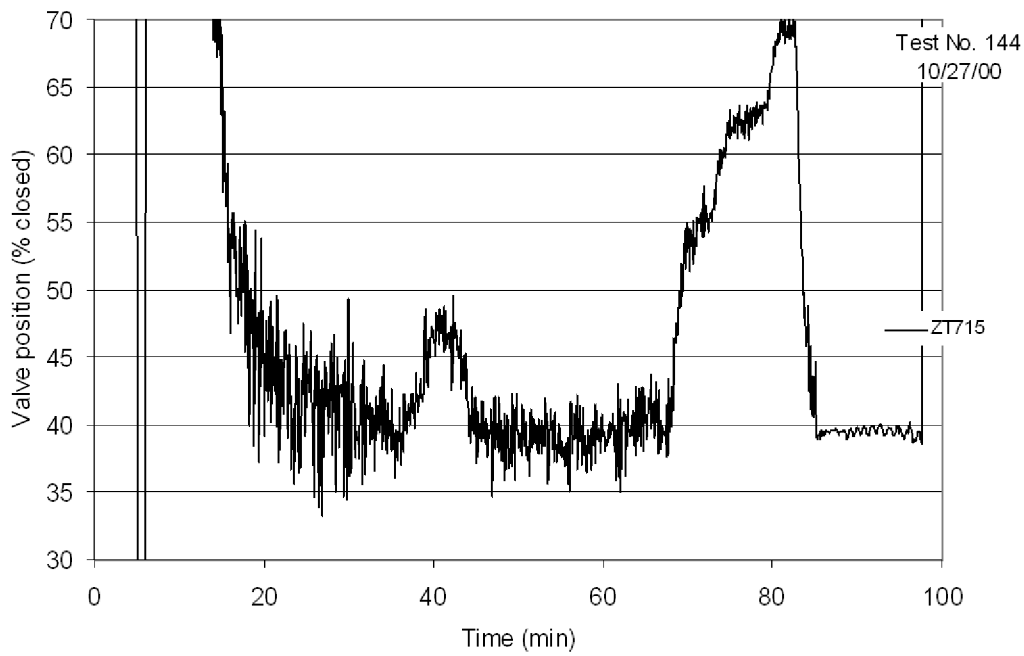


Figure D.18: Compressor surge bypass valve position vs. time.



APPENDIX D – GN2 COMPRESSOR TEST DATA (cont'd)

Figure D.19: Compressor motor voltage vs. time.

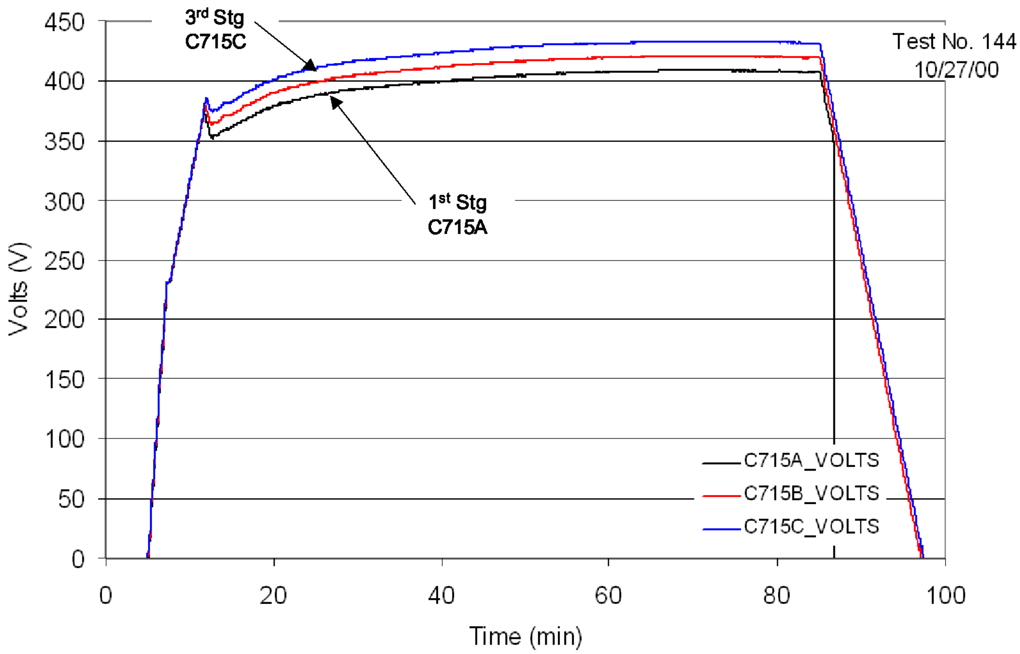
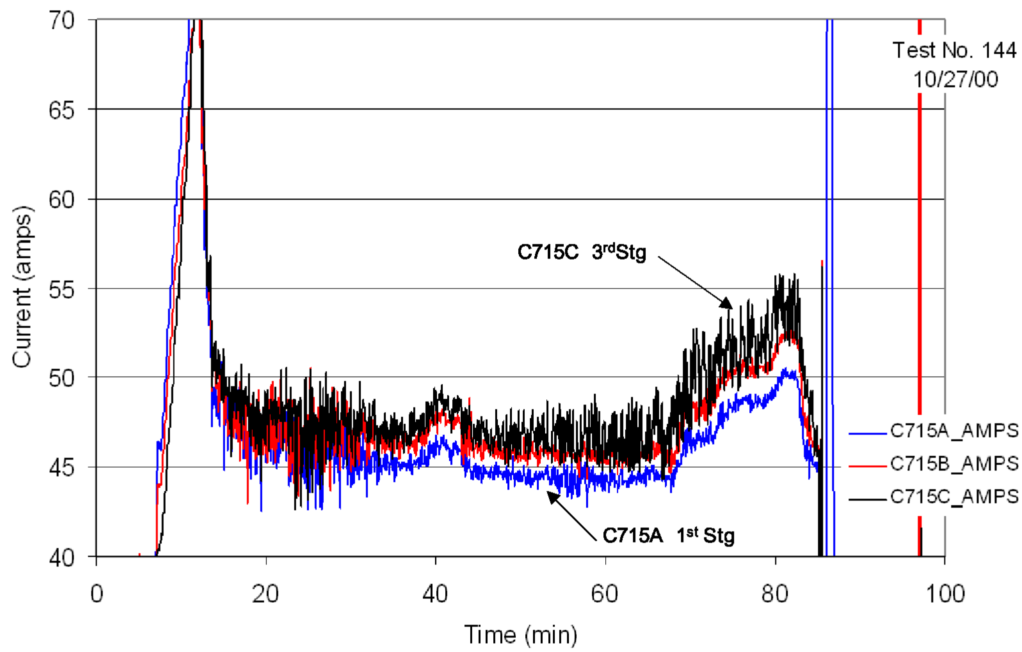


Figure D.20: Compressor motor current vs. time.



APPENDIX D – GN2 COMPRESSOR TEST DATA (cont'd)

Figure D.21: Compressor stage motor winding temperature profiles.

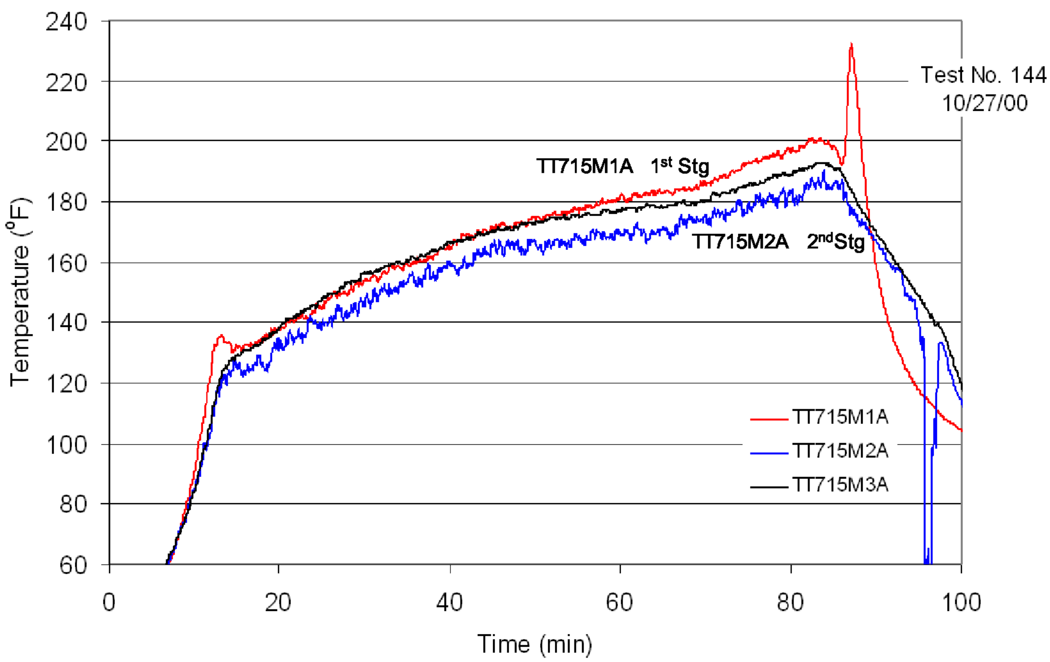
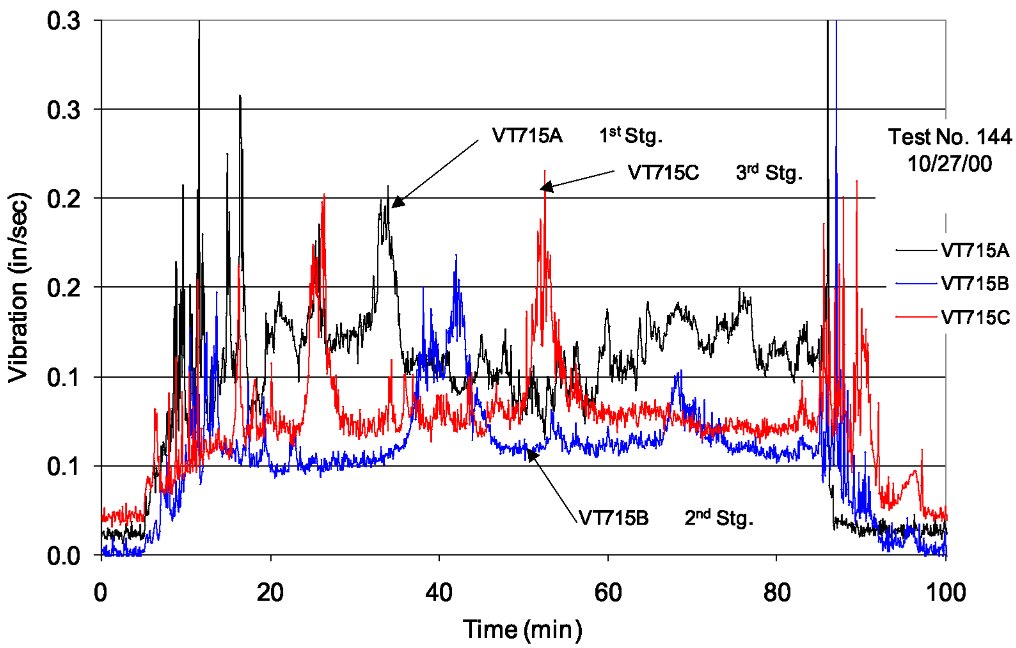


Figure D.22: Compressor motor vibration history.



APPENDIX E

LO2 RECIRCULATION PUMP TEST DATA

APPENDIX E – LO2 RECIRCULATION PUMP TEST DATA

Figure E.1: Cryo-Mach pump speed vs. time.

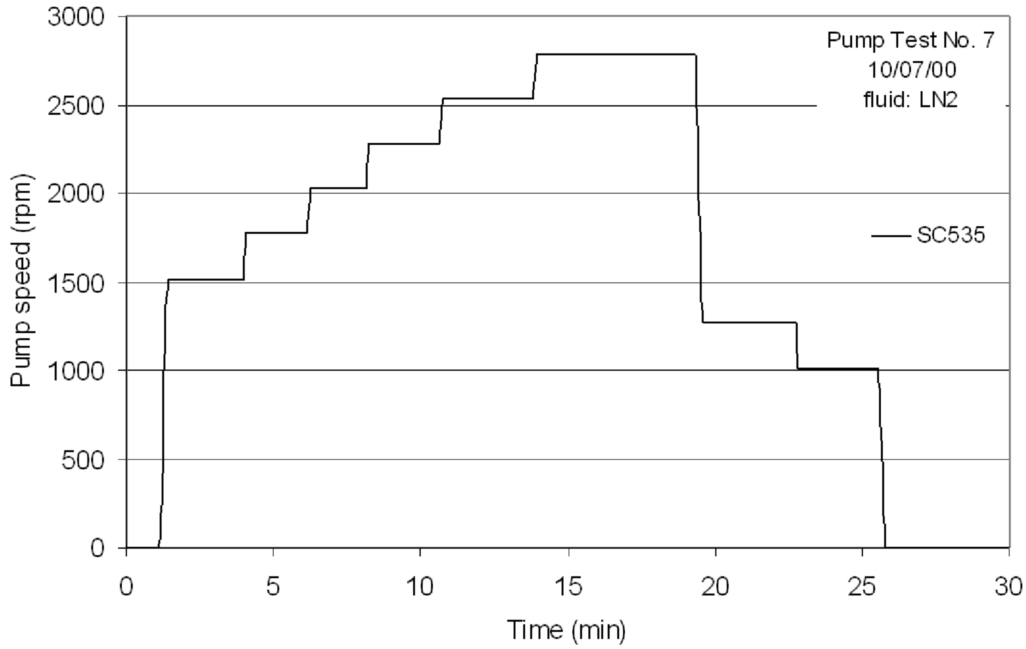
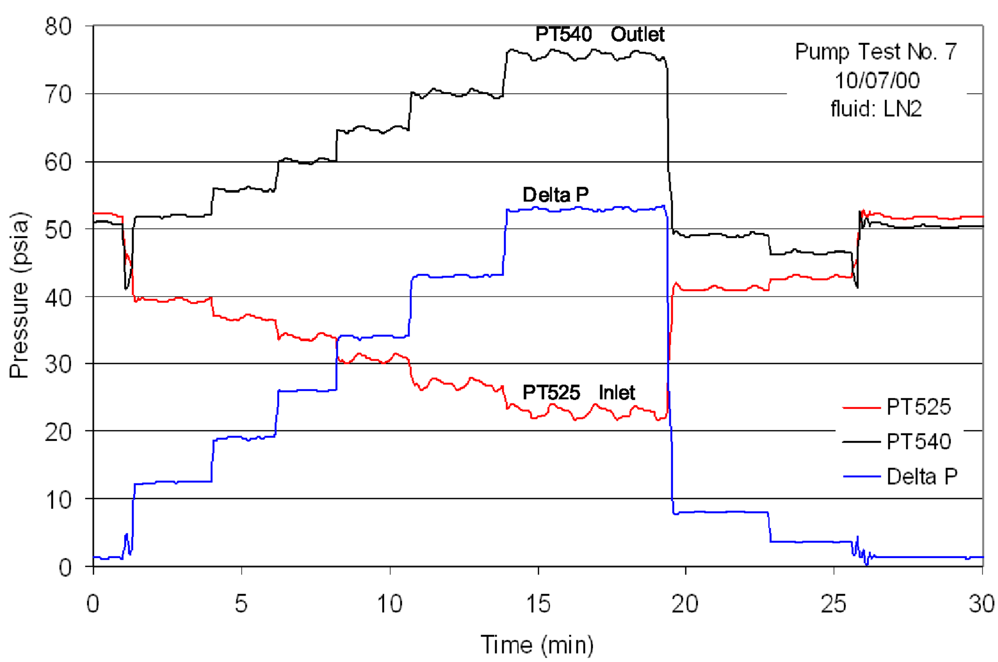


Figure E.2: Cryo-Mach pump inlet, outlet and differential pressure vs. time.



APPENDIX E – LO2 RECIRCULATION PUMP TEST DATA (cont'd)

Figure E.3: Cryo-Mach pump LN2 mass flow rate vs. time.

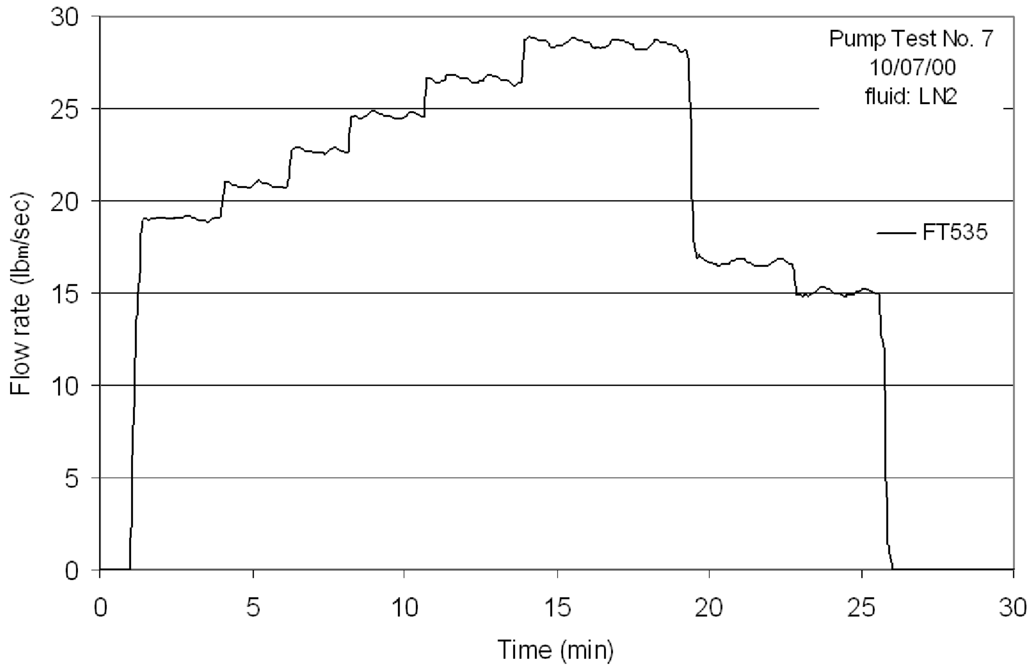


Figure E.4: Cryo-Mach pump inlet and outlet temperature vs. time.

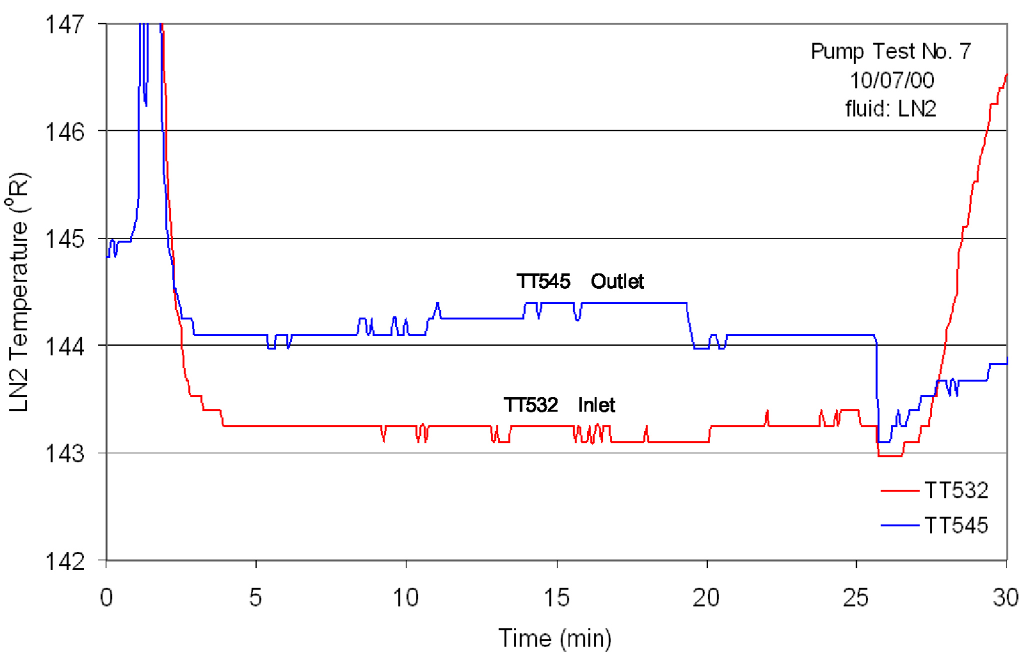


Figure E.5: Cryo-Mach pump speed vs. time.

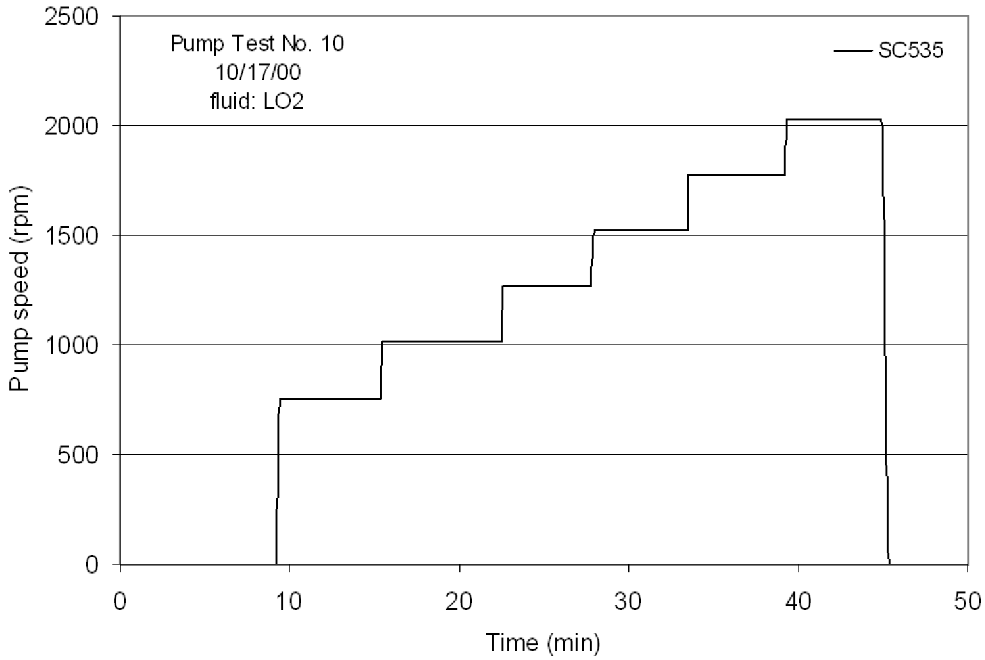
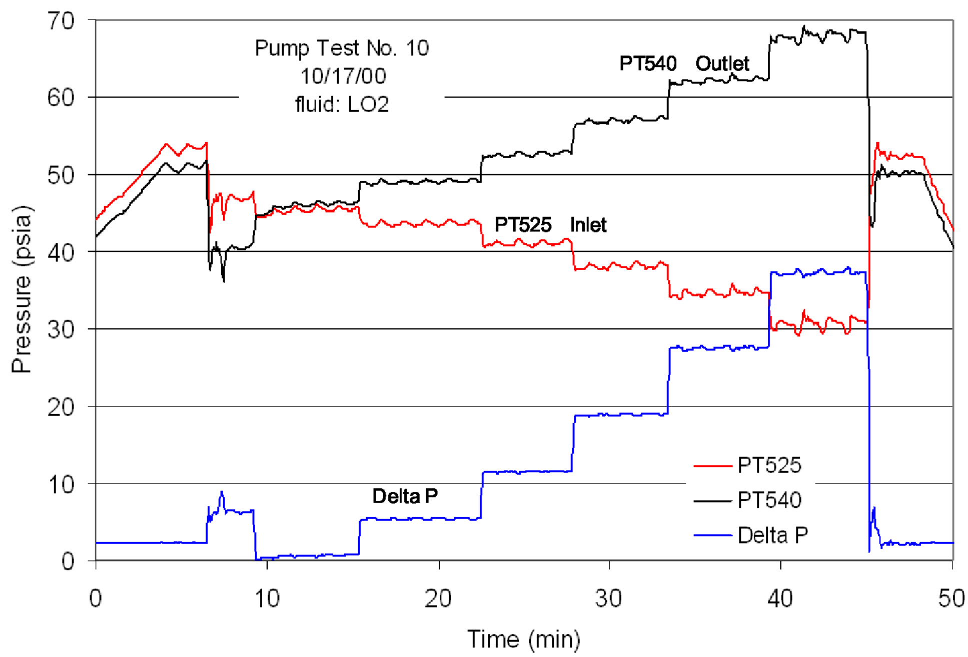


Figure E.6: Cryo-Mach pump inlet, outlet and differential pressure vs. time.



APPENDIX E – LO2 RECIRCULATION PUMP TEST DATA (cont'd)

Figure E.7: Cryo-Mach pump LO2 mass flow rate vs. time.

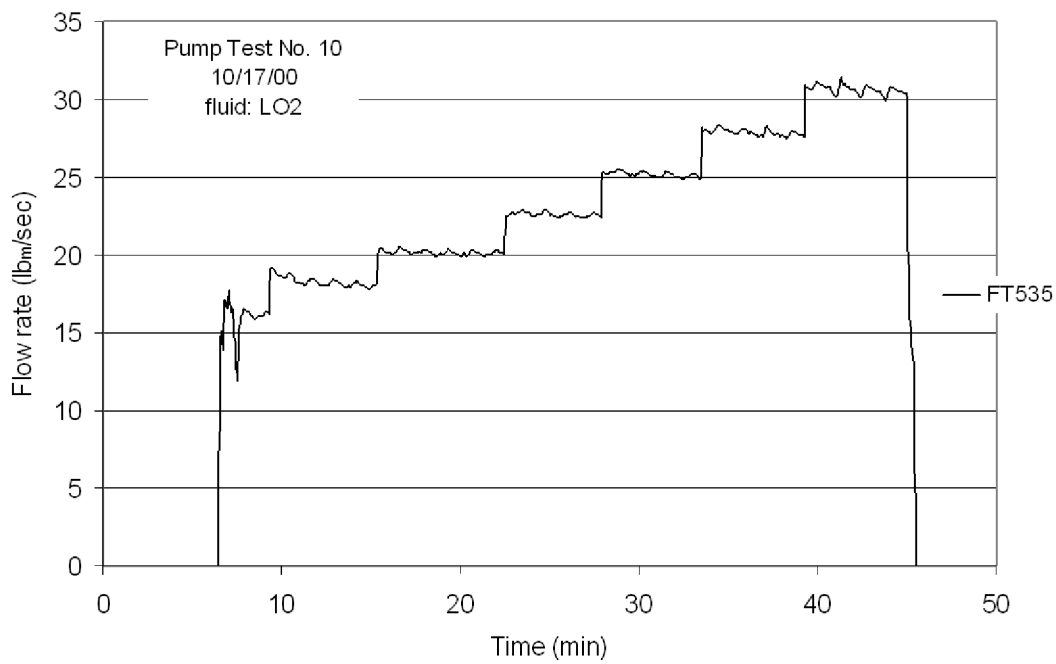
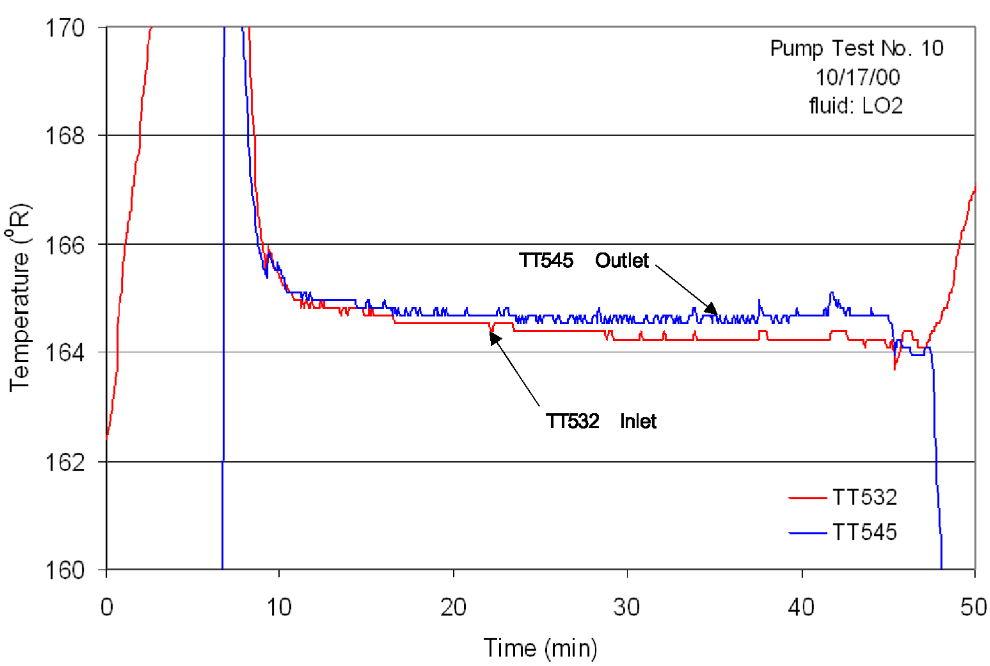


Figure E.8: Cryo-Mach pump inlet and outlet temperature vs. time.



APPENDIX F

LN2 PERFORMANCE TEST DATA with LOX PDU

APPENDIX F – LN2 PERFORMANCE TEST DATA with LOX PDU

Figure F.1: gN2 compressor speed vs. time.

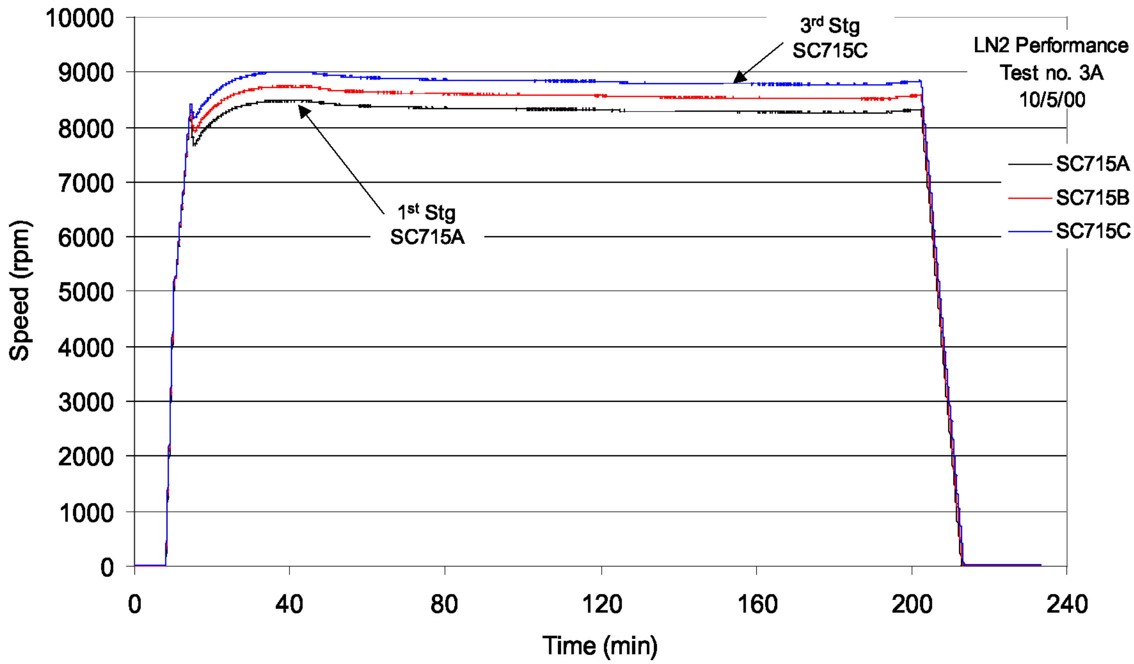


Figure F.2: Compressor interstage pressure profile.

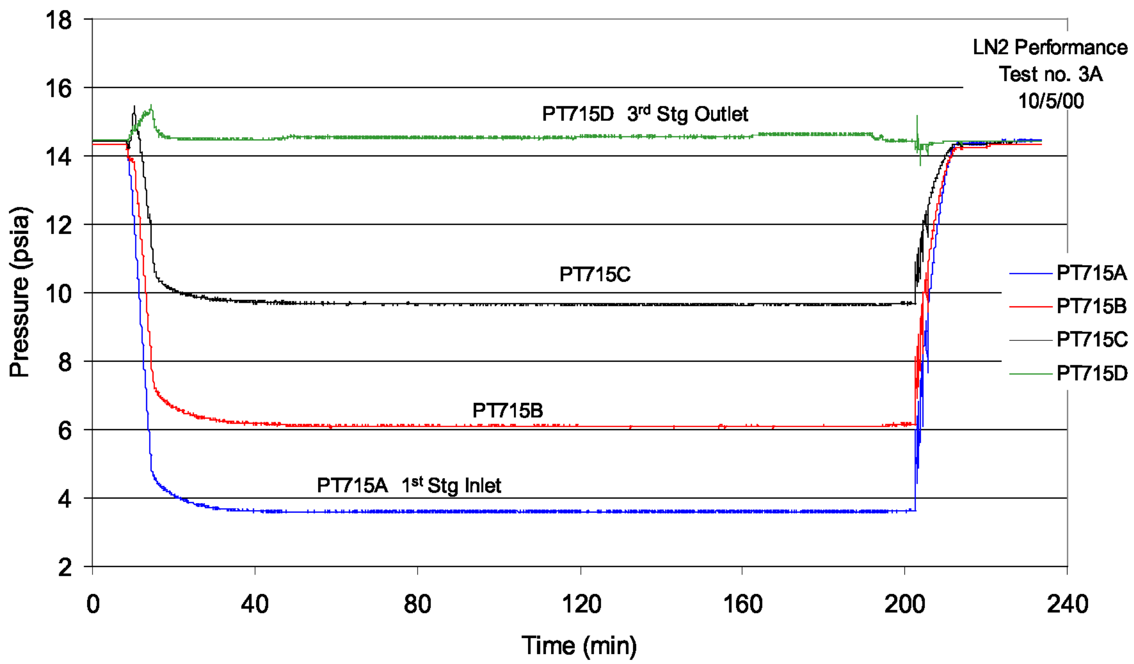


Figure F.3: Compressor interstage gas temperature vs. time.

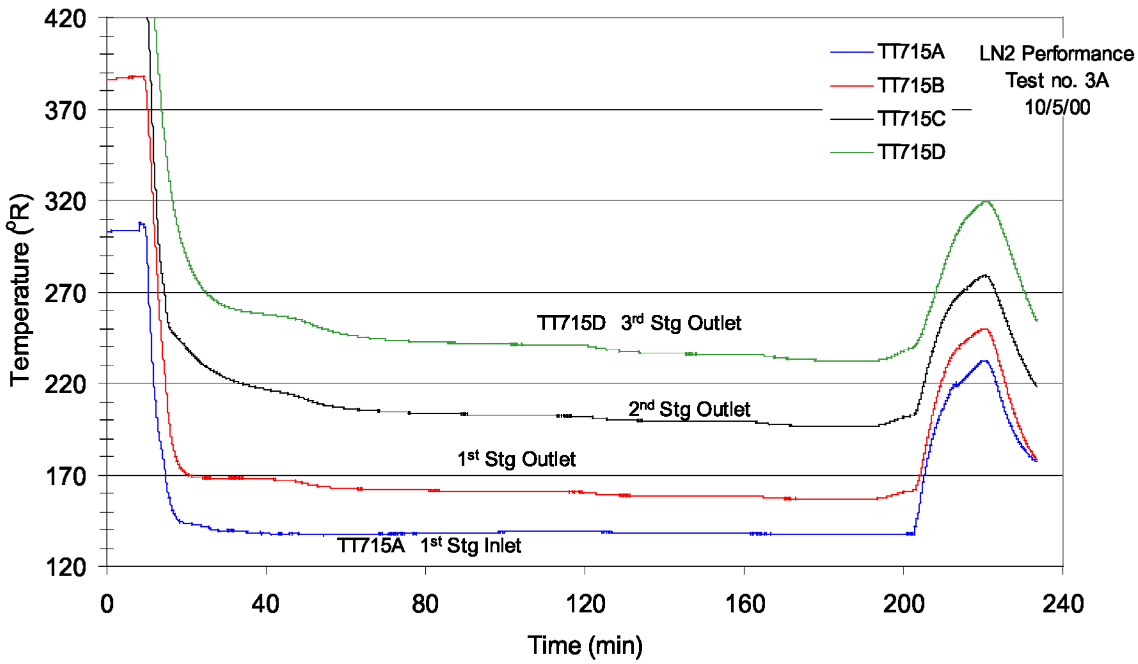


Figure F.4: Compressor discharge mass flow and gas bypass flow vs. time.

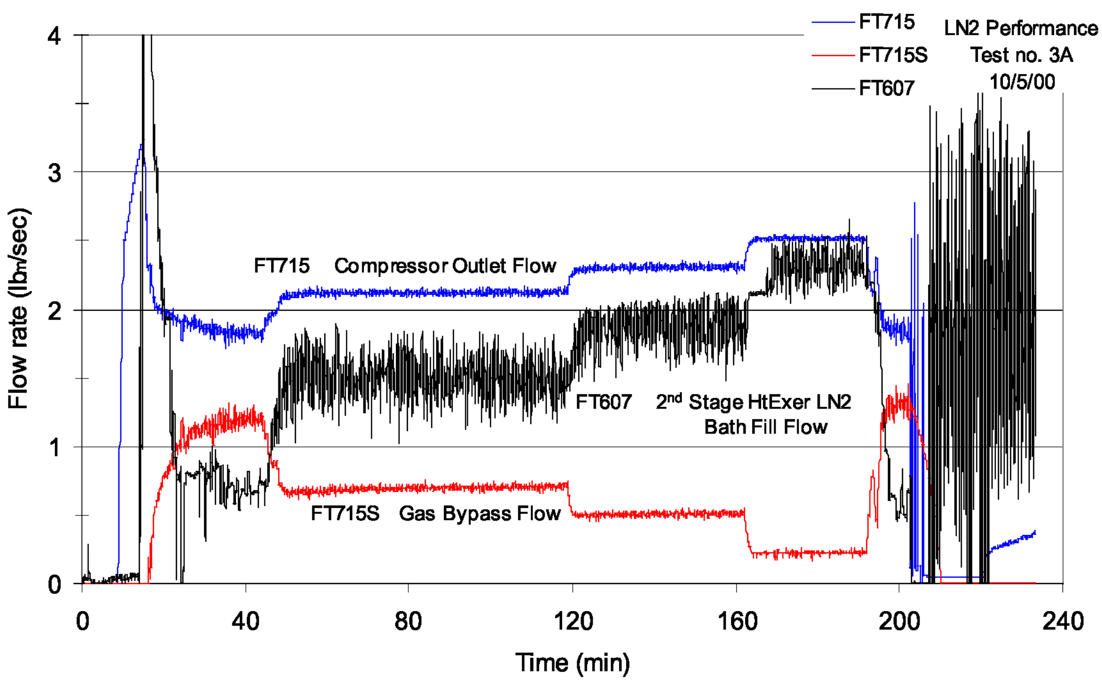


Figure F.5: Compressor flow coefficient profile vs. time.

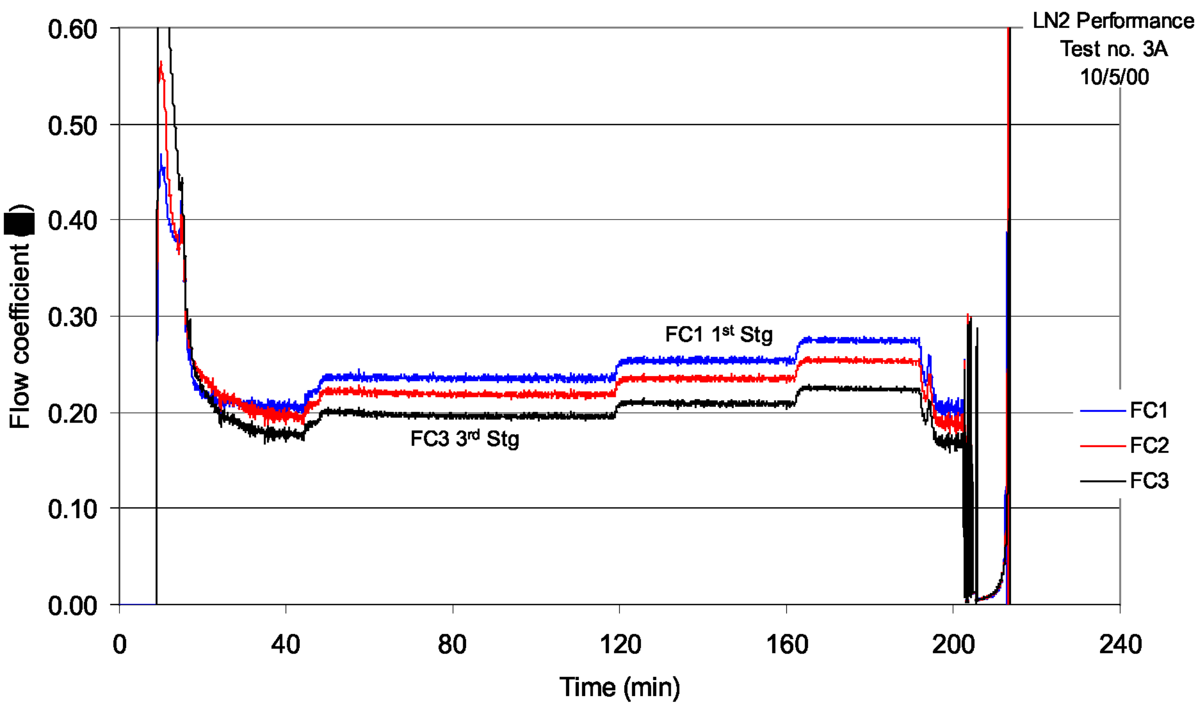


Figure F.6: Compressor motor current draw vs. time.

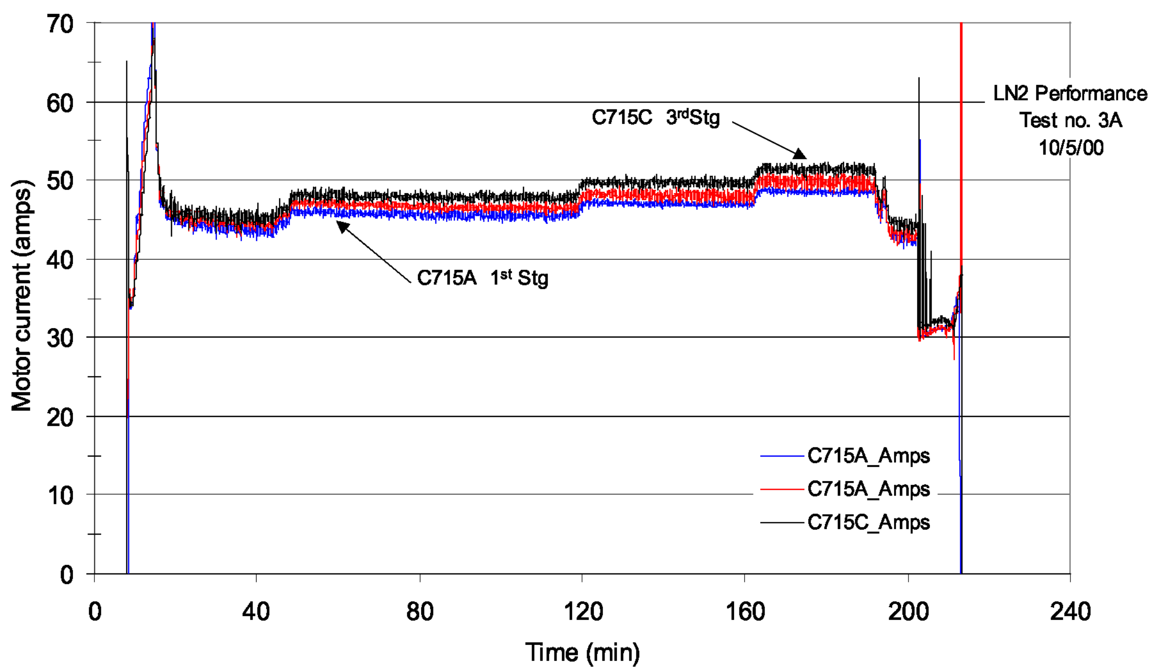


Figure F.7: Cryo-Mach outlet LN2 mass flow rate vs. time.

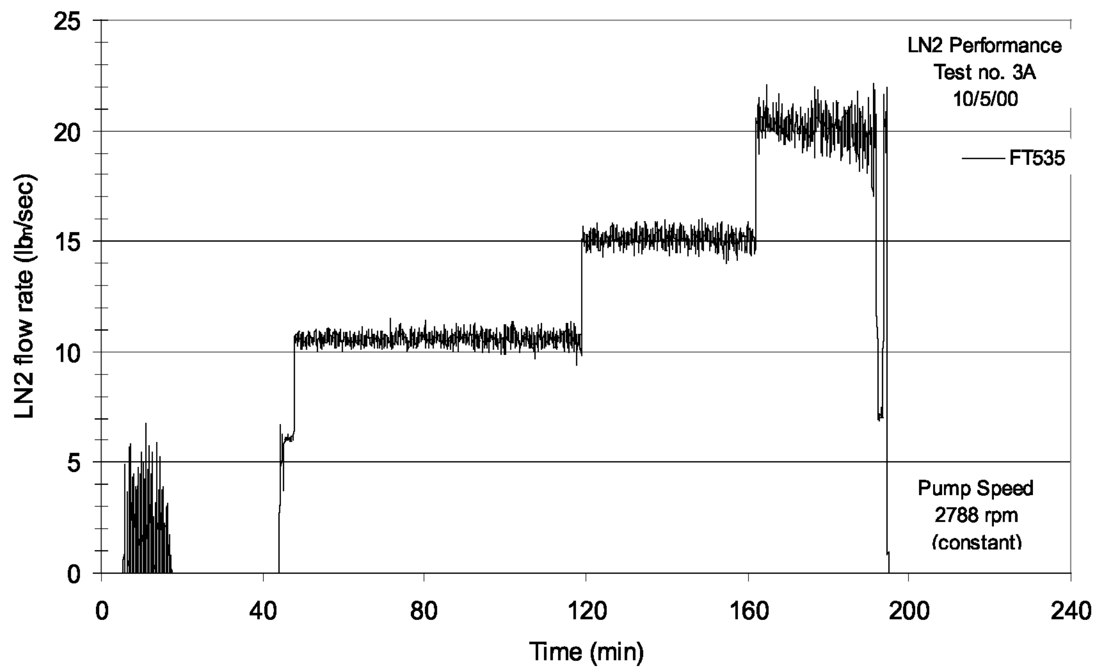


Figure F.8: LN2 stream temperatures across PDU skid vs. time.

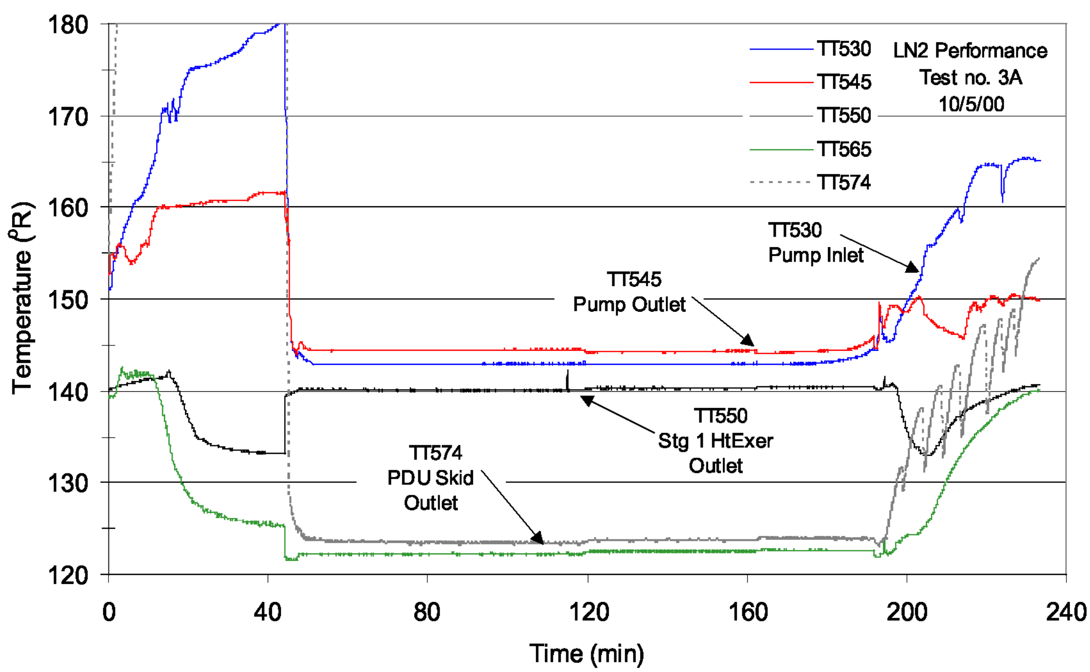


Figure F.9: LN2 stream pressures across PDU skid vs. time.

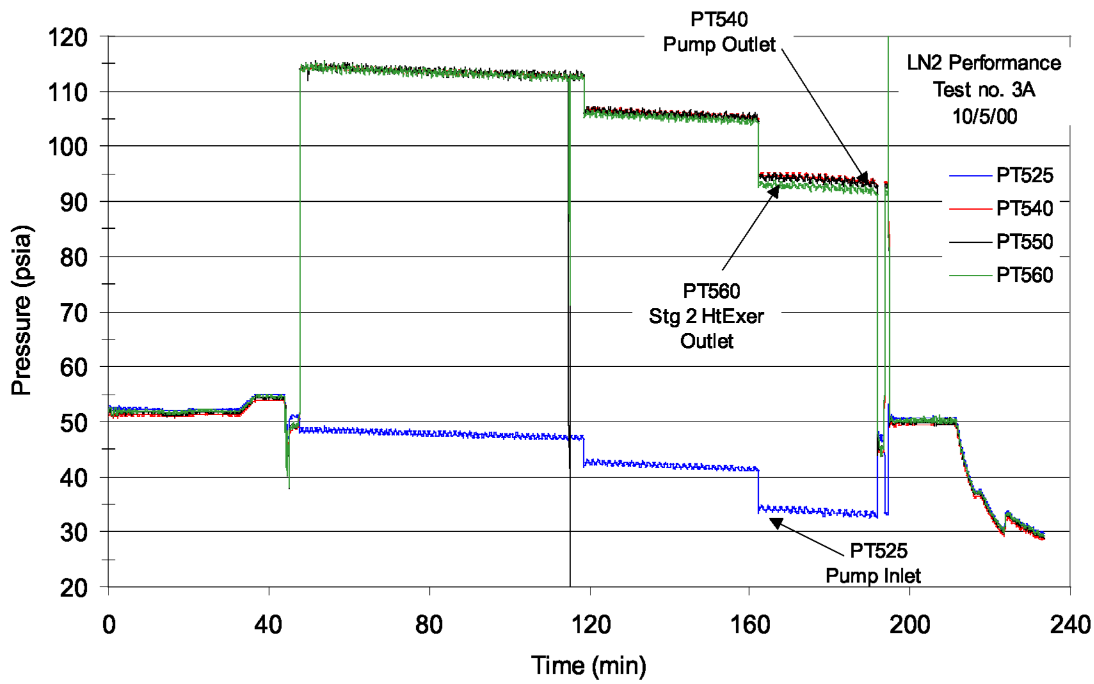


Figure F.10: Heat exchanger LN2 bath and ullage temperatures vs. time.

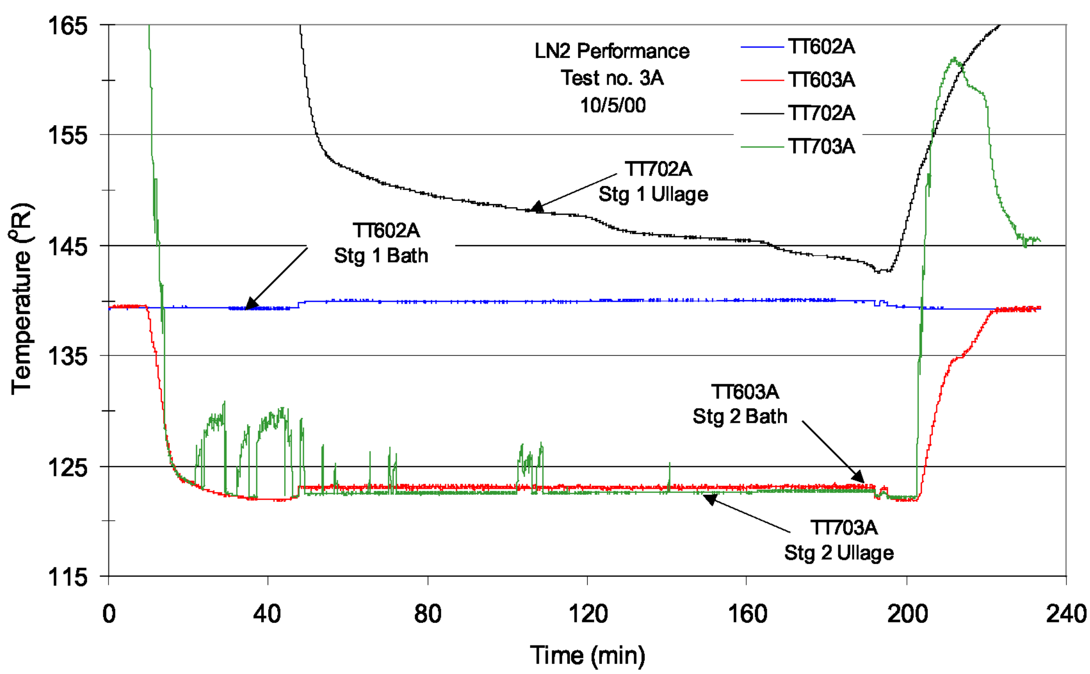


Figure F.11: STA vertical diode temperture profile during DLN2 fill.

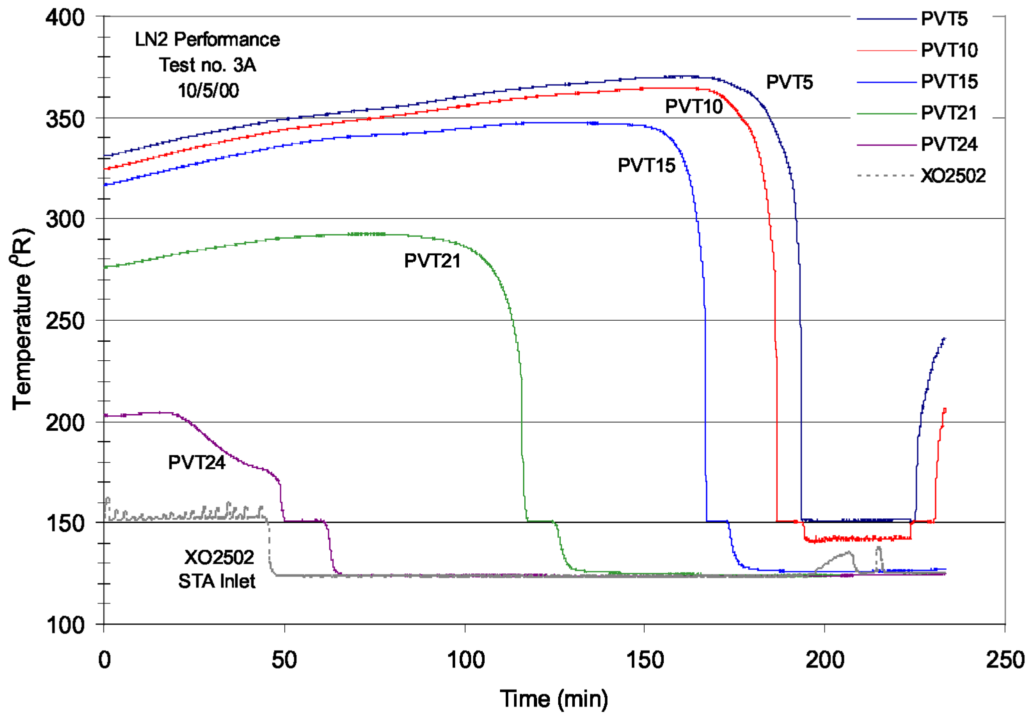


Figure F.12:STA LN2 vertical temperature gradient at end of DLN2 loading test 3A

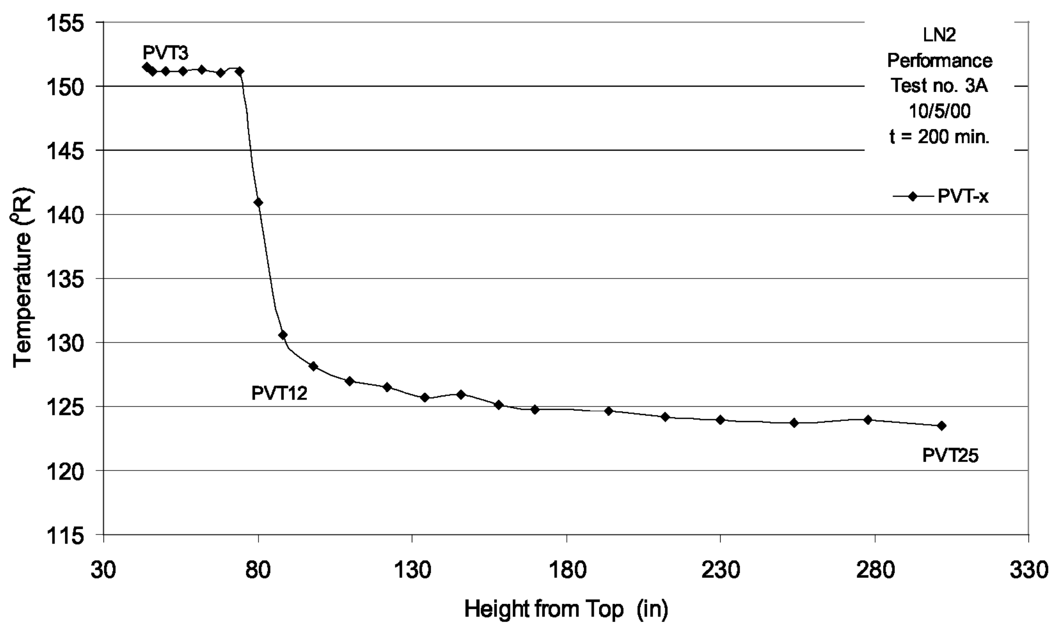


Figure F.13: Dewar N83 and N71 volume change during PDU test operation.

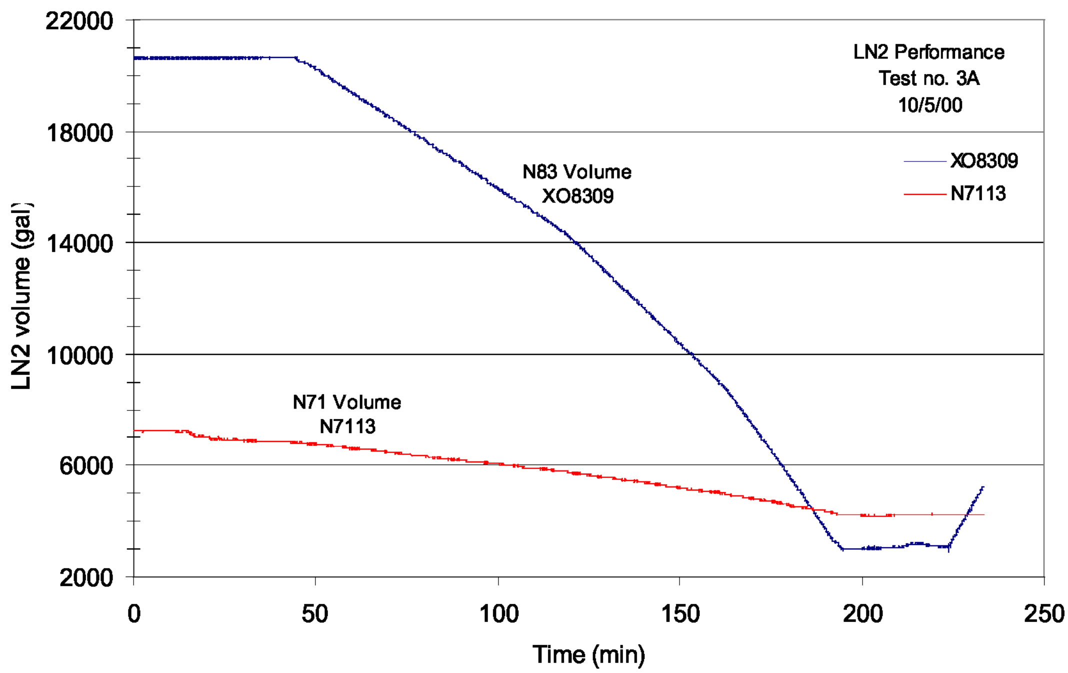
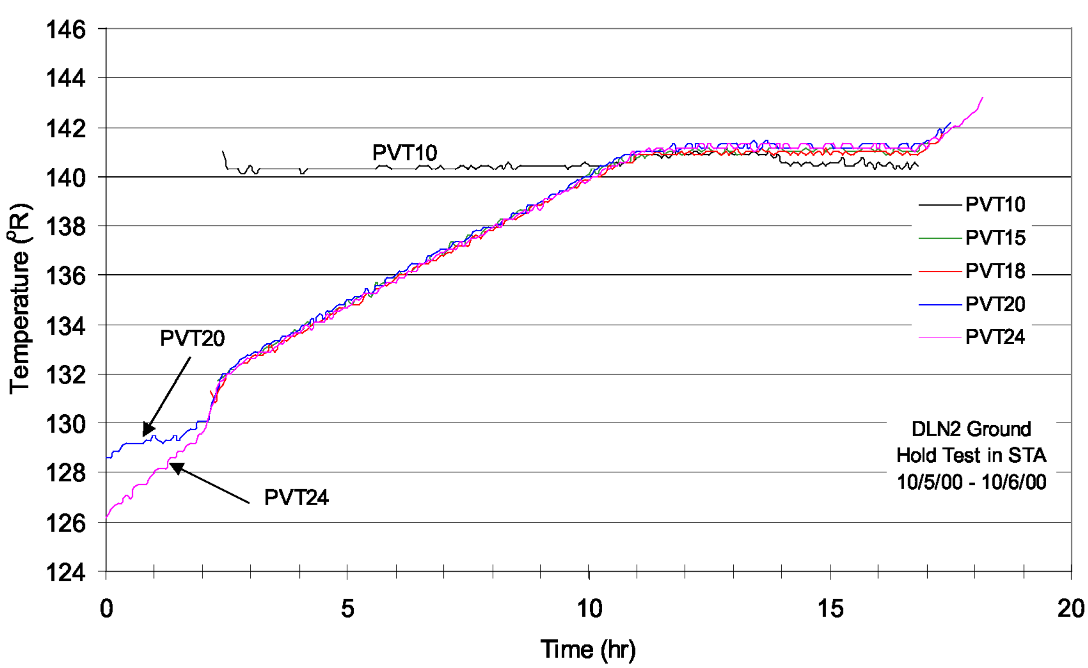


Figure F.14: DLN2 resaturation and warm-up temperature during storage in STA.



APPENDIX G

LO2 PERFORMANCE TEST DATA with LOX PDU

APPENDIX G – LO2 PERFORMANCE TEST DATA with LOX PDU

Figure G.1: STA inlet LO2 flow and LO2 STA tank make-up rate.

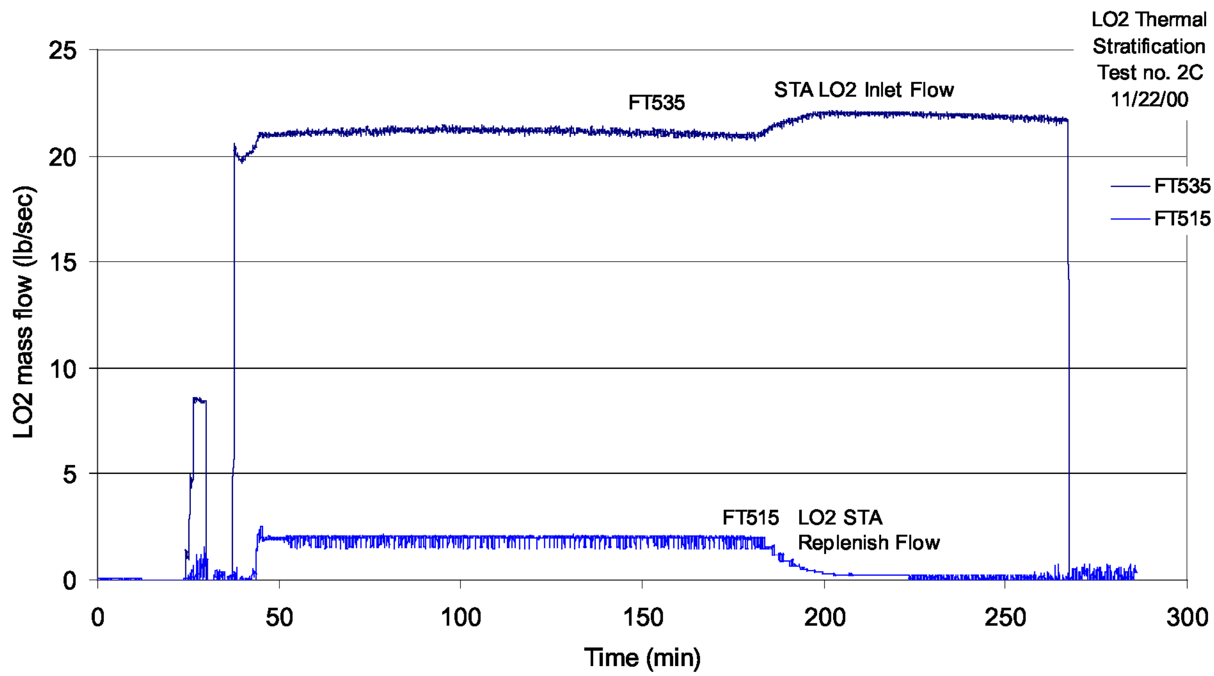


Figure G.2: STA thermal stratification temperature profile data.

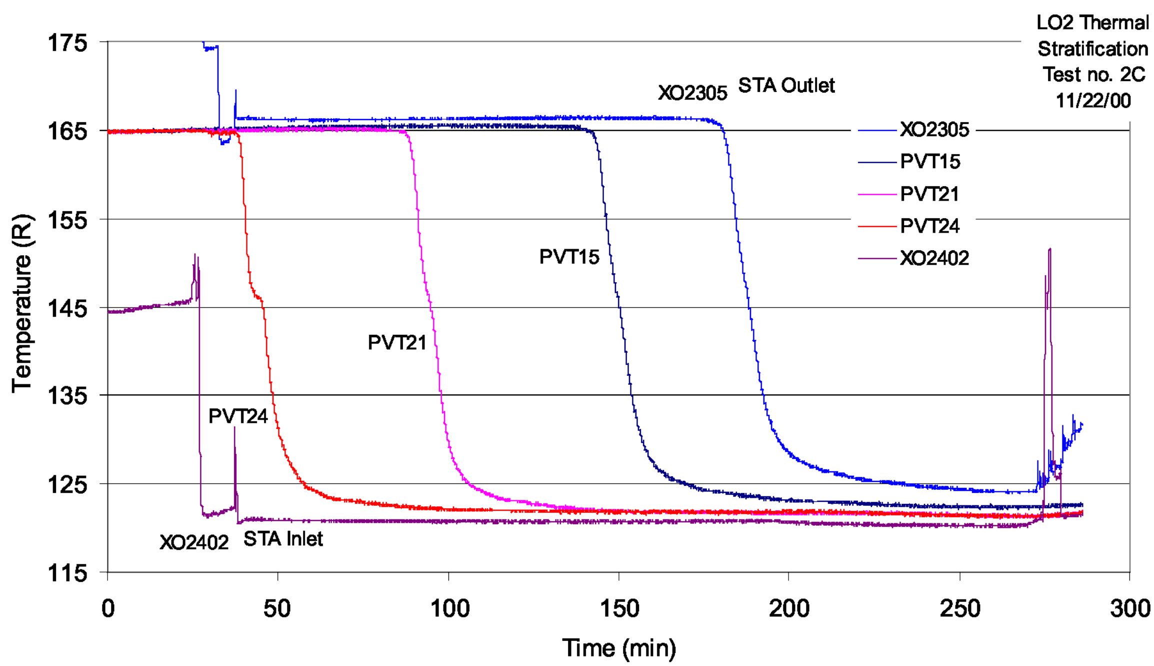


Figure G.3: STA liquid level capacitance probe data.

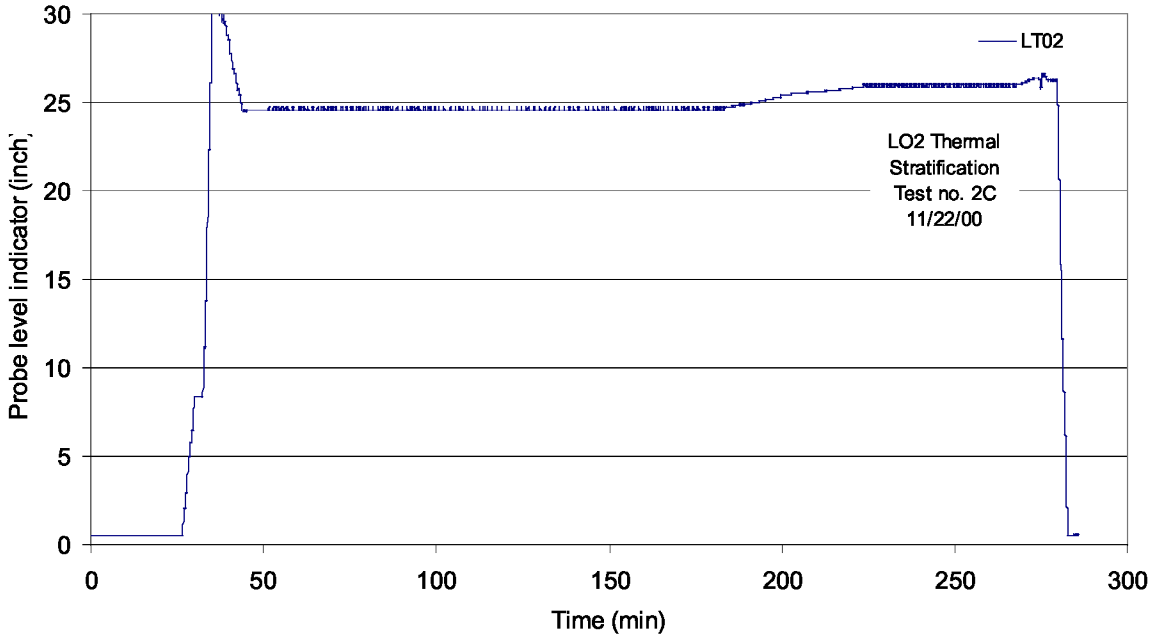


Figure G.4: Compressor inlet and discharge pressure vs. time.

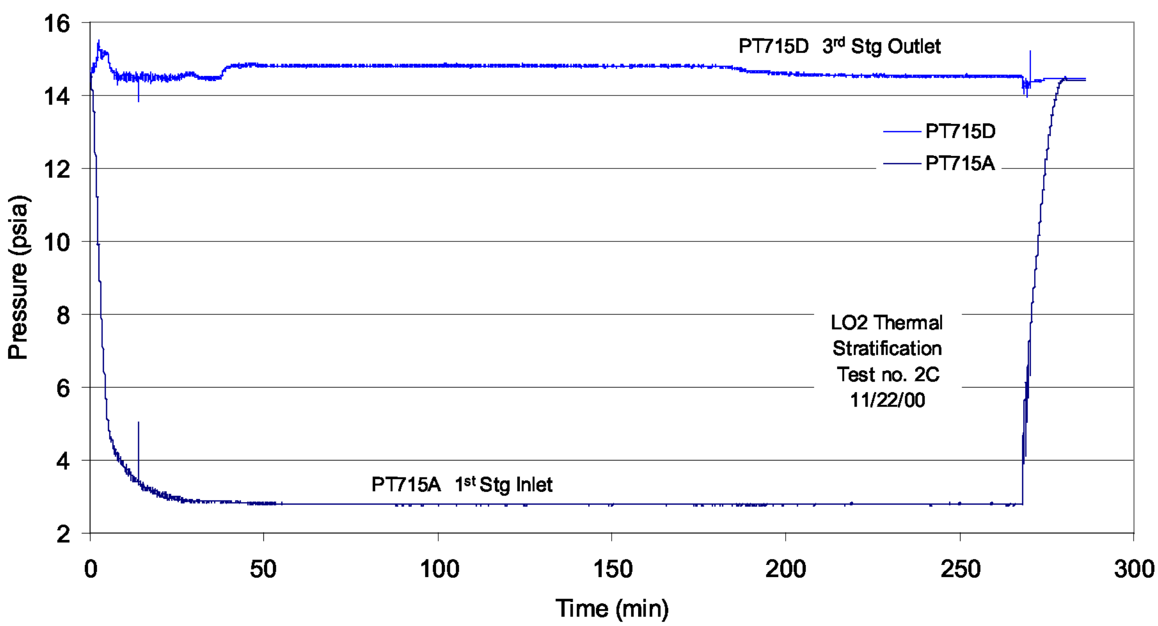


Figure G.5: Compressor mass flow rate history.

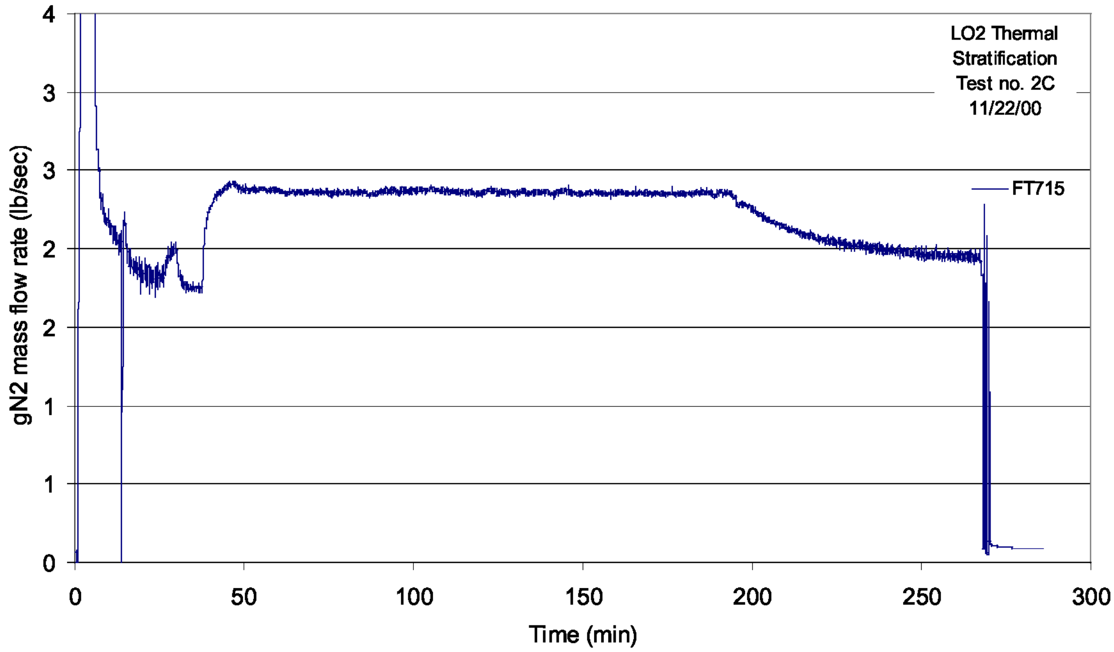


Figure G.6: LO2 stream temperatures vs. time.

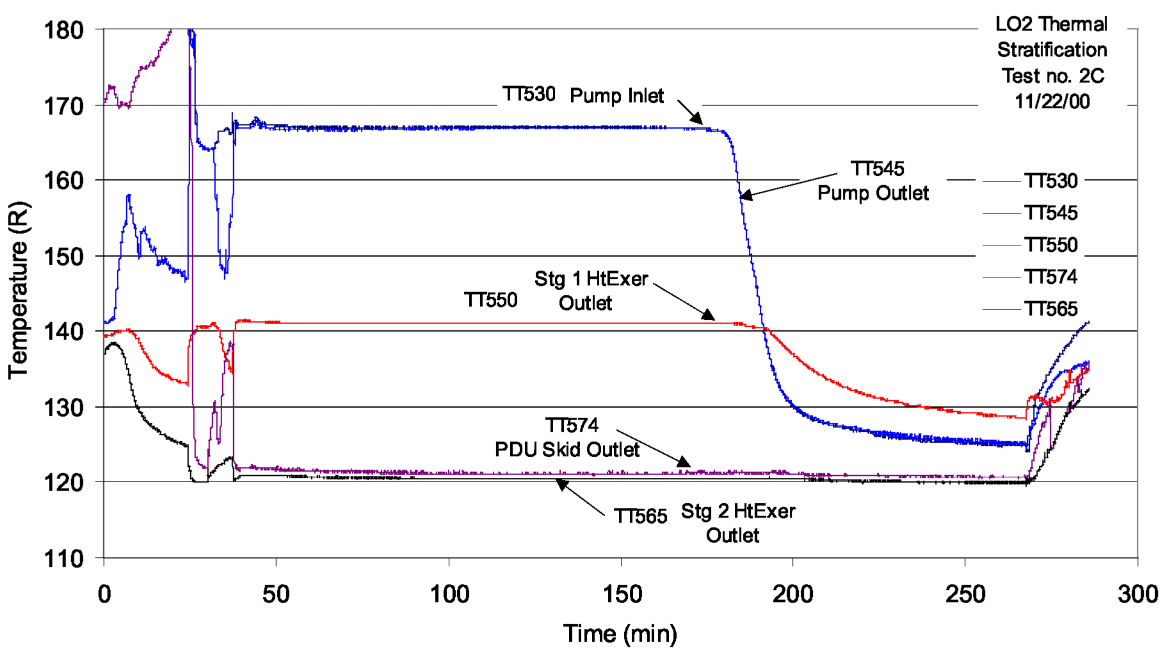


Figure G.7: LO2 stream pressure history.

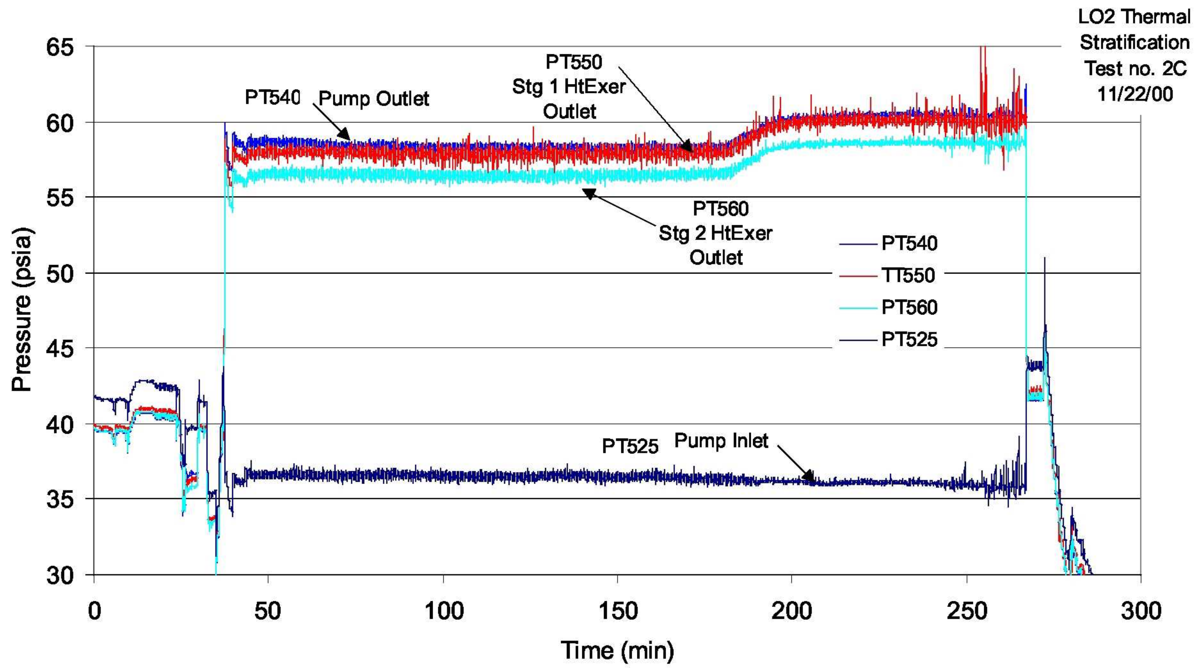


Figure G.8: Heat exchanger LN2 bath and ullage temperature history.

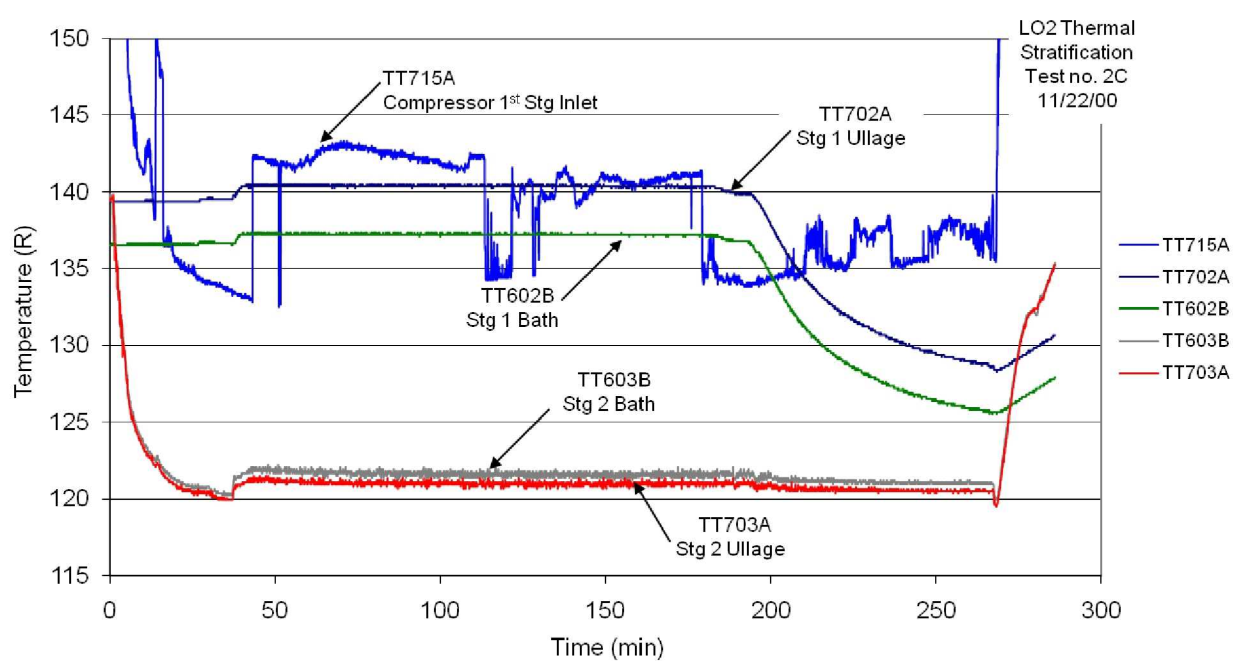


Figure G.9: Heat exchanger ullage pressure history - stage 2.

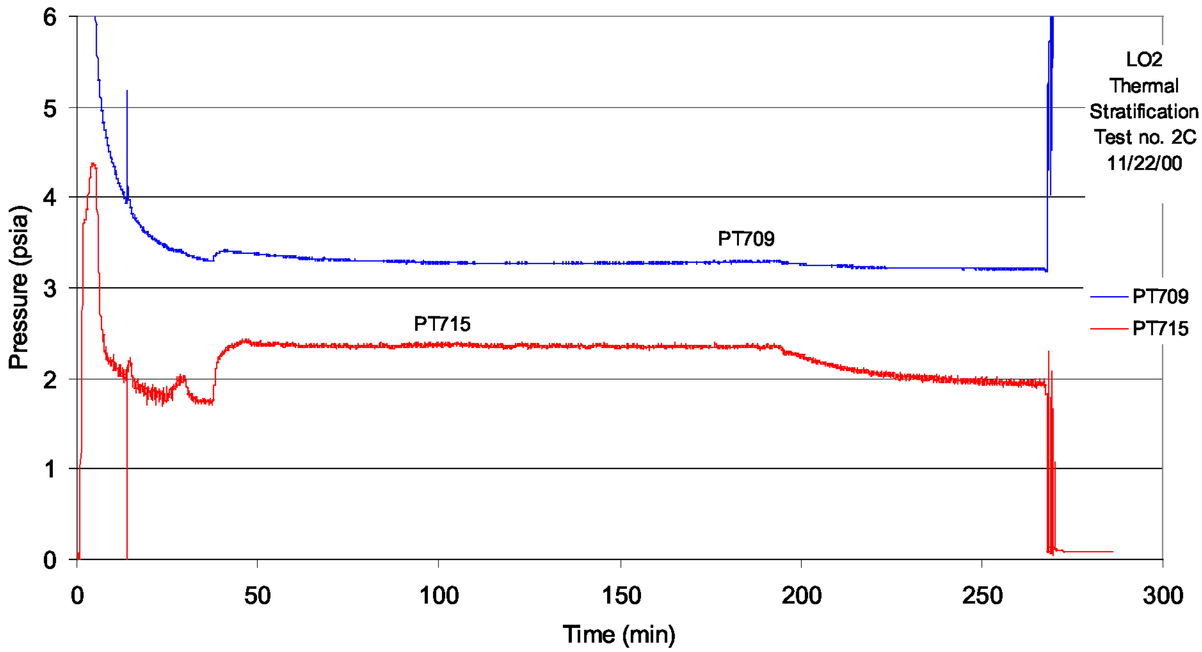


Figure G.10: STA inlet LO2 flow and LO2 STA tank make-up rate.

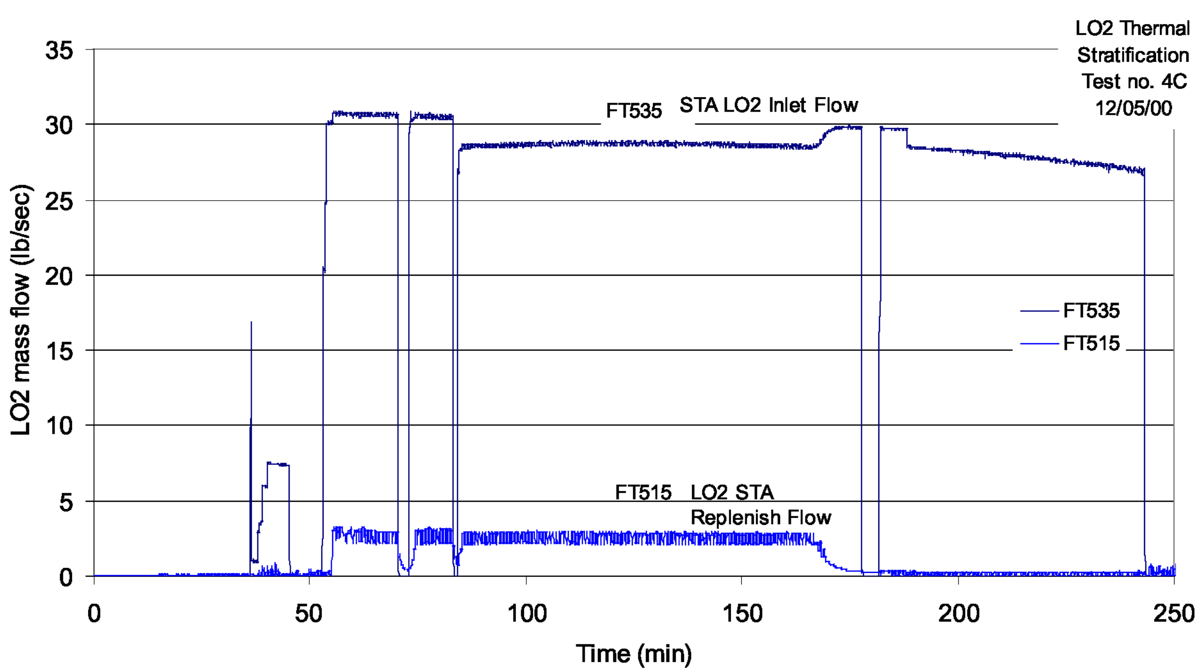


Figure G.11: STA thermal stratification temperature profile data.

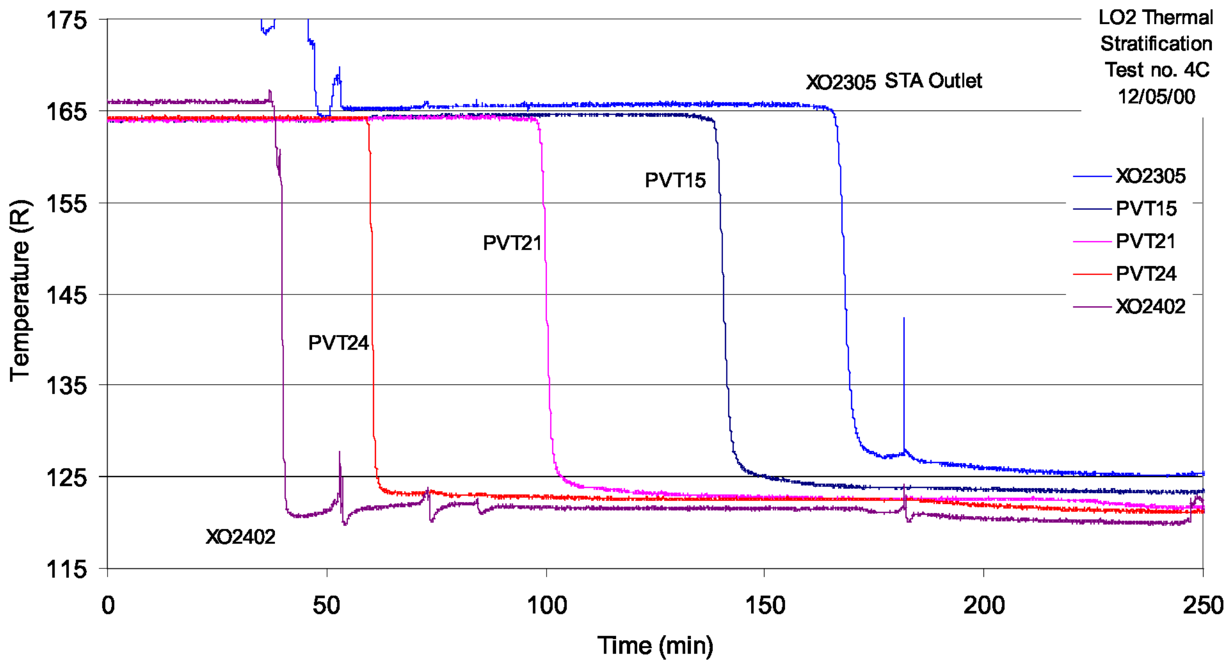


Figure G.12: STA liquid level capacitance probe data.

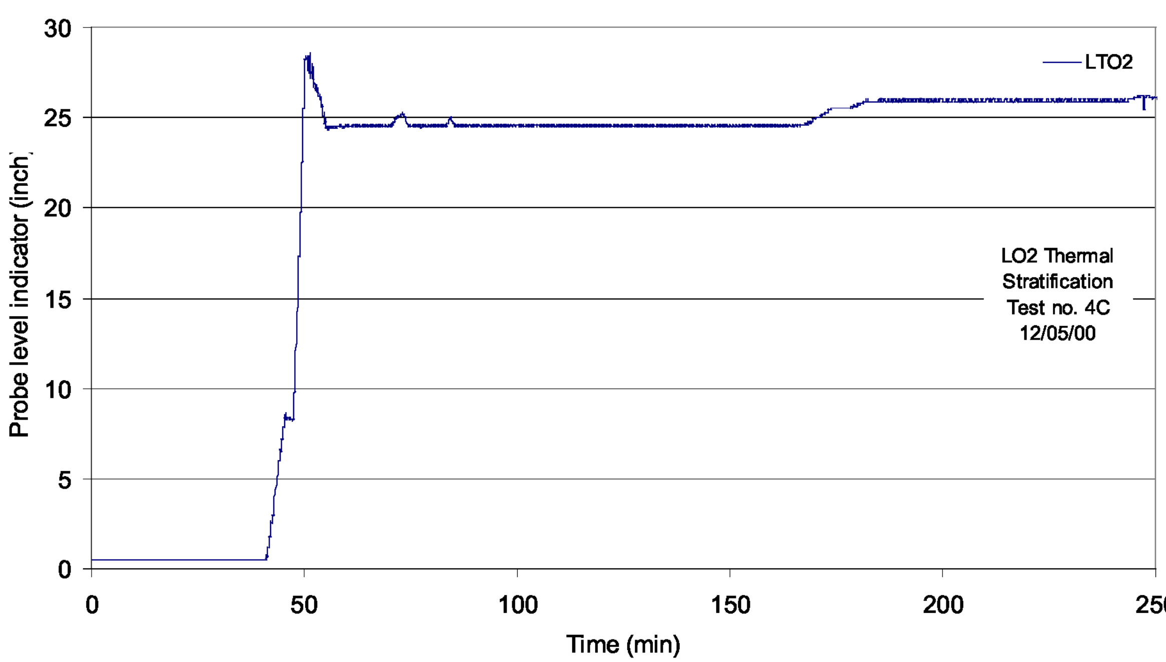


Figure G.13: Compressor inlet and discharge pressure vs time.

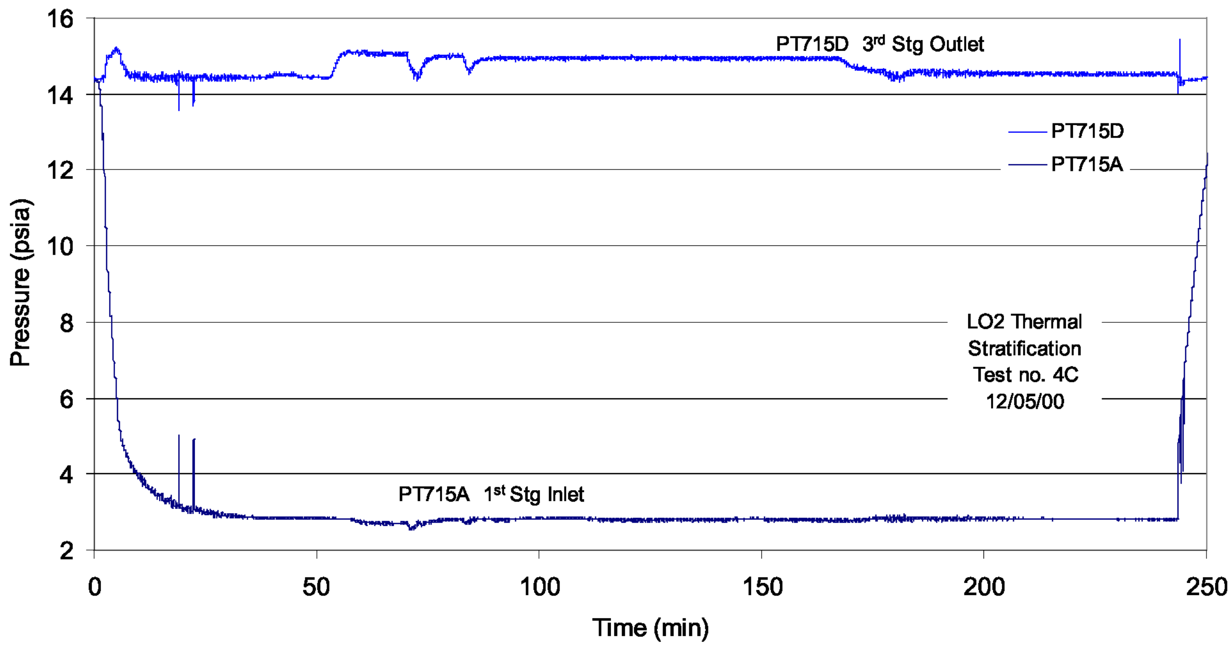


Figure G.14: Compressor mass flow rate history.

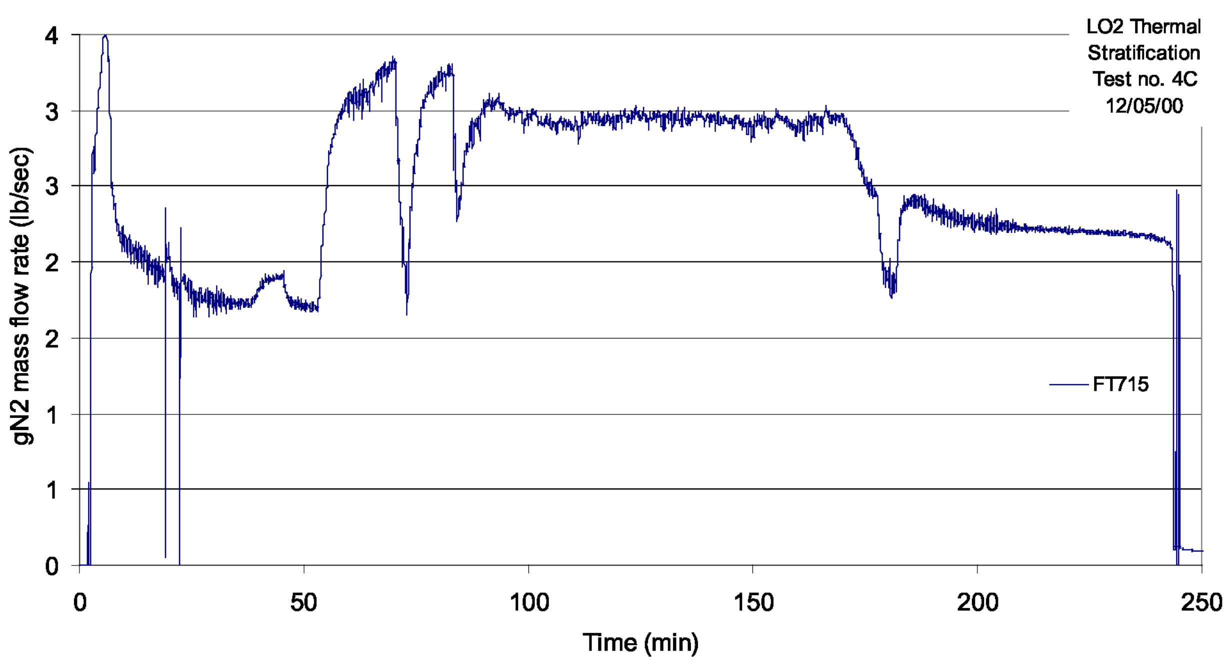


Figure G.15: LO2 stream temperatures vs. time.

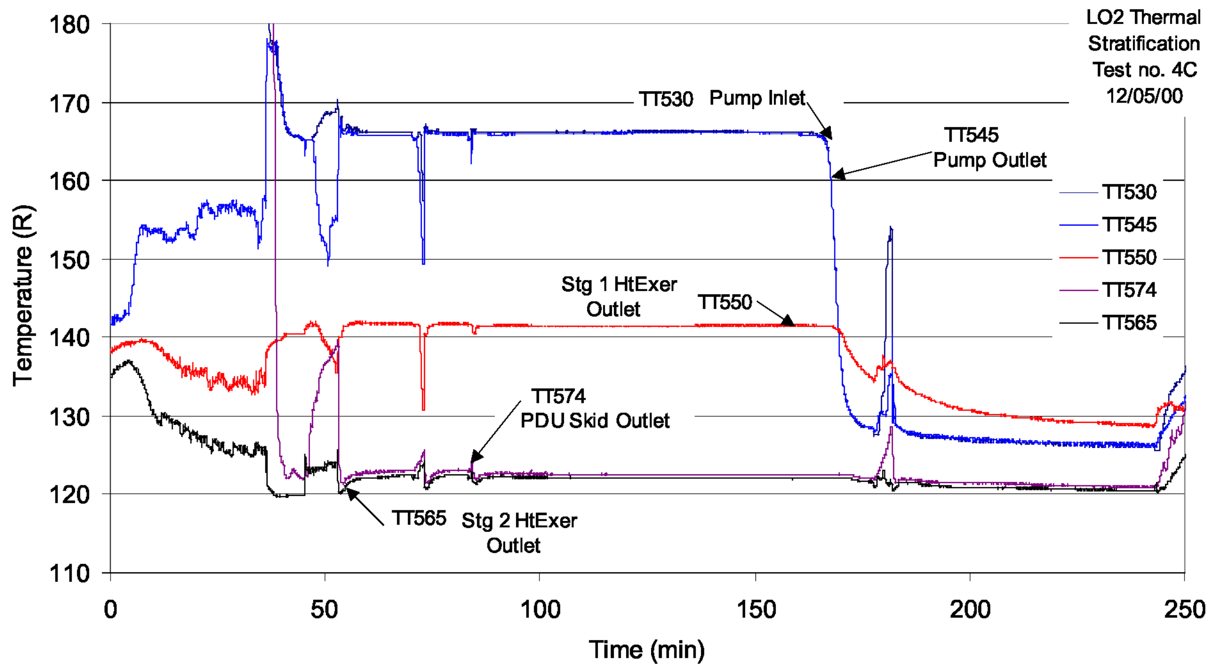


Figure G.16: LO2 stream pressure vs. history.

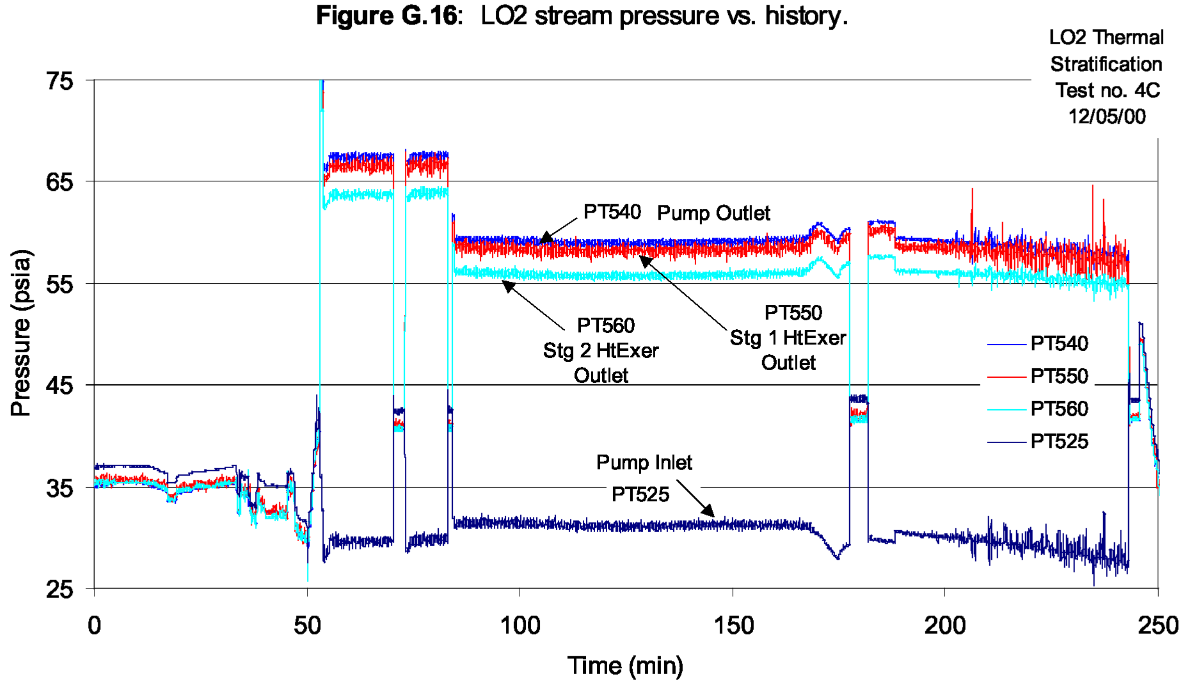


Figure G.17: Heat exchanger LN2 bath and ullage temperature history.

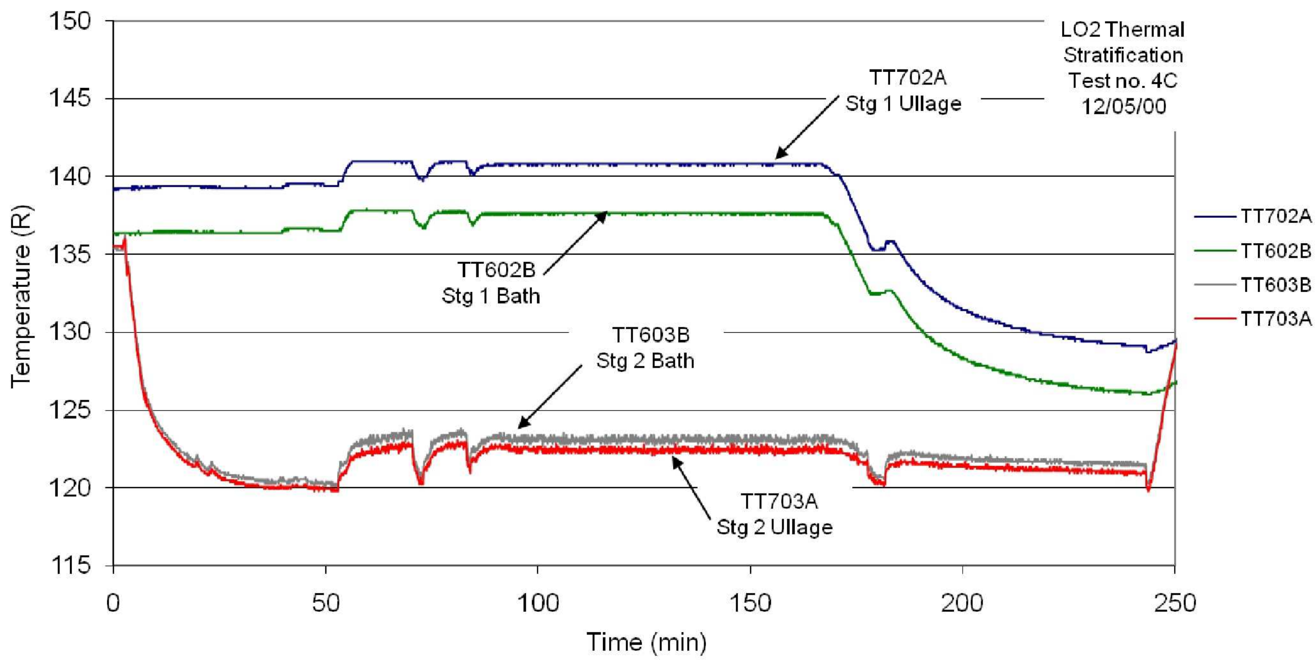
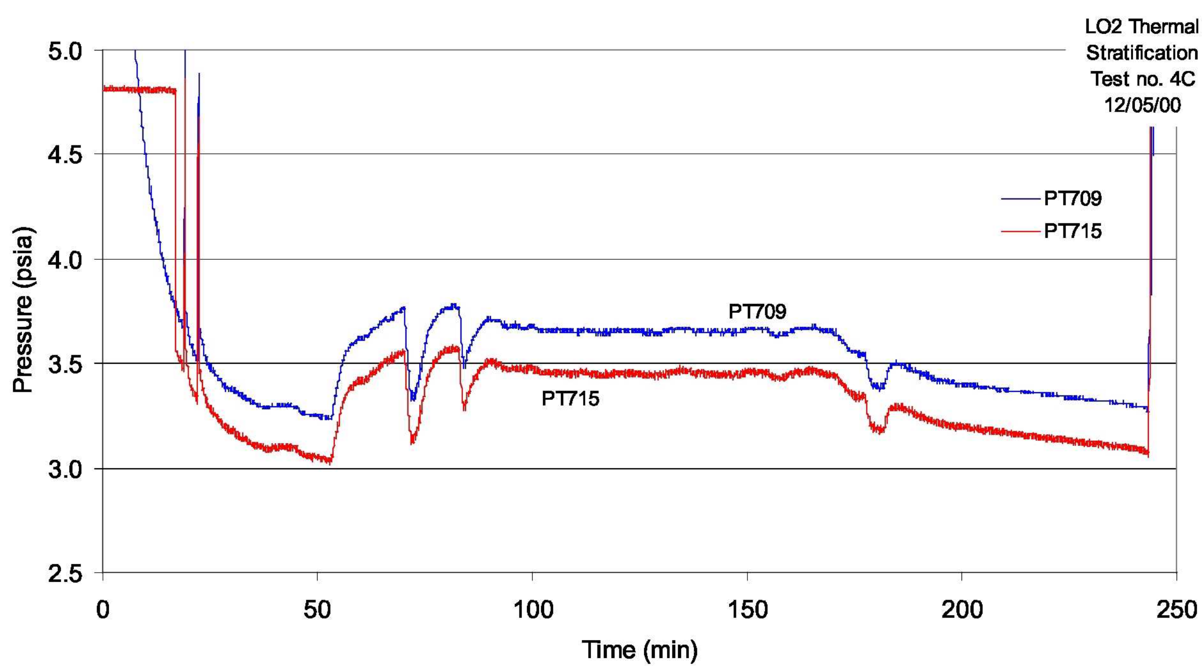


Figure G.18: Heat exchanger ullage pressure history - stage 2.



APPENDIX H

LO2 PDU and S40 FACILITY FLOW SCHEMATICS

Figure H.1: LO2 PDU flow schematic, heat exchangers and LO2 pump, sht 1 of 4.

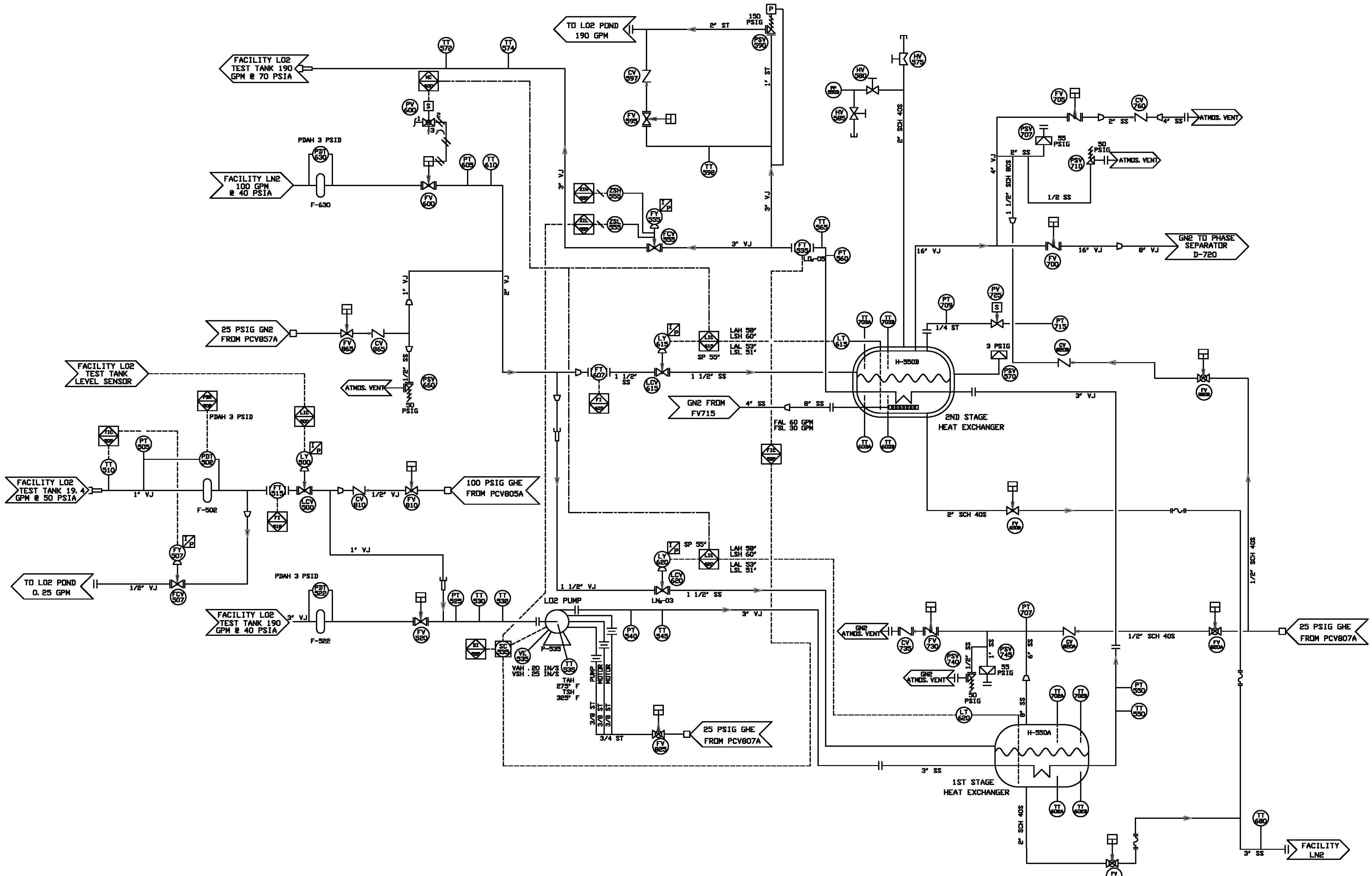


Figure H.2: LO2 PDU flow schematic, GN2 compressor, sht 2 of 4.

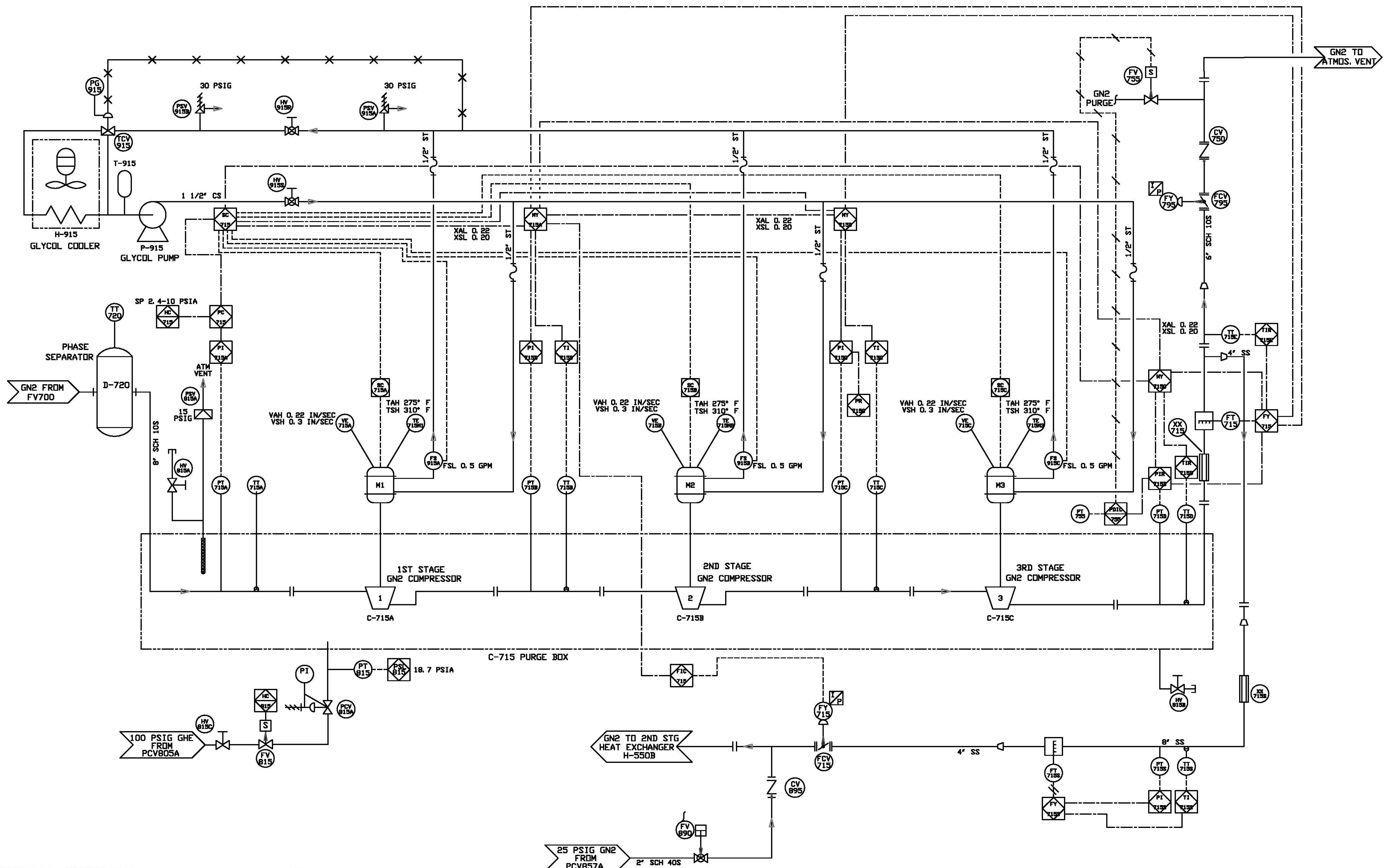


Figure H.3: LO2 PDU flow schematic, GHe and GN2 System, sht 3 of 4.

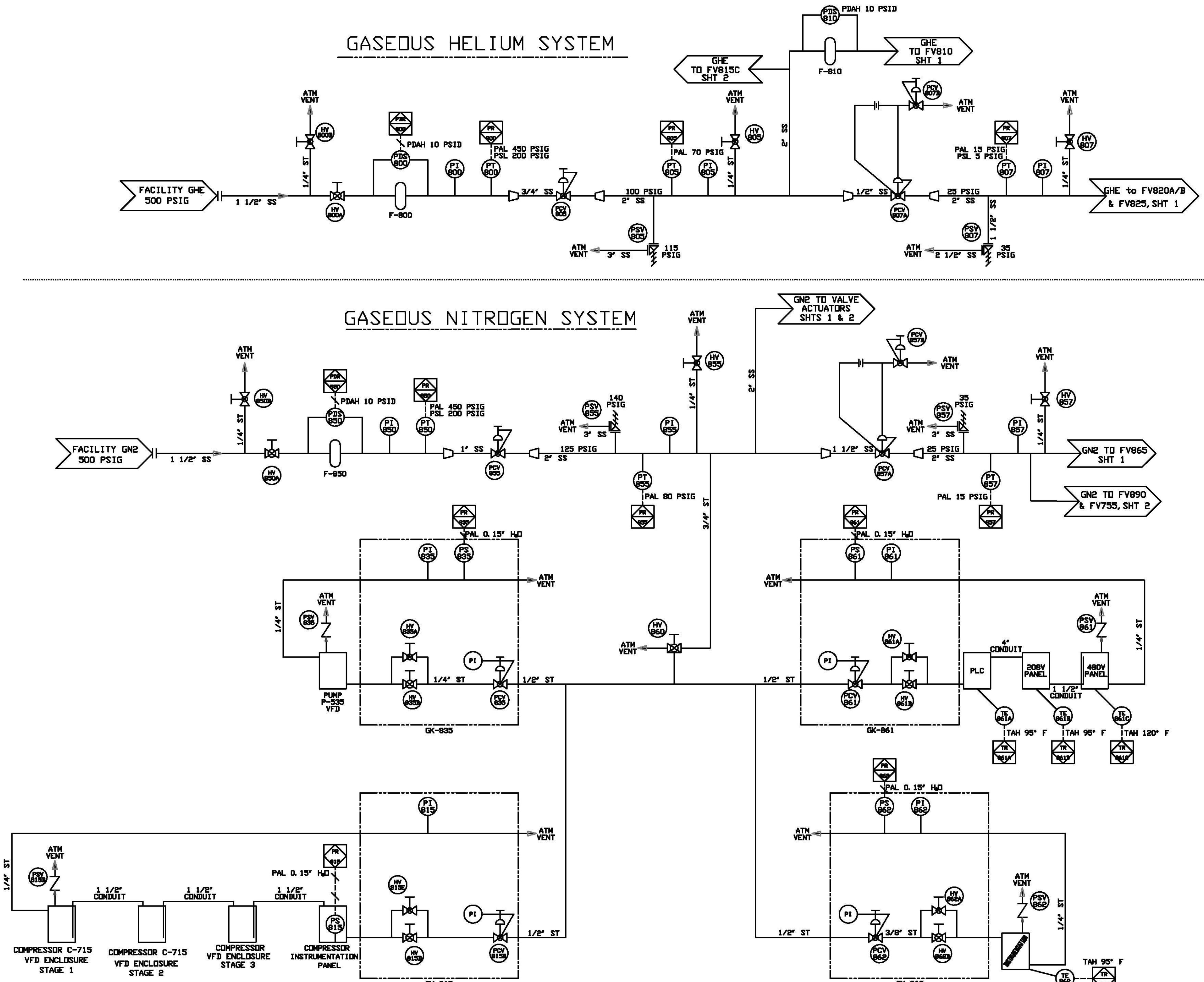


Figure H.4: LO2 PDU flow schematic, P&ID symbols, sht 4 of 4.

Table 1 - Identification Letters

	FIRST-LETTER (4)		SUCCEEDING-LETTERS (3)		
	MEASURED OR INITIATING VARIABLE	MODIFIER	READOUT OR PASSIVE FUNCTION	OUTPUT FUNCTION	MODIFIER
A	Analysis (5, 19)		Alarm		
B	Burner, Combustion		User's Choice (1)	User's Choice (1)	User's Choice (1)
C	Check			Control (13)	
D	User's Choice (1)	Differential (4)			
E	Voltage		Sensor (Primary Element)		
F	Flow Rate	Ratio (Fraction) (4)			
G	Purge		Glass, Viewing Device (9)		
H	Hand				High (7, 15, 16)
I	Current (Electrical)		Indicate (10)		
J	Power	Scan (7)			
K	Time, Time Schedule	Time Rate of Change (4, 21)		Control Station (22)	
L	Level		Light (11)		Low (7, 15, 17)
M	Flow Coefficient	Momentary (4)			Middle Intermediate (7, 15)
N	User's Choice (1)		User's Choice (1)	User's Choice (1)	User's Choice (1)
O	User's Choice (1)		Orifice, Restriction		
P	Pressure, Vacuum		Point (Test) Connection		
Q	Quantity	Integrate, Totalize (4)			
R	Radiation		Record (17)		
S	Speed, Frequency	Safety (6)		Switch (13)	
T	Temerature			Transmit (18)	
U	Multivariable (6)		Multifunction (12)	Multifunction (12)	Multifunction (12)
V	Vibration, Mechanical Analysis (19)			Valve, Damper, Louver (13)	
W	Weight, Force		Well		
X	Unclassified (2)	X Axis	Unclassified (2)	Unclassified (2)	Unclassified (2)
Y	Event, State or Presence (20)	Y Axis		Relay, Compute, Convert (13, 14, 18)	
Z	Position, Dimension	Z Axis		Driver, Actuator, Unclassified Final Control Element	

NOTE: Numbers in parentheses refer to specific explanatory notes in Section 5.1 of ANSI/ISA - S5.1

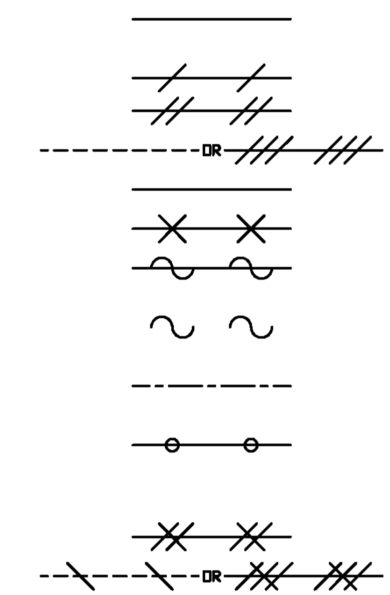
Instrument Line Symbols

ALL LINES TO BE FINE IN RELATION TO PROCESS PIPING LINES.

(1) INSTRUMENT SUPPLY* OR CONNECTION TO PROCESS
(2) UNDEFINED SIGNAL
(3) PNEUMATIC SIGNAL **
(4) ELECTRIC SIGNAL
(5) HYDRAULIC SIGNAL
(6) CAPILLARY TUBE
(7) ELECTROMAGNETIC OR SONIC SIGNAL *** (GUIDED)
(8) ELECTROMAGNETIC OR SONIC SIGNAL *** (GUIDED)
(9) INTERNAL SYSTEM LINK (SOFTWARE OR DATA LINK)
(10) MECHANICAL LINK

OPTIONAL BINARY (ON-OFF) SYMBOLS

(11) PNEUMATIC BINARY SIGNAL
(12) ELECTRIC BINARY SIGNAL



General Instrument or Function Symbols

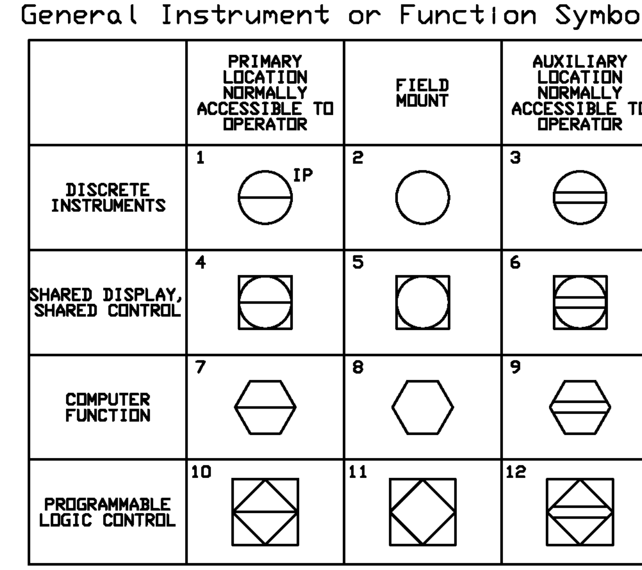


Figure H.5: South Forty Facility Flow Schematic, LN2, LO2 & STA subsystems, sht 1 of 2.

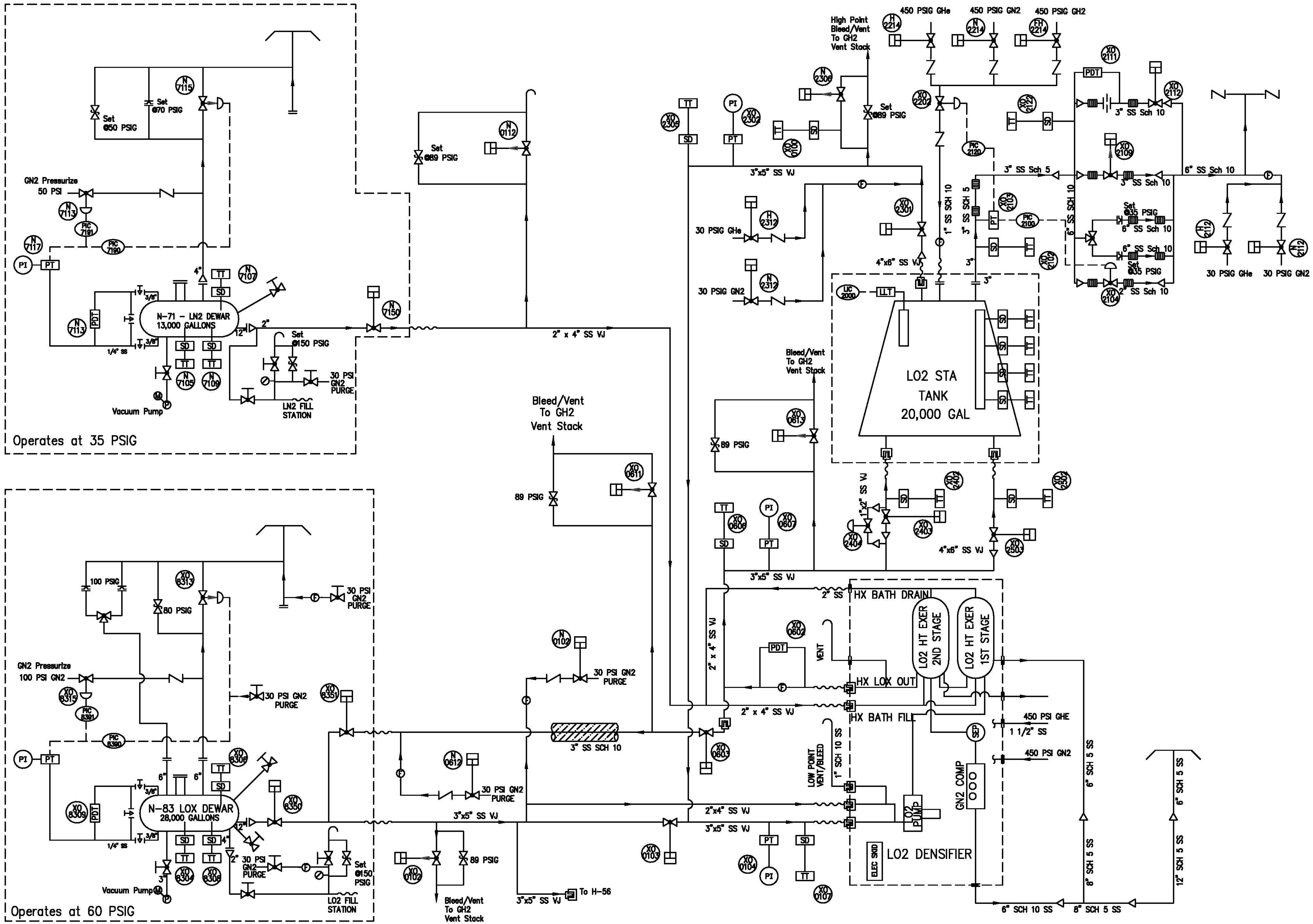
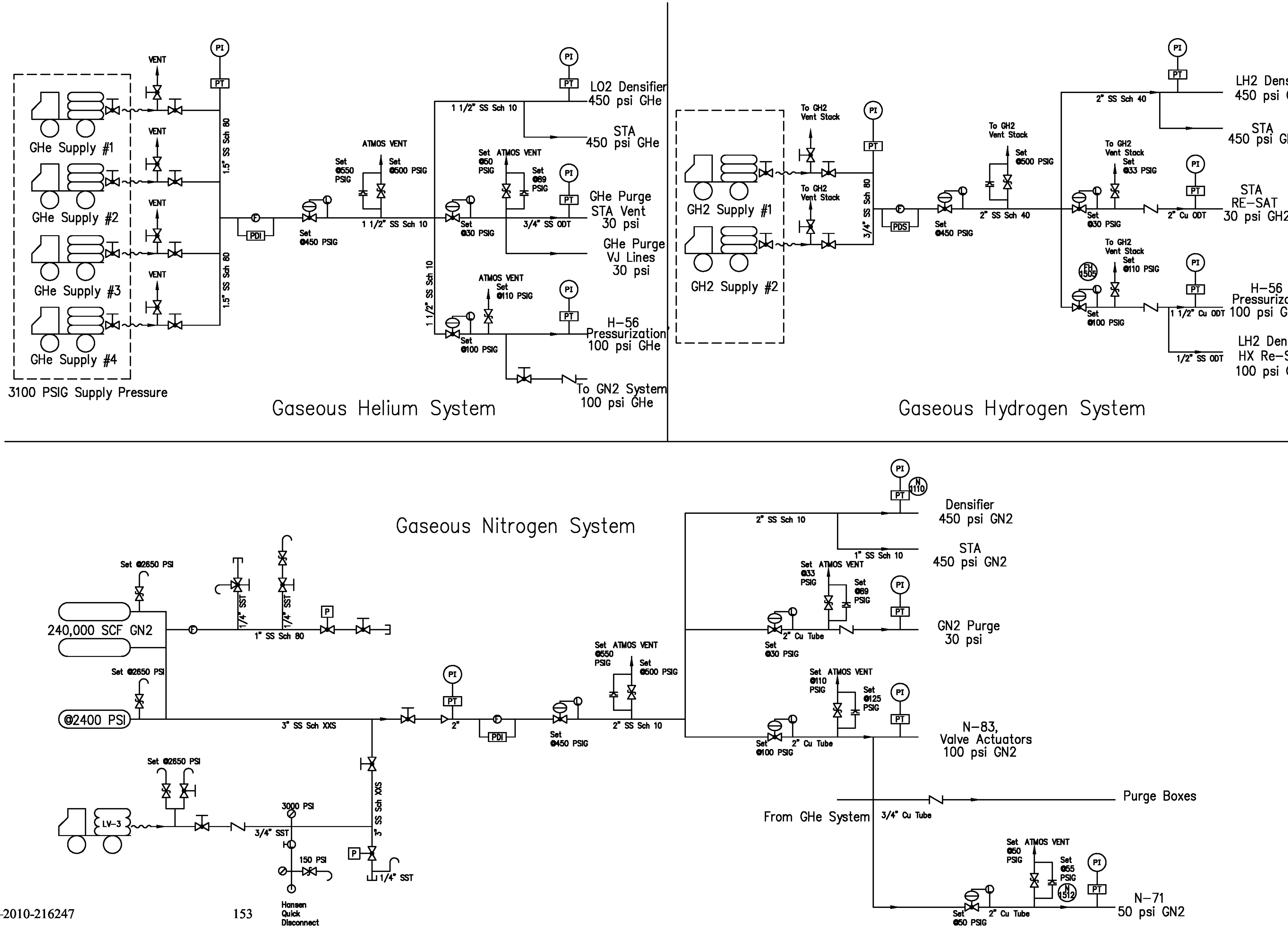


Figure H.6: South Forty Facility Flow Schematic, GHe & GN2 subsystems, sht 2 of 2.



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13. SUPPLEMENTARY NOTES

14. ABSTRACT
This paper describes in-detail a test program that was initiated at the Glenn Research Center (GRC) involving the cryogenic densification of liquid oxygen (LO2). A large scale LO2 propellant densification system rated for 200 gpm and sized for the X-33 LO2 propellant tank, was designed, fabricated and tested at the GRC. Multiple objectives of the test program included validation of LO2 production unit hardware and characterization of densifier performance at design and transient conditions. First, performance data is presented for an initial series of LO2 densifier screening and check-out tests using densified liquid nitrogen. The second series of tests show performance data collected during LO2 densifier test operations with liquid oxygen as the densified product fluid. An overview of LO2 X-33 tanking operations and load tests with the 20,000 gallon Structural Test Article (STA) are described. Tank loading testing and the thermal stratification that occurs inside of a flight-weight launch vehicle propellant tank were investigated. These operations involved a closed-loop recirculation process of LO2 flow thru the densifier and then back into the STA. Finally, in excess of 200,000 gallons of densified LO2 at 120 oR was produced with the propellant densification unit during the demonstration program, an achievement that's never been done before in the realm of large-scale cryogenic tests.

15. SUBJECT TERMS
Propellant densification; Subcooled cryogens; Liquid oxygen

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