



Demonstration of Liquefaction for Lunar and Martian Surfaces Using Tube-on-Tank Heat Exchanger With Integrated Cryocooler and Prototype Lander Tank

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Summary

As in-situ resource utilization (ISRU) concepts and systems emerge, applicable technologies are being developed and matured in tandem. Although there are many different ways to use the resources found on other bodies, one of the most prevalent applications suggested is manufacturing propellants. One of the key technologies for the eventual use of these propellant-production-based ISRU systems is the liquefaction and storage of the produced propellants. The most-mentioned propellant combinations include oxygen-hydrogen and oxygen-methane. The liquefaction of oxygen in these systems will differ from oxygen liquefaction systems on Earth due to the requirements, which are more highly constrained for efficiencies driven by mass and power as opposed to cost. These systems have been developed conceptually and many of the

components have been tested previously or are in development. However, the need to demonstrate the system-level operations still exists. The demonstration of a prototypical oxygen liquefaction system using tube-on-tank broad area cooling was completed to gain a better understanding of system-level operations during liquefaction activities. Demonstration testing included system performance determination, constant liquefaction demonstrations, and transient liquefaction demonstrations. The demonstrations showed the operational capabilities of the tube-on-tank system with an integrated cryocooler. Testing met all target liquefaction rates and completed all planned demonstrations of transient operations. Additional testing explored subsurface versus ullage introduction of the gaseous oxygen (GO₂) flow stream, as well as demonstrating a novel fiber optic sensor that measured the temperature gradients along the fluid center line within the tank.

Nomenclature

Acronyms

BAC	broad area cooling
BBR	broadband reflector
CryoFILL	Cryogenic Fluid In-situ Liquefaction for Landers
DSNE	Design Specification for Natural Environments
EMI	electromagnetic interference
FBG	fiber Bragg grating
FOSS	Fiber Optic Sensing System
HMI	human-machine interface
ISRU	in-situ resource utilization
MAV	Mars Ascent Vehicle
MLI	multilayer insulation
MOXIE	Mars Oxygen ISRU Experiment
P&ID	pipng and instrumentation diagram
PID	proportional-integral-derivative
PLC	programmable logic controller
RTD	resistance temperature detector
slpm	standard liters per minute
SMiRF	Small Multipurpose Research Facility
THC	total hydrocarbons
ZBO	zero boil-off

1.0 Introduction

1.1 Liquefaction Background

Sending explorers to Mars is an energy-intensive proposition. Launching significant mass to Mars requires launching even more mass from the surface of the Earth to propel the mass required to land. Production of return propellant on the martian surface is key, both to reducing the mass that must be launched from the Earth and reducing the mass that must be landed on Mars (Refs. 1 and 2). Based on the traditional rocket equation, the lowest mass fraction of propellant capable of returning large masses is nearly 75 percent. For an oxygen-methane-based propulsion system, more than 75 percent of that propellant mass is liquid oxygen (LO_2); for an oxygen-hydrogen-based propulsion system, more than 85 percent of that propellant mass is LO_2 . Thus, by producing oxygen on the surface, the mass of the return vehicle required to be delivered to the surface is reduced by more than 55 percent. Additional production of the methane (LCH_4) or hydrogen can reduce the mass by up to the full propellant mass or greater than 75 percent. However, this does require extra hardware to produce the propellant. Figure 1 illustrates the benefits of in-situ resource utilization (ISRU) based on analysis done by NASA during the Evolvable Mars Campaign (Ref. 1).

Since the 1990s, NASA has been developing technology to allow for the mass production and storage of propellants on the

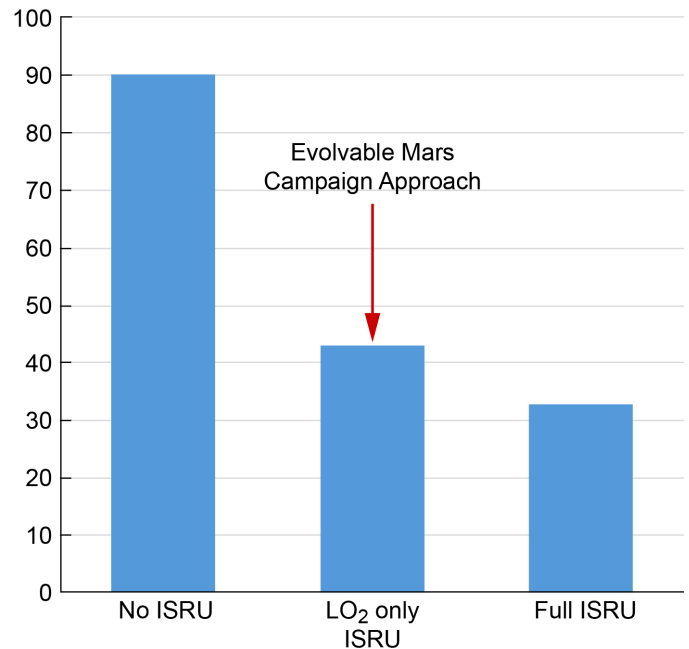


Figure 1.—Relative lander sizes using no ISRU, LO_2 production only, and production of both LO_2 and LCH_4 (full ISRU) (Ref. 1).

surface of both Mars and the Moon. However, operations for liquefaction of these propellants inside of lander propellant tanks have not been fully demonstrated. In order to perform this demonstration, the Cryogenic Fluid In-situ Liquefaction for Landers (CryoFILL) project was established.

1.2 Choice of Liquefaction Fluid

Many different types of ISRU and propulsion systems have been envisioned. Both hydrogen-oxygen and methane-oxygen ISRU systems have been seriously proposed and developed over recent times. The commonality of oxygen within those systems, as well as the fact that oxygen would generally be at least 75 percent of the mass of a methane-oxygen system and 85 percent of the mass of a hydrogen-oxygen system, suggest that starting with oxygen provides a good reference point for methane. The commonality of usage between fuels and larger relative benefits of oxygen suggested that oxygen was a good starting point for a liquefaction fluid.

Studies performed by Polsgrove and others as a part of the Evolvable Mars Architecture suggested that initial missions to the martian surface should consider an oxygen-production-only concept (Ref. 1). This was because a majority of the mass was oxygen and that the production of methane and hydrogen are both more complicated and more energy intensive than oxygen only. Additionally, by only doing CO_2 electrolysis, the working fluid within the Mars atmosphere comes directly to the process plant as opposed to it having to be actively gathered and

returned to the plant. This approach has been demonstrated on the Mars surface by the Mars Oxygen ISRU Experiment (MOXIE) multiple times while residing on the Mars Perseverance Rover (Ref. 3).

Furthermore, the development of flightlike cryocoolers has been under development for several years (Ref. 4). The analysis performed by Nugent, et al., shows that the power of heat removal (or lift) for cryocoolers in the 90 to 120 K range is much closer to the power required for liquefaction activities than hydrogen at 20 K-class cryocoolers. Thus, a near-term activity could be initiated that eventually integrates the flightlike cryocoolers in development for system-level testing. This liquefaction system could be designed to work with oxygen or methane. With oxygen having the higher heat removal requirements of the two, the oxygen system would work well for methane.

These three factors made starting with oxygen liquefaction the best choice because it also covers future methane liquefaction needs. This does not lessen the need for liquefaction of hydrogen but leaves future gaps to be closed in the development of hydrogen liquefaction processes.

1.3 Mars and Moon Architecture and Target Production Rate

As the architectural concepts for ISRU were put together and began slowly maturing, both for the Moon and Mars, general trends began to surface. In the development of load requirements and production rates, the requirements to refuel (or initially fuel) a minimally capable lander were in the range of 10 mT on the lunar surface and 20 mT on the martian surface (Refs. 1 and 5). Although it is probable that a much higher usage will be required eventually (Ref. 6), it should be expected that a gradual buildup (perhaps even starting with smaller ISRU plants) will occur. Based on the fuel production quantities and general timeframes assumed, the production rates for oxygen are determined for both methane- and hydrogen-based systems to fall into the range of 2 kg/h (Ref. 7).

Given the general rates of the ISRU system requirements, combined with the facts that most landers contain more than one tank and ISRU systems may be modular, the required liquefaction power was calculated both as a function of gas inlet temperature (Figure 2) and liquefaction rate (Figure 3). The temperature of the gas leaving the ISRU reactor varies depending on the methodology used to produce the oxygen; in general, it could be much warmer than 300 K based on correspondence with the NASA ISRU community; however, radiative precooling down to at least 300 K is assumed and further investigation similar to that performed by Hauser (Ref. 8) for Mars should be completed. Although the possibility of precooling the incoming oxygen gas

with the test facility environmental shroud was investigated, this was ultimately not pursued. The assessments on storage pressure show some sensitivity to input power (decreasing enthalpy change required with higher pressure, see Figure 4). Given most users' (i.e., engines') preference for liquid as cold as possible, but with hardware only qualified down to one atmosphere of pressure, it somewhat makes sense to start at 101.3 kPa. However, the pressure dependence of the liquefaction rate is something that could be tested on the system to assess the impact on the cryocooler system running at higher temperatures because cryocoolers get more efficient at higher temperatures.

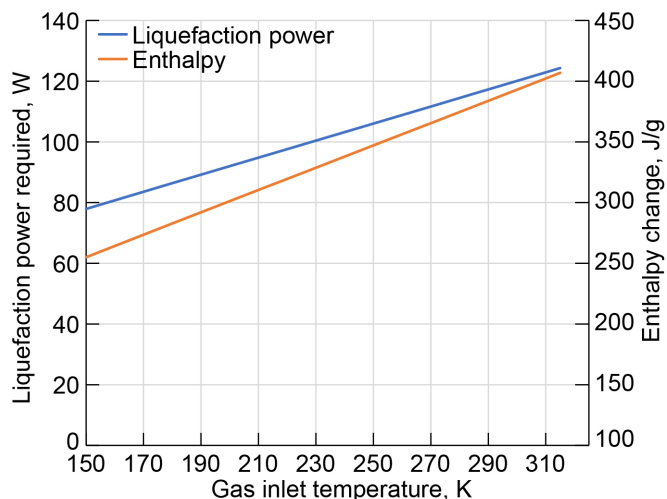


Figure 2.—Liquefaction power required as function of gas inlet temperature for 1.1 kg/h at 207 kPa.

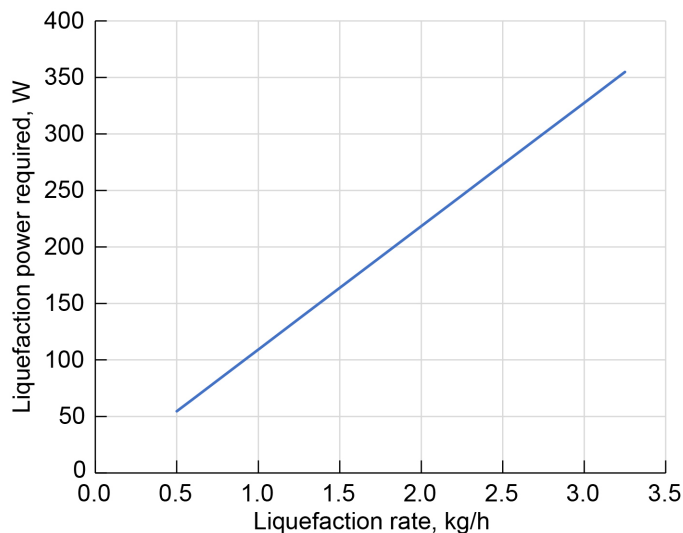


Figure 3.—Liquefaction power required as function of liquefaction rate with inlet conditions of 300 K and 207 kPa.

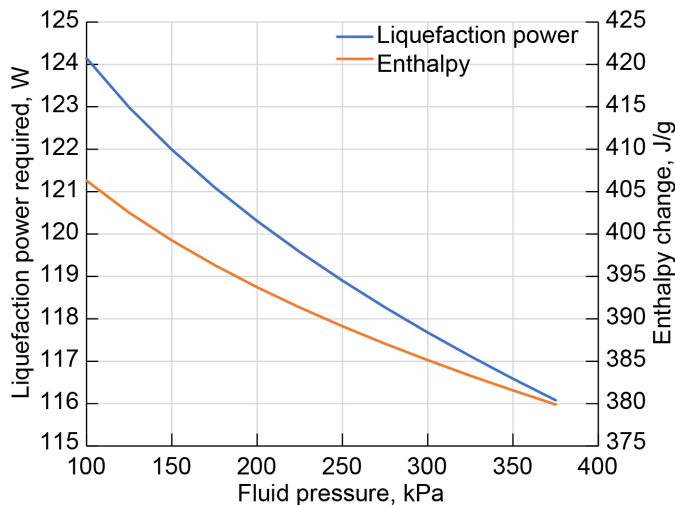


Figure 4.—Liquefaction power required as function of system pressure with inlet conditions of 300 K and 1.1 kg/h.

1.4 CryoFILL Test Series

To demonstrate the capability of liquefying the incoming oxygen gas, a series of tests of maturing the technology in both hardware fidelity and testing environment was defined. The first in the test series was the Brassboard testing, completed at Marshall Space Flight Center over the course of 2018 and 2019 (Ref. 9). The Brassboard testing focused on exploring several liquefaction operational processes while pulling together a simple test using existing test hardware with ISRU-like gaseous nitrogen (GN_2). The current Prototype activity, the second in the test series, introduces the Prototype test hardware and ISRU-like gaseous oxygen (GO_2). The test matrix is focused on expanding on the results from the Brassboard testing. The final test sequence will use the same Prototype hardware, with the exception of the cryocooler. The 150 W at 90 K flight-like cryocooler developed by Creare LLC (Hanover, New Hampshire) will replace the industrial cryocooler unit used for the initial Prototype testing. It will continue to expand on the operational aspects of the liquefaction system, including some aspects of conditioning the propellant and pressurizing it while the cryocooler is operational. Additionally, this will provide initial run-time on the flight-like cryocooler and give NASA experience operating the flight-like cryocooler, both of which will help future integration into flight vehicles. This report is based on the test data achieved in the second test series, the initial test with the Prototype hardware.

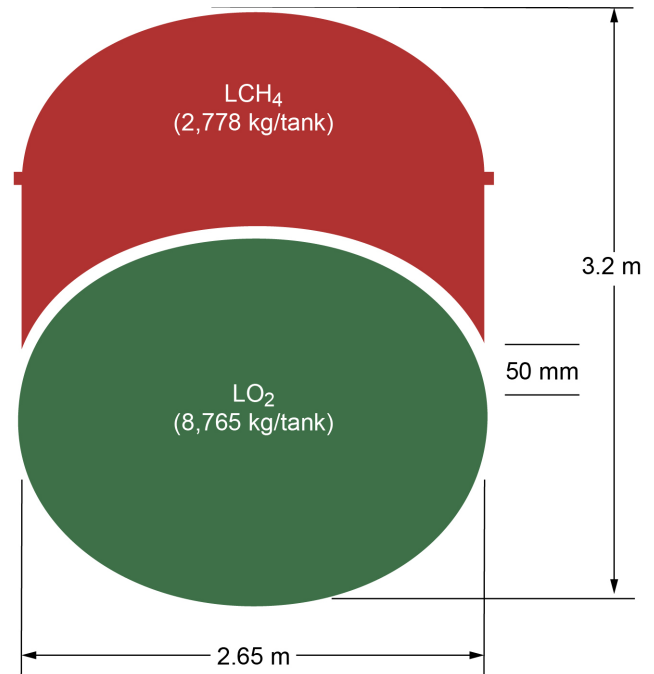


Figure 5.—First-stage MAV tank with dimensions.

1.5 Scaling

As the test requirements were developed, taking into account the test facilities at NASA, the general test configuration began to take shape. However, a key determination had to be made: How big of a tank was required? To determine tank size, a scaling assessment was completed. This scaling effort started with the existing Mars Ascent Vehicle (MAV) tanks (Ref. 1). Those tanks' shapes and surface areas are shown in Figure 5 and Table 1. Initial estimates showed that the largest tank that could fit within the Small Multipurpose Research Facility (SMiRF) at NASA Glenn Research Center was on the order of half the surface area of the MAV tanks. This made further sense, given the modular approach that could be taken on the ISRU system at the 2 kg/h requirements, where two systems producing 1 kg/h could be used with a third smaller system for redundancy. This would allow a less massive approach to meeting redundancy requirements.

To get 50 percent of the surface area of the first-stage MAV tanks while keeping within the SMiRF maximum diameter of 1.37 m, the required tank height was 2.25 m, as shown in Table 2. Using a 2:1 elliptical dome, this gave a volume of 2.51 m^3 and a surface area of 9.8 m^2 . However, the 2.25 m

turned out to be too tall once the SMiRF cold wall top was to be used. To assess this, three different tank sizes were generated. The 1.85-m-tall tank required no modification to the cold wall, whereas the 2.02-m-tall tank required a 0.17-m extension to the cold wall. The 0.17-m extension still kept the cold wall out of the way of the diffusion pumps on the top of the chamber, minimizing any interference with pulling a vacuum in the chamber. As such, the intermediate tank size was chosen and a 0.17-m cold wall extension (just an aluminum u-tube) was fabricated. Figure 6 shows this tank inside the SMiRF vacuum chamber and cold wall, including the 17.8-cm (7-in.) cold wall extension.

To further assess the scaling, a heat transfer model of the liquefaction process was created, taking into account the tank surface areas for condensation (the ullage or vapor space and the liquid/vapor interface) as a function of fill level and determining a first-order limit on the liquefaction rate as a function of fill level. The cryocooler was assumed to have no more lift than required to liquefy 1.1 kg/h. The wetted and dry surface areas of the tank were calculated as a function of fill height along with the area of the liquid vapor interface (assuming a fully settled and quiescent interface) assuming that they were uniform at 90 K. The total area for heat transfer to the incoming vapor was assumed to be the dry surface area of the tank and the liquid-vapor interface. To calculate the tank inner thermodynamics, the tank was split up into three sections, the lower dome, cylinder, and upper dome. Convection and condensation coefficients of heat transfer were determined for each surface that was in contact with the vapor based on the work from Yang and West (Ref. 10). See Equations (1) to (6).

$$\text{Nu}_{conv} = 0.08\text{Ra}^{0.25}, 10^{12} > \text{Ra} > 10^7 \quad (1)$$

$$\text{Nu}_{conv} = 4.5, \text{Ra} < 10^7 \quad (2)$$

$$\text{Ra} = \frac{g\beta\Delta TL^3}{\nu\alpha} \quad (3)$$

$$\text{Nu}_{cond} = 1.368 \left(\frac{\text{Ra}_{cond}}{\text{Ja}} \right)^{0.2} \quad (4)$$

$$\text{Ra}_{cond} = \frac{g\rho_L(\rho_l - \rho_G)L^3 \text{Pr}_L}{\mu_L^2 \text{ or } \mu_L^2} \quad (5)$$

$$\text{Ja} = \frac{c_p dT_{cond}}{h_{fg}} \quad (6)$$

TABLE 1.—MAV FIRST- AND SECOND-STAGE
TANK SURFACE AREAS

	First stage	Second stage
	Surface area, m ²	
O ₂ tank	9.77	8.61
To ambient:	8.08	6.92
To LCH ₄ tank:	1.69	1.69
CH ₄ tank	12.62	9.47
To ambient:	10.92	7.78
To LO ₂ tank:	1.69	1.69

TABLE 2.—TANK OPTIONS CONSIDERED FOR CRYOFILL TANK

Tank	Diameter, m	Length, m	Dome ratio	Volume, m ³	Fluid mass at 95% full, kg	Surface area, m ²	Length/ diameter	Capacity, gal	Days to fill at 1 kg/h	SA ratio to MAV first stage	SA ratio to MAV second stage
Desired surface area	1.25	2.25	2.00	2.51	2,713	9.77	1.8	629	103	0.50	0.82
Current limits	1.25	1.85	2.00	2.02	2,184	8.20	1.5	506	82.7	0.42	0.69
Final compromise	1.25	1.96	2.00	2.14	2,323	8.61	1.6	538	88.0	0.44	0.73

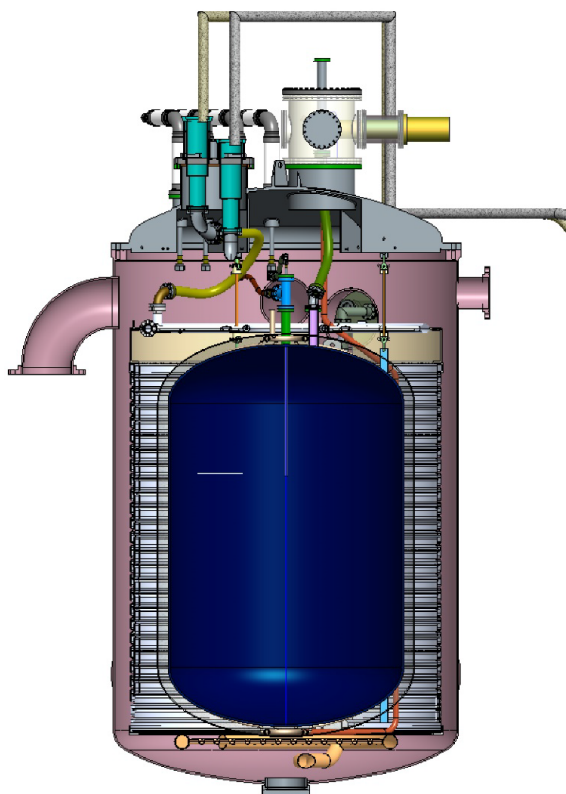


Figure 6.—CryoFILL test tank in SMiRF vacuum chamber with aluminum cold wall extension.

Based on the user-provided maximum incoming mass flow rate (the tank was not allowed to liquefy more mass than the incoming flow) and the condensation heat transfer coefficient, and assuming a liquefaction temperature differential of 0.3 K, the area required for condensation was calculated. Then the remaining area was allocated for convection heat transfer; if the convection heat transfer rate did not meet the required minimum convection heat transfer rate to cool the incoming gas to saturation, then the area allocation for condensation was reduced and the associated liquefaction flow rate was reduced to less than the maximum allowed mass flow rate. Both the total heat transfer possible and the calculated mass flow rate to be liquefied was plotted. As such, it was possible to determine when the tank internal surface area became the limiting factor in the liquefaction process using a tube-on-tank heat exchanger. For different tank shapes and sizes, this was shown to vary between 80 to 96 percent, depending on the flow rate and configuration. Figure 7 shows the effect of fill level and surface areas on the liquefaction rate for the CryoFILL tank; Figure 8 shows the same for the Evolvable Mars Campaign first-stage MAV oxygen tank. Reviewing these figures, it is easy to see that the limiting value for a majority of the liquefaction operation would be the flow rate (or associated cryocooler), not the surface area of the tank. As such, the constant temperature tank assumption for liquefaction would be expected to overpredict liquefaction rates.

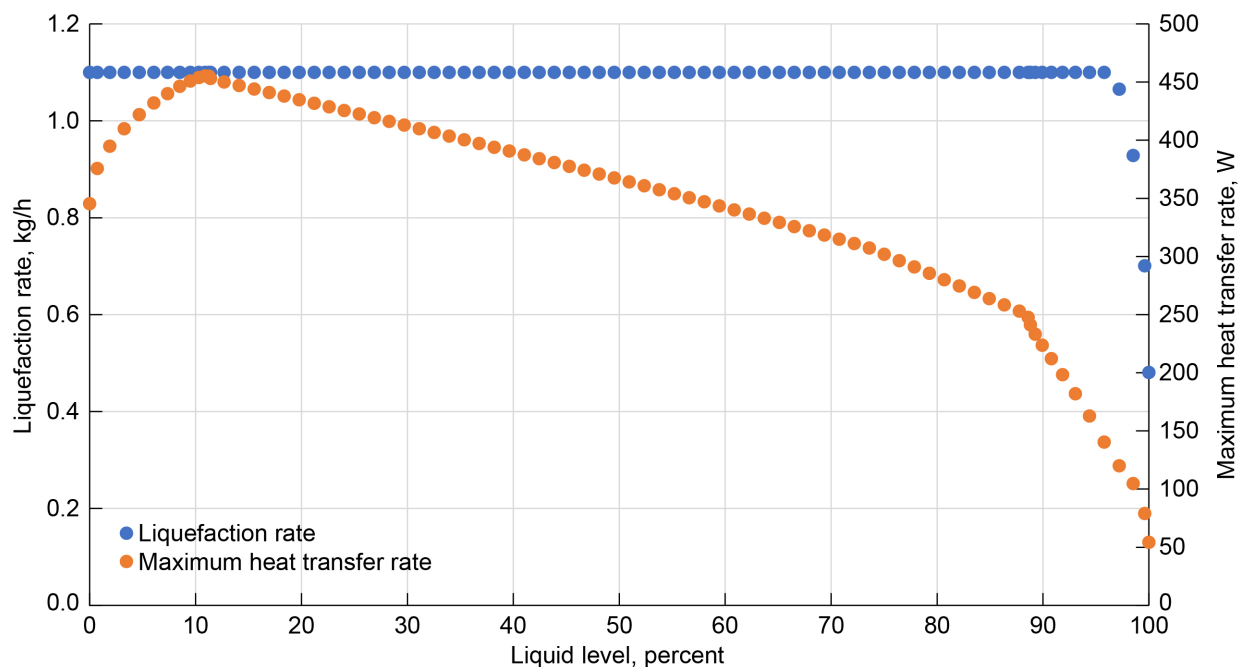


Figure 7.—CryoFILL tank performance as function of fill level. It becomes surface area poor at 96 percent full, given liquefaction rate of 1.1 kg/h.

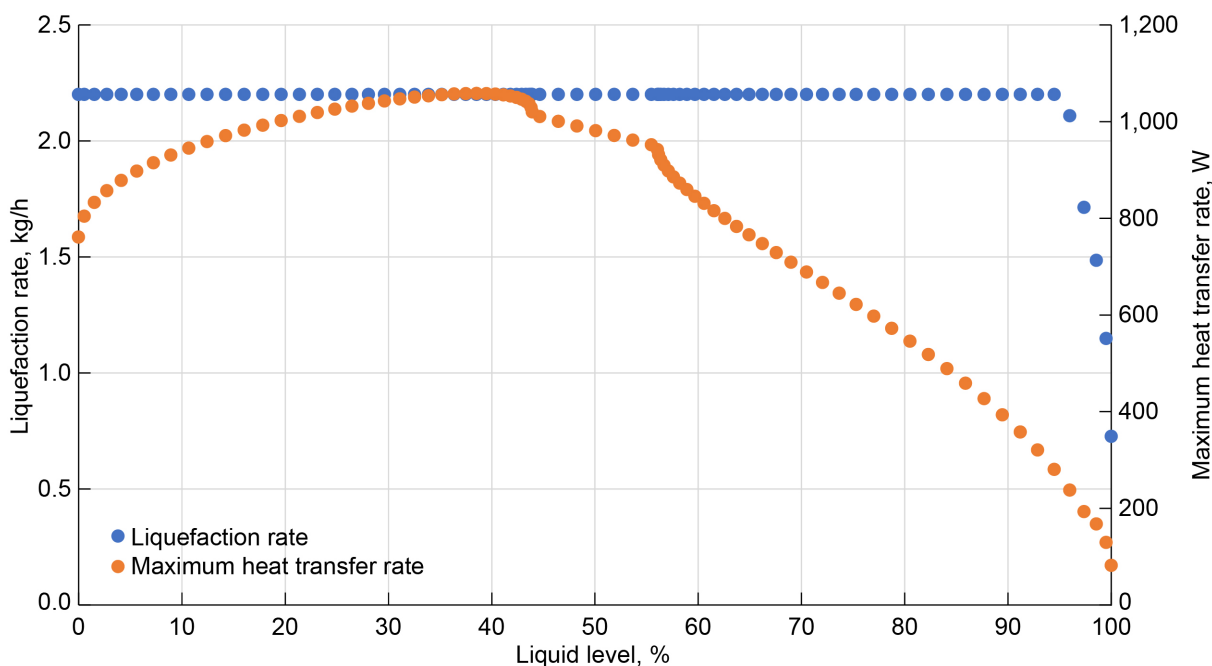


Figure 8.—MAV first-stage performance as function of fill level. It becomes surface area poor at 94 percent full, given liquefaction rate of 2.2 kg/h.

1.6 Environments

Data from the Viking II landing site showed daily temperatures ranging from 190 to 250 K during the summer months and from 160 to 180 K during the winter months (Ref. 11). Similarly, NASA's Cross Program Design Specification for Natural Environments (DSNE), Rev G (Ref. 12), Table 3.4.6.3-1, shows the local noon temperature at 85° latitude as a maximum temperature of 224 K. Based on these inputs, and the fact that the main environment of concern is the oxygen pressure and temperature at which the liquefaction occurs, it was determined that the worst-case environment could be matched at 250 K on the cold wall.

2.0 Test Hardware

2.1 Small Multipurpose Research Facility (SMiRF)

The SMiRF at NASA Glenn Research Center is used to conduct research in cryogenic fluids (see Refs. 13 and 14). In the center of the two-story SMiRF is a vertically oriented cylindrical thermal vacuum chamber with a volume of 7,400 L. It can accommodate test articles as large as 1.8 m in diameter and up to 2.3 m tall. The use of a nitrogen-cooled thermal shroud reduces the maximum test article diameter to 1.37 m. The thermal shroud temperature can be controlled in the range of 110 to 360 K and can be programmed to simulate lunar and martian diurnal cycles. The lower level of

the SMiRF houses mechanical and oil diffusion vacuum pumps used to maintain a vacuum down to 6.7×10^{-4} Pa (5×10^{-6} Torr). The upper level has multiple cryogenic-rated fill, drain, and vent lines that attach to the vacuum chamber lid. A mass spectrometer-based gas analyzer continuously monitors the residual gas composition in the chamber.

Test articles are suspended from the vacuum chamber lid, then placed inside the vacuum chamber. All electrical and fluid connections pass through the lid of the vacuum chamber. The fill system consists of a 20-mm main supply line that branches into a number of independent fill paths. The fill lines can be used to fill multiple tanks within the vacuum chamber with different liquid cryogens if desired. Over-the-road tanker trucks are used to deliver cryogen to the facility. The main vent, which has a diameter of 50 mm, can either vent directly to atmosphere or control the test article backpressure within 130 Pa (0.02 psi) by modulating a series of parallel control valves. One of three mass flow meters with a range of 0.57 to 30,000 standard liters per hour (slph) can measure the flow rate of the vented gas. The flow meters were calibrated with oxygen gas for the CryoFILL testing. The facility supply/vent systems limit the maximum working pressure of test articles in the vacuum chamber to 2 MPa.

A LabVIEW®-based (National Instruments Corporation) data collection system supports recording up to 425 channels of data at a rate of 1 Hz and an additional 24 channels at a rate of 0.1 Hz. Data acquisition from standard instruments such as thermocouples, pressure transducers, flow meters, and silicon diodes is

preconfigured. Instrument cabinets with modular jack-type field connections are located throughout the facility to enable installation and checkout of research hardware. Control of the facility operations is via a programmable logic controller (PLC) with a human-machine interface (HMI). Interlocks, alarms, and shut-downs protect both the facility and the research hardware. The control system and the data system are independent, but data can be shared between the two systems if necessary.

SMiRF has an interconnect and electric work area adjacent to the main test facility that is maintained at positive pressure during testing to provide an explosion-proof electrical classification of adjoining areas when required. The SMiRF control room is located at a safe distance from the test facility; the facility can be operated remotely when testing flammable propellants, and either remotely or locally when testing inert fluids.

Multiple upgrades were made to the facility to accommodate the CryoFILL hardware. The piping for the chiller that helps protect temperature-sensitive equipment was upgraded from 1 to 2 in. to allow a higher flow rate throughout the facility. The gas and LO₂ systems were repaired and rebuilt after an extended period of inactivity. An additional remote PLC drop was installed to control the new test-specific hardware.

A cryocooler system composed of three Cryomech AL300 (Bluefors) cryocoolers was used to cool GNe, which was then circulated through a tube-on-tank manifold by a cryogenic-rated fan. The GNe cooled the walls of the test tank and allowed for condensation of the process gas inside of the tank. The cryocooler cold heads and fan were enclosed in an evacuated cold box enclosure to isolate them from environmental stimuli. Figure 9 shows the cryocooler assembly in the SMiRF.

2.2 Test Tank

The test tank is custom-made from aluminum 5052. Eight aluminum 3003 cooling D-shaped tubes are welded along its length with manifolds on both ends. The tubes have expansion joints that are antisymmetrical to the tubes next to them, but symmetrical around the tank quarters. The tubes are welded in 50-mm weld stitches that alternate across the two sides of the tubes. The expansion joints and the D-tube with a base thicker than the curved portion simplified the tubing assembly and welding to the tank wall. A single thermally isolated return tube connects the bottom of the tank to the top to return the cryocooler flow from the bottom manifold around the tank. Several additional features are designed to allow for the future integration of a lightweight vacuum-jacketed concept without requiring welding onto the main tank pressure boundary. These include the weldment at the top of the tank, studs around the tank cylinder top and bottom, and feet. The tank wall is penetrated in two places. At the top,



Figure 9.—Cryocooler assembly connected to facility.

a 55-mm-diameter passthrough is used for fill, drain, and instrumentation; at the bottom, a 25-mm-OD tube is used for cleaning the tank for oxygen usage.

The tank is a stamped ASME Boiler and Pressure Code Vessel, with a design pressure of 414 kPa (60 psig)/–103 kPa (15 psig) at a temperature of 4.3 K. The tubes and manifolds are designed to ASME B31.3 with a design pressure of 5.5 MPa (800 psig). Figure 10 illustrates the tank and includes enlarged views of the manifolds. The mass of the tank is ~231 kg, the volume of the tank is 2.1 m³ warm and 2.0 m³ cold, and the outer surface area is 9.1 m². The inner diameter of the tank is 1.238 m, and the internal diameter of the tubes is 12.7 mm. Each tube is 4.8 m long. The domes are nominally 2:1 ellipsoidal domes. External dimensions of the tank are shown in Figure 11. The height of the tank is 1.96 m (77 in.).

The tank has three aluminum cylinders on the top from which it can be hung and three feet on the bottom on which it can be placed. The feet are specially designed to handle the weight of a tank full of oxygen while also handling the shrinkage of the tank. The structural elements were designed to be more representative of a lander tank heat load than of an ideal calorimeter-like tank. The completed CryoFILL tank is shown in Figure 12.

The test tank was not designed to be an ideal thermally isolated tank but to be more representative of the flight heat

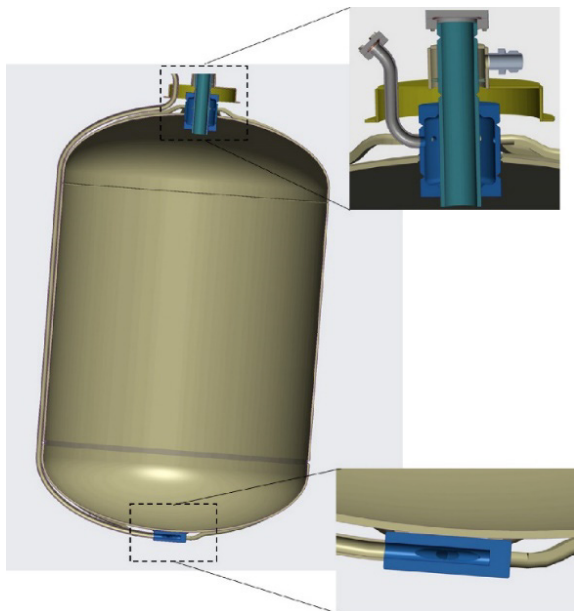


Figure 10.—Tank cutaway with exploded views of manifolds.

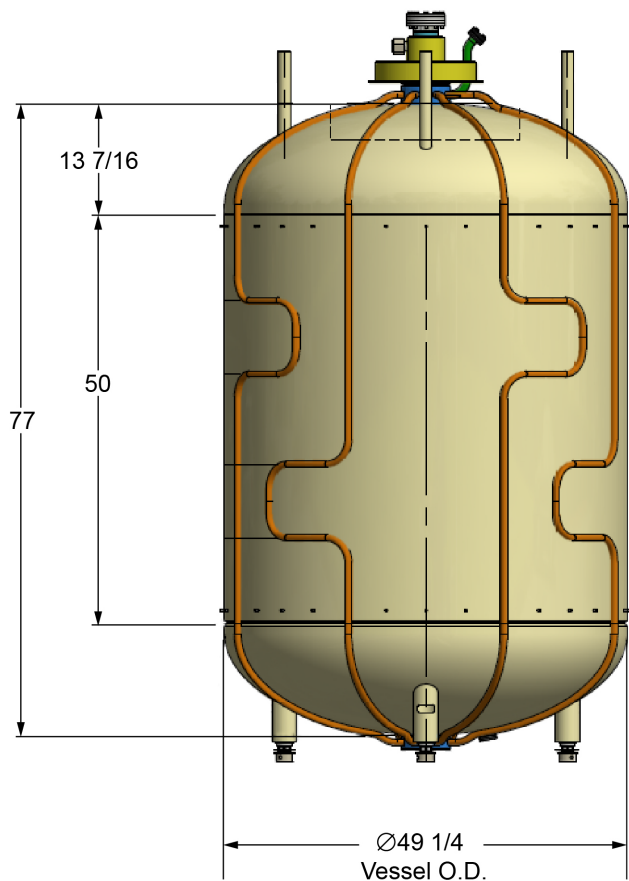


Figure 11.—CryoFILL tank dimensions. All dimensions are in inches.



Figure 12.—CryoFILL tank resting on its feet on pallet.

loads anticipated on a lander tank. As such, the heat loads from the hanging rods, feet, and fluid lines were designed in an attempt to keep the heat loads within a target range of 150 W, including the liquefaction enthalpy (allowed for 31 W of heat load into the system). This is much closer to the heat load that might be expected for a lander tank of similar size, rather than for an ideal test tank (Ref. 15).

2.3 Cryocooler System

Active cooling is applied to the tank's surface via broad area cooling (BAC) tubes utilizing a fully integrated cryocooler loop. An industrial, integrated cryocooler system from Cryomech (Syracuse, New York) was purchased to fit this project's needs. It provides cooling to a tubing network that circulates cold GNe over the tank's surface. The neon tubing network consists of a cryofan, the cryocooler cold head heat exchanger, external heaters, an eight-tube BAC network split between two manifolds, and a Coriolis flow meter. The cryofan and cold head were isolated from the main vacuum chamber in a cold box under vacuum. This was done because space was limited within the SMiRF vacuum chamber. Vacuum-jacketed lines connect the test vacuum chamber and cold box. Figure 13 illustrates the neon cooling loop, as well as the subcomponents required for the cryocooler to function.

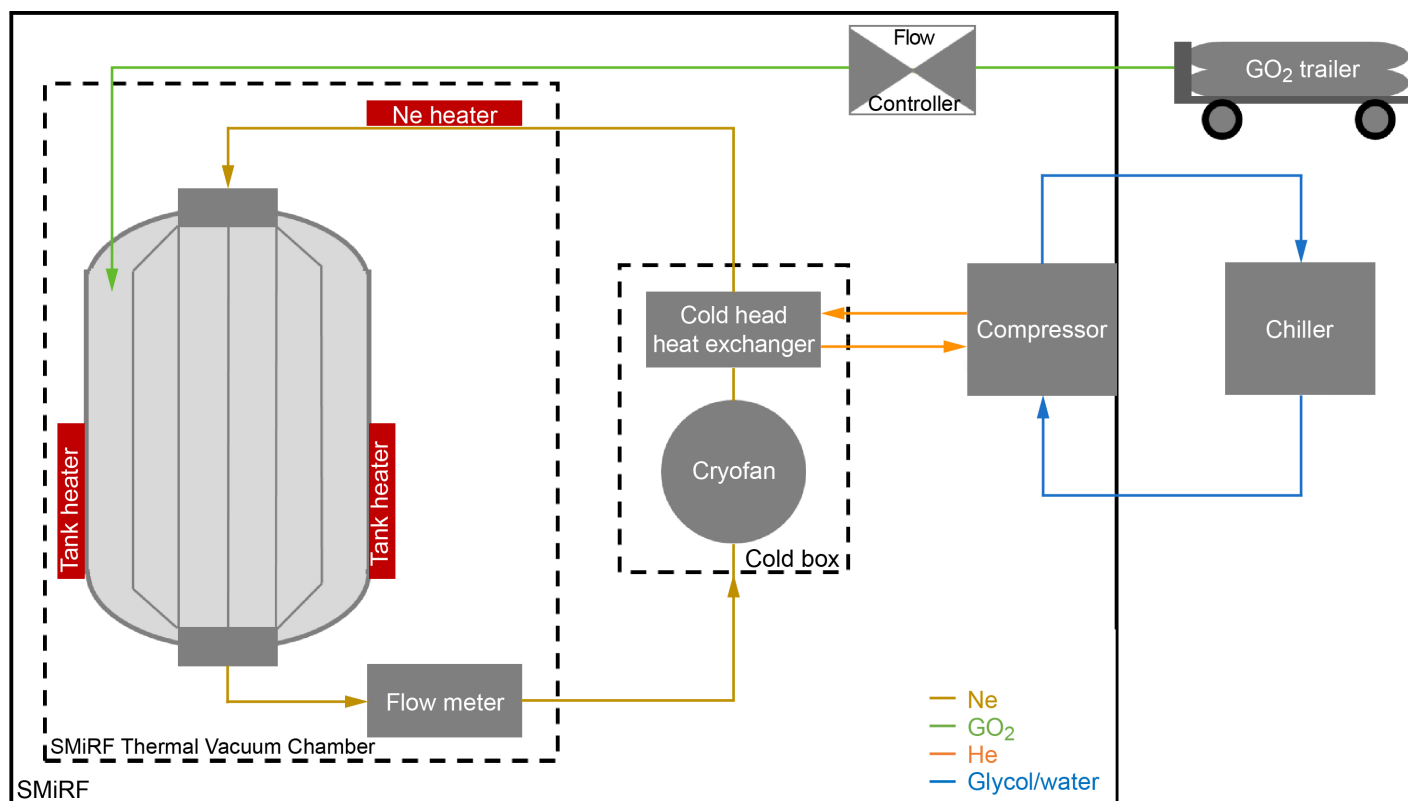


Figure 13.—Neon cooling loop and integrated cryocooler system.

The integrated cryocooler system consisted of a cryofan and cryocooler. The cryofan from Absolut System (Eybens, France) (Figure 14) was utilized for circulating neon in the cooling loop. Pretest analysis deemed the Absolut cryofan capable of achieving a desirable mass flow rate range by providing a positive pressure differential that can overcome all expected pressure losses along the neon loop. The fan was mainly operated at a speed of ~ 20 krpm during testing.

The system includes three AL300 cryocoolers from Cryomech (Syracuse, New York), one of which was used throughout testing. Each cryocooler cold head has helium lines to its own gas compressor, which is contained in a blast-proof, positive-pressure container. The compressors circulate helium to expand and provide cooling at the cold head and to reject heat from the neon loop into lines circulating a mixture of water and glycol supplied by a chiller at SMiRF. Only the first cold head and compressor were active for the test series; they could provide up to 200 W of cooling at 90 K to the neon loop. When used together, all three cold heads and compressors could provide up to 1,200 W of cooling at 110 K. This cryocooler is rated to 20 BarA. Figure 15 shows the cold box during check out testing. The cooling capacity of a single cold head in the cryocooler operating with GNe at different fan speeds is mapped out from testing done by Cryomech. The decrease in performance with fan speed is due to the decreased effectiveness of the heat exchanger between the cryocooler and neon flow at



Figure 14.—Absolut cryofan.

higher mass flow rates, which are associated with smaller temperature drops within the neon flow rate.

A Micro Motion® flow meter (Micro Motion, Inc.) and Omega® polyimide film heaters (Omega Engineering, Inc.) were selected for use in the neon loop (see Figure 17). The heaters were installed externally on the cooling loop tubing between the cold head exit and the BAC entrance. This added further control of the GNe temperature before it entered the BAC section over the tank surface, effectively allowing greater control of the lift occurring across the tank's surface. Figure 11 and Figure 12 show some of the BAC tubes over the surface of the tank. Heat transfer between the oxygen, tank wall, tube wall, and neon occurs along the length of the BAC tubes. The flow meter was installed in the cooling loop to measure the mass flow of the circulating neon downstream of the BAC tubes and return manifold. The heater and flow meter installed on the neon cooling loop are shown in Figure 17. See Section 2.5 for further details on these instruments.

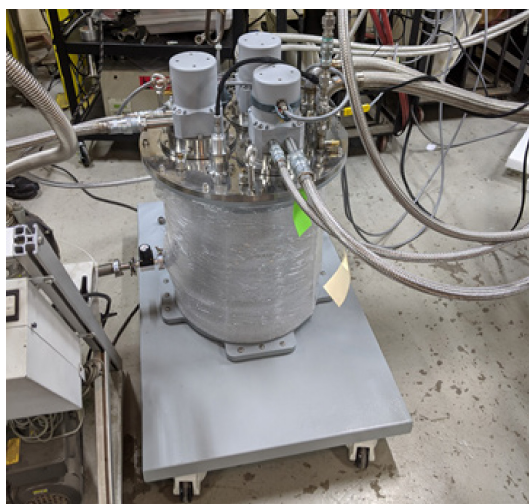
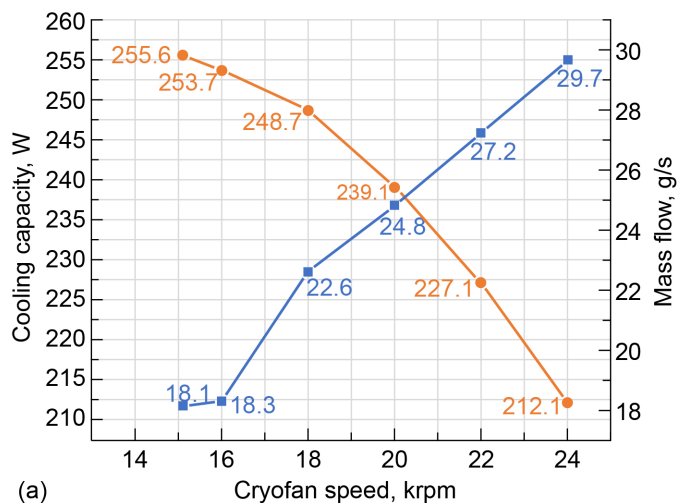
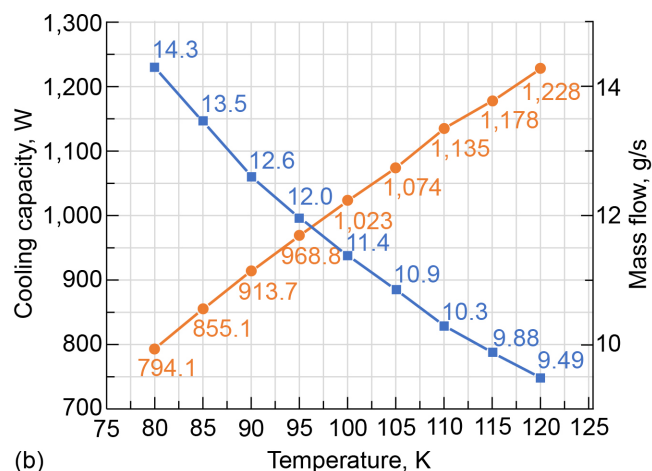


Figure 15.—Cold box for cryofan and coldheads.



(a)



(b)

Figure 16.—Cryocooler cooling capacity. (a) Of single 90 K cold head at various fan speeds circulating GNe at 200 psig. (b) For three cold heads at 40 krpm fan speed and 280 psig GNe as function of temperature.

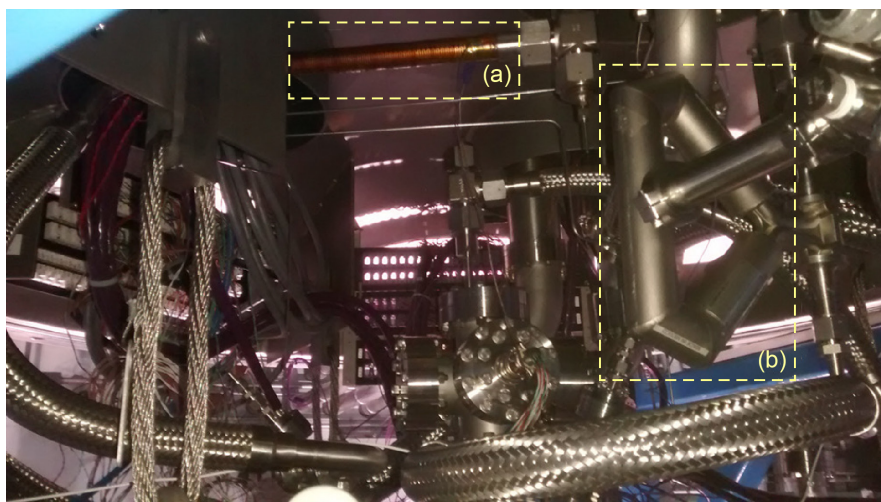


Figure 17.—Instruments on neon cooling loop underneath SMiRF vacuum chamber lid. (a) Neon cooling loop heaters. (b) Neon cooling loop flow meter.

2.4 Integrated System

Figure 18 is the piping and instrumentation diagram (P&ID) for the integrated system. As the diagram shows, the test tank interfaces with the GO₂ feed system, the neon flow loop that exchanges energy with the cryocooler, the LO₂ feed system, and the vent and back pressure control system of the facility. The P&ID does not include all of the instrumentation inside the tank or on the tank wall; it mainly includes the instrumentation used to control the system and the instrumentation within the cryocooler loop.

LO₂ or liquid nitrogen (LN₂), which is used only for system checkout, is fed into the tank from a dewar located outside the facility to achieve the desired tank fill level before the start of a test series (typical fill levels achieved are 5, 50, and 90 percent). LO₂ is introduced through the tank lid via a dip tube that runs to the bottom of the tank. The fill level is measured by a capacitance probe within the tank (not shown in Figure 18). The GO₂ is fed into the tank from a tube trailer supply. The temperature and pressure of the oxygen stream into the tank are measured; its flow rate is measured and controlled by the FC-1 flow controller. By selecting the appropriate valves, oxygen can be introduced into the ullage at the top of the tank or injected into the liquid at the bottom of the tank via the LO₂ feed system's dip tube and bubbled upwards into the ullage.

The boil-off gas exits from the top of the tank and interfaces with the vent and back pressure control system of the SMiRF. The vented gas temperature at the top of the tank is monitored and the flow rate is measured as well. The parallel control valves allow for appropriate pressure control bands to be maintained at different flow rates; the parallel flow meters allow measuring a wide band of boil-off flow rates.

The cryocooler and the neon flow loop are described in detail in Section 2.2. After exiting the cryocooler cold head, the GNe passes through a tube section heated by a loop heater to condition its temperature and adjust the effective lift of the cryocooler. The gas enters an inlet manifold mounted on the top of the tank, then is distributed to the cooling tubes in the BAC assembly. After exchanging heat with the outer surface of the tank wall, GNe from the cooling tubes flows through a thermally isolated return tube to an exit manifold mounted on the top of the tank, flows through a Coriolis flow meter (FS-1), then completes the loop to the cryocooler inlet.

As the neon flows over the tank surface, its direction of flow in the tests conducted was from the top of the tank toward the bottom. Although flow in either direction is possible, top-to-bottom flow was chosen for two reasons. First, this would ensure that the coldest stream of neon at the inlet to the cooling tubes would be closer to the ullage so it could readily extract heat from the ullage and promote greater condensation. Second, due to the design of the inlet and exit manifolds for neon supply and return from the BAC tubes, there was a concern that a

bottom-to-top flow of neon might not distribute the neon flow well among the cooling tubes (see Figure 10).

Figure 18 also shows a few sensors available in the test tank and the SMiRF. See Appendix A for the complete list of sensors used. The sensors can be categorized as (1) thermocouples to measure temperature on the outside surface of the tank, MLI, and cold shroud, (2) silicon diodes to measure fluid temperature in a rake within the tank, vented gas, and in the neon flow loop, (3) pressure transducers to measure pressure within the tank, in the neon loop, and in the vacuum chamber, and (4) flow meters to measure the flow rate of GO₂, GNe, and the vented gas.

Using the sensors and controlling the operation of hardware in the system (valves, heaters, etc.) allows controlling several test parameters. Most notably, the tank pressure can be kept constant during liquefaction by proportional-integral-derivative (PID) control of the GO₂ metering valve or the heater on the neon loop. In addition, the cryofan speed can be adjusted over a certain range to dial the neon flow rate up or down. Heaters on the tank surface (near the bottom of the tank) and in the neon loop can be adjusted to control the effective lift of the cryocooler and the cooling capacity of the neon flow.

Various safety precautions and protocols for nominal operation of test articles in the SMiRF facility are available and were followed for the tests conducted. For CryoFILL-specific testing, unattended continuous operation during nights and weekends was the chief concern. Specific actions implemented to mitigate the risk of unattended operation are described in Section 2.1.

2.5 Instrumentation Overview

2.5.1 Introduction

Instrumentation used during CryoFILL Prototype testing was selected based on each sensor's ability and flexibility to meet the project's stated goals, objectives, and requirements to obtain data by monitoring and measuring parameters set forth in the project's test plan. Approximately 121 sensors are used in support of testing and installed across various locations on the test hardware. These sensors cover these parameters: temperature, pressure, mass flow, liquid level, and heating. In support of CryoFILL Prototype testing, a Fiber Optic Sensing System (FOSS) is being developed to measure temperature in the fluid.

2.5.2 Instrument List

Instrumentation used during CryoFILL testing is included in the Instrument List, a primary tool used to track locations and parameters of instruments installed on the testing platform. Researchers and test operators can also use it to reference the manufacturer and model number of each device, range, output type, and data channel, along with any alarms or shutdowns the device will trip. The CryoFILL Instrument List is part of Appendix A.

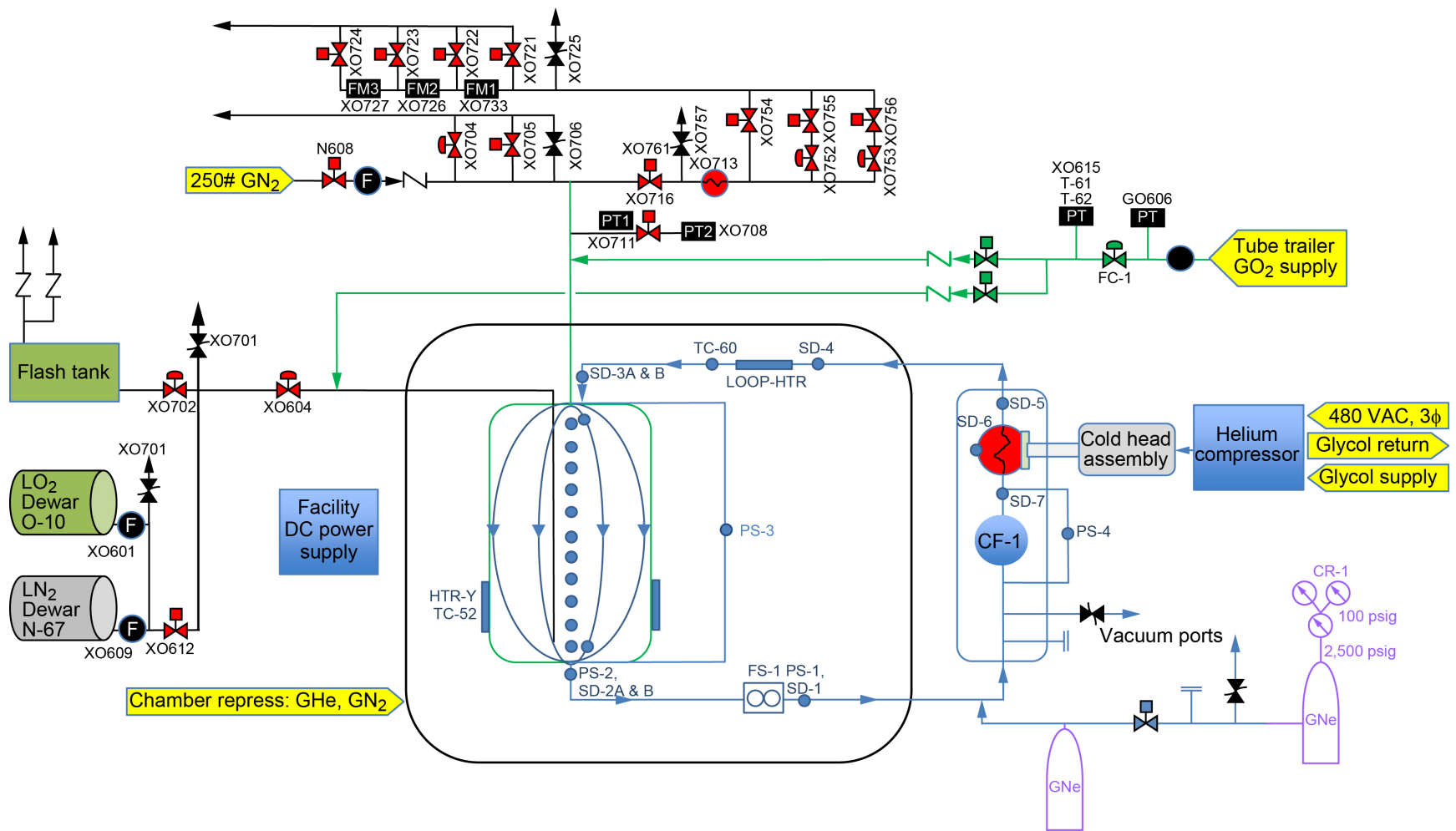


Figure 18.—P&ID for integrated system.

2.5.2.1 Temperature Sensors

Three primary temperature monitoring sensors are used in CryoFILL Prototype testing: silicon diodes, resistance temperature detectors (RTDs), and Type E thermocouples.

The temperature sensors used in CryoFILL testing operate based on a change in voltage that represents a change in temperature. The DT-670 silicon diode's thermometry is based on the temperature dependence of the forward voltage drop in a p-n junction, where electrons from the cathode or n-junction flow to the anode or p-junction through the depletion region when a biased constant current, typically 10 μ A, is applied. The resulting signal is an output voltage from 0.1 to 2 VDC, which is calibrated to a millivolt per kelvin curve. Similarly, platinum RTDs function by an increase or decrease in resistance as the temperature rises or falls. An output voltage is generated as the result of a small excitation current, typically 1 mA, being passed through the device. The standard coefficient per IEC 60751 for 100- Ω platinum RTDs is 0.00385 $^{\circ}\text{C}^{-1}$. Type E thermocouples are made of two dissimilar metals, (+) nickel-chromium and (–) nickel-aluminum, that form a node. Calibration curves for thermocouples are based on an error percentage from a reference temperature.

2.5.2.1.1 Silicon Diodes

The silicon diodes used in CryoFILL testing are Lake Shore Cryotronics' (Westerville, Ohio) DT-670B sensors. The silicon diodes are primarily used because of their accuracy within their standard range of 1.4 to 500 K, which meets the temperature range of LO₂, the cryogenic material used during testing. The standard uncalibrated sensor uncertainty from 25 to 100 K is ± 0.25 K; from 100 to 305 K, it is ± 0.5 K (Ref. 16). The DT-670B sensors are located on the instrument rake, which is mounted from the top flange and hangs down the center of the tank and has also been used on the MLSTC (Ref. 16) and LN2ZBO (Ref. 17) tests to monitor fluid level in the storage tank. The sensors are also located on the neon cooling loop piping and are used to monitor the temperature of the fluid entering and exiting that subsystem. The silicon diodes are attached to the surface of the piping using Stycast® (Henkel Corporation) thermally conductive epoxy.

2.5.2.1.2 Diode Rake (LL1 to LL19)

The diode rake (a part of the instrument rake) is used during CryoFILL Prototype testing to monitor the liquid level inside the LO₂ storage tank.

The DT-670 silicon diode was chosen as the temperature sensor used on the instrument rake for measuring the fluid level inside the storage tank. Nineteen DT-670 silicon diodes are located at 5 percent intervals on the 77-in. rake, each having a response time of ~ 100 ms at 77 K. The 10- μ A excitation current is used to create an output voltage that corresponds to a change in temperature. This change in fluid temperature enables monitoring the liquid

TABLE 3.—SUSPECTED SOURCES OF EMI IN TESTS

Tests	Likely source of EMI	Noticeably affected instrumentation
1 to 5	Test cell fluorescent lights and cryofan wiring	Silicon diodes LL1 to LL20 RTD-9 to RTD-16
All tests	Cryofan wiring	

level. When employed in a wet/dry mode, the instrument rake's excitation is increased to 10 mA, which was intended to clear any liquid from the body of the sensor, which would indicate whether the diodes are in liquid or the ullage.

Overall, the instrument rake operated and produced data that allowed for the safe operation of the test experiment. However, there were a few issues with the hardware. For example, the 19 DT-670 silicon diodes located on the instrument rake experienced susceptibility to EMI generated within the test facility. Table 3 defines the suspected leading source of EMI for each test and the instrumentation affected. Also, the instrument rake wet/dry mode did not function as expected due to condensation continually present on the diodes. See comments in Section 6.2, Lessons Learned, for an extended discussion on instrumentation performance.

2.5.2.1.3 Platinum RTDs (100 Ω)

RTDs used during CryoFILL testing are platinum 100- Ω sensors, Model P0K1.232.4W.Y.010, manufactured by Innovative Sensors Technology. The Pt-100 RTDs are four-wire temperature sensors with a range of 73.15 to 473.15 K and are mounted using 3M's Scotch-Weld® 2216 epoxy to the outer surface of the cooling loop tubes for monitoring the temperature of the neon flowing through each loop. These sensors offer the project a cost-effective solution for monitoring temperature on the cooling loop. The Pt-100 has a 20-mW power dissipation at its maximum range, which is noted in the project's bookkeeping of parasitic heat leaks.

2.5.2.1.4 Platinum RTDs (1,000 Ω)

The platinum 1,000- Ω RTDs used during CryoFILL testing are provided by Cryomech as a part of the integrated cryocooler system and monitor the temperature within the cryocooler's cold box. The sensors are manufactured by Honeywell (Model HEL-707-U-1-12-00). The two-wire sensors have an accuracy of 0.00375 $\Omega/\Omega/^{\circ}\text{C}$ with a resistance trim of ± 0.1 percent and a temperature range of -75 to 540 $^{\circ}\text{C}$. Three RTDs are located within the cold box, one each at the inlet, outlet, and body of the cryofan.

2.5.2.1.5 Thermocouples (Type E)

The thermocouples used during CryoFILL testing are manufactured by Omega Engineering and monitor temperatures on external surfaces of the test article. The Type E Model 5TC-TT-E-24-72 sensors used have a PFA or glass braid insulation

with a temperature range of -270 to 1,000 °C. These sensors have the highest percentage of use on the test article and are located on the external surface of the storage tank and support structures. The sensor has been used successfully in cryogenic experiments and has yielded reliable results with uncertainties at ~2.5 percent in degrees Celsius.

Silicon diodes and thermocouples performed as expected. Although the RTDs did not perform as expected on the top installation, they worked as expected in the integrated cryo-cooler loop and on the bottom installation on the tube-on-tank network. See Section 6.2, Lessons Learned, for comments on installation.

2.5.2.2 Pressure Sensors

Pressure sensors used during CryoFILL Prototype testing were selected based on their operational range, minimum pressure drop, and accuracy over their operational range, along with their positive performance history in this lab's test environment. Three primary types of pressure sensors were used during testing: the Rosemount 3051S Coplanar™ pressure transmitter and Setra Systems' Model 204 and Model 205-2 pressure transducers. The transmitters are located on an instrument panel outside of the test chamber. The transducers are mounted both up- and down-stream of the GO₂ valve piping. A Setra Model 239 pressure transducer is also used to measure the differential pressure across the storage tank; a Dwyer Model 636D pressure transmitter measures the differential pressure across the cryofan. Both differential pressure sensors have a 0 to 10 psid range.

When a pressure change occurs in the area the pressure transmitter is monitoring, its internal piezoresistive sensor reacts to generate a 4 to 20 mA output representing the change in pressure. Calibration is set for a range from 0 to full scale with an accuracy inherent to this model.

Pressure transducers used during testing generate a 0 to 5 VDC output because a change in pressure results in a change in resistance across the resistive bridge inside the device.

2.5.2.2.1 Pressure Transmitter (Rosemount 3051S)

Rosemount's Model 3051S is a scalable pressure transmitter; the two used on CryoFILL have a range of 0 to 100 psia on the inlet transmitter and 0 to 50 psia on the outlet of the vent valve. The 3051S is a hermetically sealed device with a span accuracy of 0.035 percent and a range down of 150:1. Specifications and operational limits are detailed in the Rosemount 3051S Product Data Sheet (Ref. 18). The Rosemount 3051S pressure transmitters are used on the test article at the inlet and outlet of the storage tank's vent for monitoring and control of the system via tank pressure.

2.5.2.2.2 Pressure Transducers (Setra 204 and 205-2)

The Setra Model 204 is a large selection range pressure transducer. Two Model 204 pressure transducers, which have a pressure range of 0 to 3,000 psig, were used during testing; both are installed upstream of the GO₂ flow control valve. The Model 204 provides a response time of <1 ms at 0 to 5 VDC output voltage with a ±0.073 percent full-scale accuracy over a wide temperature range.

The Setra Model 205-2 is the other pressure transducer used. Three 205-2 are used during testing; one has a pressure range of 0 to 50 psia and is installed downstream of the GO₂ flow control valve. Two Setra 205-2 transducers with a pressure range of 0 to 500 psia are mounted at the inlet and outlet of the storage tank. The Model 205-2 provides a response time of <1 ms at 0 to 5 VDC output voltage with a ±0.073 percent full-scale accuracy over a wide temperature range.

During testing, the pressure sensors used performed as expected. See Section 6.2, Lessons Learned, for installation comments.

2.5.2.3 Flow Sensor

The flow monitoring sensor used during CryoFILL Prototype testing was selected based on the project's requirements for a minimum pressure drop, as well as a direct conversion to a mass flow measurement. The flow meter chosen was Micro Motion's CMF series Coriolis flow transmitter.

The Coriolis flow meter consists of two primary parts: the sensor, which is a triangular tubular inline-mounted piece of 316 stainless steel hardware, and a remote mounted transmitter used to input measurement variables and generate a 4 to 20 mA output. The technology operates on the principles of motion mechanics, in which a fluid or gas moves through the triangular vibrating tube, where it's forced to accelerate toward the point of peak-amplitude vibration, causing a phase shift. This phase shift is proportional to the mass flow.

2.5.2.3.1 Micro Motion CMF025/Micro Motion 2700

The flow sensor used was a Micro Motion Coriolis meter ¼-in. inlet/outlet. The meter has a mass flow accuracy of ±0.10 percent (liquid) and ±0.35 percent (gas). The meter has a temperature accuracy of ±1 °C and maximum working pressure of 1,500 psig. The meter is mounted inside the test facility's vacuum chamber lid. The meter is paired with the Micro Motion 2700 transmitter, which is Intrinsically Safe and generates a 4 to 20 mA output. The transmitter is mounted remotely in the test facility outside the vacuum chamber and is used during testing to monitor the neon flowing in the test tanks cooling loop.

During testing, the Coriolis flow meter did not perform as expected due to installation configuration and improper straight tubing path prior to the entrance of the flow meter. See Sections 5.2 and 5.3 for analysis of the flows and Section 6.2, Lessons Learned, for further comments on the performance of the Coriolis neon flow meter.

2.5.2.4 Flow Controller

One CryoFILL Prototype testing requirement is that the system must be capable of liquifying 1.1 kg/h of GO₂, which meant that the flow controller chosen had to meet that standard. The Brooks Instruments' Model SLAMf50 flow controller was chosen because it met that requirement and is suited for harsh test environments.

The Brooks Instruments' SLAMf50 functions as a controller regulating the flow of GO₂ into the system and as a flow monitor reading back the amount of flow as data. The input to the device is GO₂ via a tube trailer supplying the test facility. The input pressure from the GO₂ tube trailer is ~97 psig, then regulated down by the SLAMf50 to ~44 psia at a 12.4 slpm flow rate. The Brooks SLAMf50 also operates to monitor the regulated flow where the data is recorded as a mass flow rate. The SLAMf50 controller produces a full-scale output of 4 to 20 mA, which is used to operate the system safely. The low-flow range makes the SLAMf50 flow controller ideal for CryoFILL Prototype testing.

The SLAMf50 mass flow controller has an accuracy of ± 0.6 percent at the setpoint (SP) value or over a full range of 0.003 to 50 slpm. This model has a maximum operational pressure of 1,500 psi. The flow controller is sealed which allows for operating in harsh and hazardous environments which is representative of CryoFILL's test environment. The mass flow controller communications ports allow for calibration and diagnostic checks without removing the device from the system.

The Brooks SLAMf50 functioned as expected but a heavy duty-cycle during testing caused the small orifice output nozzle to become clogged, which stopped the device from functioning. After being sent out for cleaning and repair, the device was reinstalled and functioned as expected during the remaining portion of testing.

2.5.2.5 Liquid-Level Sensors

Three sensors are used during CryoFILL Prototype testing to monitor liquid levels inside the storage tank. The primary sensor is the capacitance probe manufactured by American Magnetics. The secondary sensor is the diode rake, which was designed and built at NASA Glenn. Also, an experimental hardware system developed by the engineering and research staff at Armstrong Flight Research Center (AFRC) called the Fiber Optic Sensing System (FOSS) was used to monitor the temperature of the liquid produced inside the CryoFILL storage tank.

2.5.2.5.1 Capacitance Probe

A capacitance probe is a pair of concentric tubes that measure the height of the liquid between the tubes based on the different dielectric constants of a liquid cryogen compared to its gaseous phase. By placing the capacitance probe along the length of the centerline of the tank, the height of the liquid phase is measured, then converted into a volume based on the known shape of the tank while cold.

The capacitance probe is mounted on a flange attached inside at the top and center of the storage tank. The capacitance probe operates when fluid migrates up the stainless-steel tube via openings and small holes located at the bottom and top of the sensor and represents the 0 to full-scale reading of the hardware. As the LO₂ migrates up the 77-in. length between the stainless-steel tubing and dielectric material of the sensor where a voltage is created representative of the calibrated height of the storage tanks volume. The 4 to 20 mA output produced by the Model 1700 is used to represent the 0 to 100 percent fill level in the storage tank.

The capacitance probe used during CryoFILL testing consists of a custom-built, 3/8-in.-OD stainless steel tube covering a dielectric inner material. The sensor's length of 77 in., which covers the entire length of the storage tank, has a BNC-SMA tank-to-vacuum chamber interface connector. The sensor's 4 to 20 mA output is processed by the Model 1700 monitor/controller. The probe's design was custom-built for CryoFILL LO₂ testing and cleaned to the levels required to process the cryogen.

The capacitance probe, manufactured by American Magnetics, functioned as expected, requiring only a recalibration after cold shocks.

2.5.2.5.2 Diode Rake (LL1 to LL19)

As mentioned in the temperature sensors section (Section 2.5.2.1), the silicon diodes were also used as fill-level sensors. When overpowering the sensors with ~1 mA, a sharp change in the sensor voltage occurs. The fill level can then be detected to the threshold of which two sensors it lies between. The diode rake with sensors LL1 to LL19 was set up such that it could be used in either temperature mode (in which it defaulted to) or for discrete level sensing upon the test team's request. This method is routinely used by Glenn Research Center and was originally mentioned by Dempsey and Fabik (Ref. 19).

2.5.2.5.3 Fiber Optic Sensing System (FOSS)

The Fiber Optic Sensing System (FOSS) is a developmental strain and temperature measuring device deployed on CryoFILL's Prototype with an initial goal and objective of monitoring the temperature of LO₂ inside the storage tank. The system has several primary components: an interrogator that houses the laser, a broadband reflector (BBR) where wavelengths are referenced, a fiber sensor, and intermediate cables. The FOSS

sensor is mounted as an attachment to the diode rake. From an instrumentation perspective, the FOSS provides a temperature sensing rake that offers more sensors at a fraction of the mass and electrical feedthroughs of a traditional temperature sensor rake. Another side benefit of using fiber sensors as instrumentation is fiber's immunity from EMI, because it is completely optical in the sensing unit. Figure 19 shows a typical laboratory setup of the FOSS; Figure 20 compares the wires required for CryoFILL's temperature rake and for the FOSS.

FOSS functions on the fiber Bragg grating (FBG) theory, in which changing the refractive index in a section of the fiber can create a specific wavelength. The functionality of FOSS as a system operating in a cryogenic environment is explained in detail (Ref. 20). FBGs are fabricated via an ultraviolet laser passing through the fiber sections that have a phase-masked pattern; it

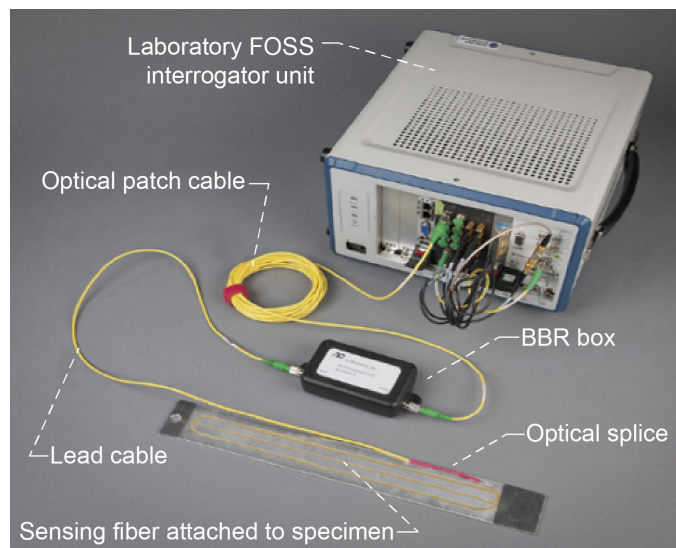


Figure 19.—Typical laboratory setup for Fiber Optic Sensing System (FOSS).

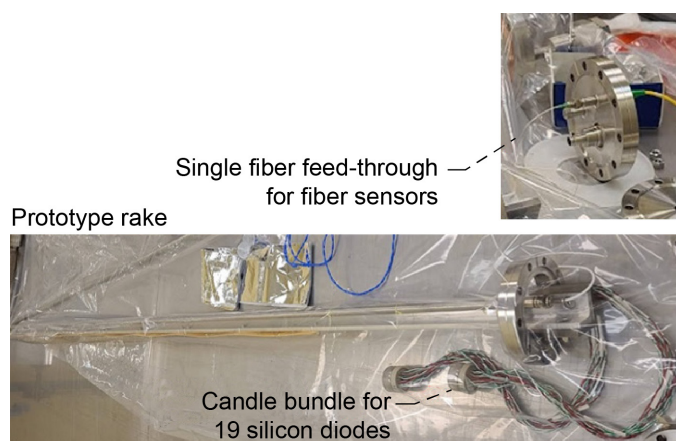


Figure 20.—Difference in weight between cable bundle for 19 silicon diodes versus single fiber feed-through for 320 fiber sensors.

reacts with the fiber's core and produces a change in the refractive index. For FOSS operations, each fiber section or grating represents a sensor; on the CryoFILL Prototype tank, there are 320 sensors on the roughly 15-ft-length of fiber. The method used to process the wavelength information from the sensors in a format suitable for data acquisition requires additional steps. Development of the sensor is a process that involves a bakeout procedure and calibration testing, which are detailed in Reference 20.

Along the length of the fibers Prototype rake, there are 331 gratings, with the length of the fiber traveling from the top of the Prototype tank to the bottom portion, then the fiber makes a U-turn to loop back to the top of tank. Of the 331 gratings, 320 of them are within the range of the tank liquid-level sensors; the other 11 extend up into the neck of the tank. The actual measurement being collected is the wavelength change of the grating due to contraction from cryogenic fluid, as shown in Equation (7):

$$\frac{\Delta\lambda_B}{\lambda_0} = (k\alpha_{CTE} + \alpha_n) \Delta T \quad (7)$$

where $\Delta\lambda_B = (\lambda_B - \lambda_0)$ is the change in Bragg wavelength due to environmental change, λ_0 is the initial Bragg wavelength of the FBG at a known temperature, $(k\alpha_{CTE} + \alpha_n)$ is the calibrated coefficient, and $\Delta T = (T - T_0)$ is the temperature change from the initial temperature.

As seen in Equation (7), it is necessary to convert the wavelength shift back to cryogenic temperature within each grating. The corresponding location between each silicon diode versus the FOSS data is listed in Table 4.

The identification process for each FOSS grating was completed prior to FOSS being integrated into the cryogenic tank. Each of the gratings represents 0.45 in. of spatial resolution from the y-axis length of the cryogenic tank. Silicon diode 19 (LL19) to silicon diode 1 (LL1) are matched with fiber gratings 20 to 158, respectively, as shown in Table 4. Although the fiber sensor array has a loop-back component from FBG ID of 159 to 330, it was used as back-up data, not for data analysis.

To accurately characterize the wavelength shift as a function of temperature decrease, each fiber Bragg grating from sensor 20 to 158 was individually mapped via a third-order polynomial curve fit at two separate LN₂ cold-shock tests. Hourly data for both LN₂ cold-shock events ranged from 78 to 290 K, and both the silicon diode data and adjacent grating's wavelength shift data was collected. For the fiber sensors without an adjacent silicon diode to directly calibrate the data, a linear extrapolation of the data was utilized. Figure 21 shows sample data from the LN₂ cold-shocked LL1, and the corresponding wavelength shift ($\Delta\lambda$) data from the fiber sensor. Figure 22 shows the third-order polynomial term for G158, where there is a unique coefficient for each unique grating.

TABLE 4.—SILICON DIODE IDENTIFICATION, LOCATION RELATIVE TO TOP OF THE PROTOTYPE TANK, AND CORRESPONDING FIBER SENSOR IDENTIFICATION

Silicon diode ID	Distance from top of tank, in.	Measured FBG ID	Measured FBG loop-back ID	Silicon diode ID	Distance from top of tank, in.	Measured FBG ID	Measured FBG loop-back ID
LL1	77.4	158	180	LL11	43.1	81	257
LL2	73.8	150	188	LL12	39.7	74	263
LL3	70.4	142	196	LL13	36.3	67	272
LL4	67.0	135	203	LL14	32.9	59	279
LL5	63.6	126	211	LL15	29.5	51	287
LL6	60.1	119	218	LL16	26.1	43	294
LL7	56.7	112	226	LL17	22.6	37	303
LL8	53.3	103	234	LL18	19.3	27	310
LL9	49.9	97	241	LL19	15.6	20	319
LL10	46.5	89	249				

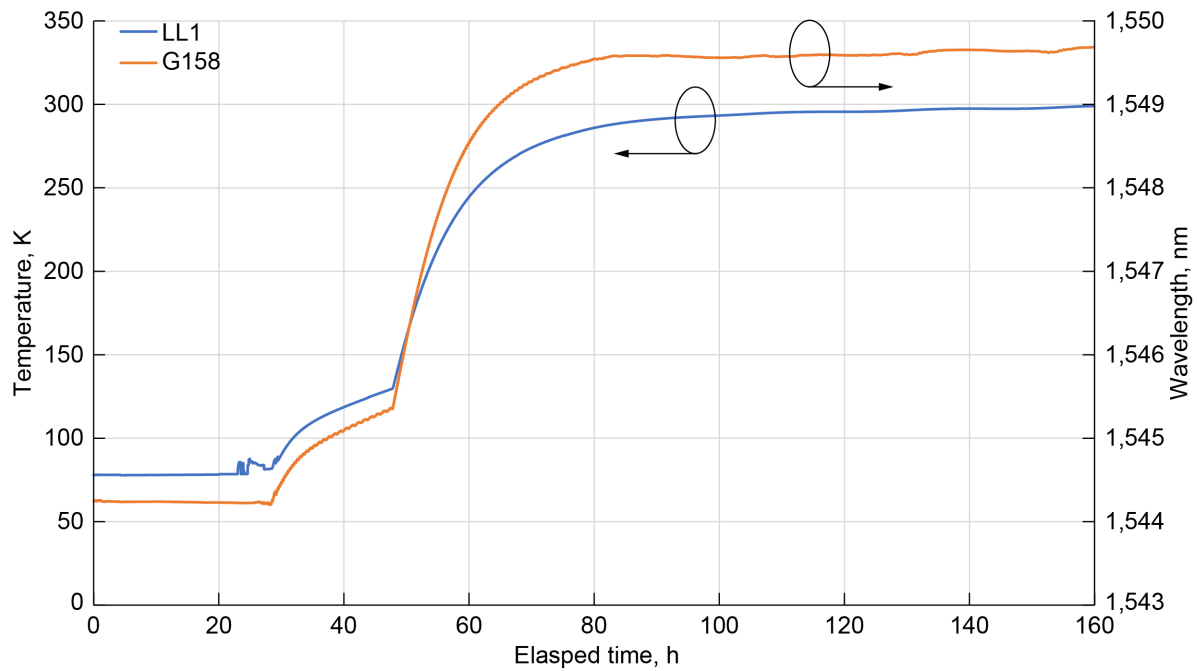


Figure 21.—Silicon diode temperature (left vertical axis) and fiber optics sensor's recorded wavelength data during LN₂ coldshock.

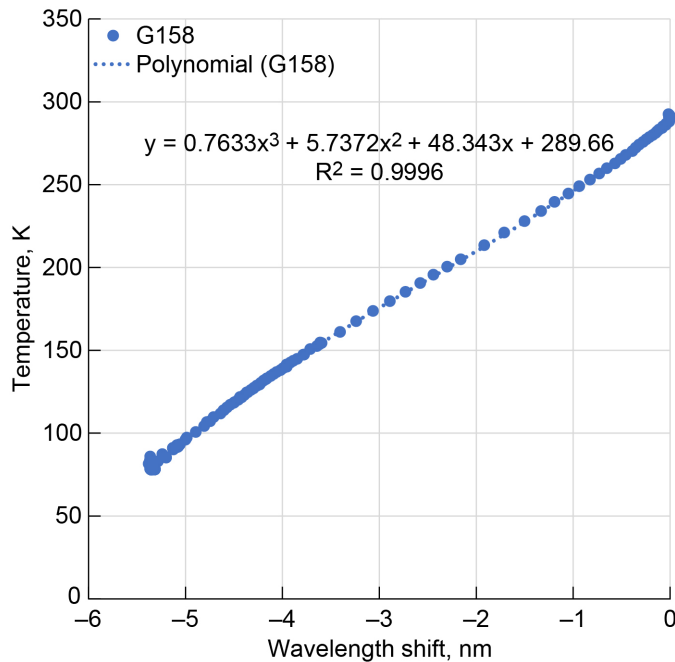


Figure 22.—Example of fiber sensor 158's wavelength difference response ($\Delta\lambda$) corresponding to its adjacent silicon diode's (LL1) temperature shift.

FOSS data is being recorded concurrently with respect to liquefaction testing. Each liquefaction test session can take multiple days, spanning hundreds of hours, and the FOSS interrogator is able to run continuously without issues. FOSS collects wavelength data at a rate of 10 Hz. A LabVIEW® application was written for data reduction and conversion, as follows.

1. Batches of 1,000 data points are collected and saved using a .csv file extension.
2. All .csv data is merged into a large .csv file, once every 12 h.
3. Data is averaged for every 120 data points, which translates to data reduction to 1 data point on the average of every 12 s.
4. Wavelength change data from grating 20 to 158 is converted into temperature data from third-order polynomial, for each data point at a particular timestamp.
5. A data-smoothing algorithm is run for a running average of each point, from grating 20 to 158.

Figure 23 illustrates the LabVIEW® data conversion process.

2.5.2.6 Heating Elements

The heating elements used in CryoFILL Prototype testing are manufactured by Omega Engineering. These flexible, polyimide

film heaters were selected because of their ability to contour to the surface of the cylindrical storage tank and piping on the system.

Four flexible heaters used for rapid warming are mounted on the exterior wall of the storage tank, near on the bottom. In addition, two flexible heaters are configured as a single heating source attached to the cooling loop and used for trim control of the liquefaction rate. The ability to add heat to the system is an important element in characterizing the CryoFILL liquefaction system. The heaters are attached to component surfaces using a 3M two-part epoxy.

2.5.2.6.1 Etched Foil Heaters

Model KHA-1212 is a rectangular heater with etched foiled elements covered with a polyimide film. The heaters operate at 115 V and have a rating of 10 W/in² over an operating range of -57 to 150 °C.

Four flexible heaters were installed on the storage tank's surface, but two malfunctioned due to power supply issues within the test facility. The two remaining flexible heaters on the storage tank and cooling loop piping functioned as expected, in accordance with the power supplies available within the test facility.

2.6 Oxygen Source and Purity

Testing required the injection of oxygen into the tank for liquefaction; although with the velocities achieved by the GO₂ (<1 m/s), injection may not provide the best connotation of the gas flow. Two different injection locations were installed: the tank dip tube and the tank vent line. The tank vent line comes into the top of the tank and introduces the gas directly into the ullage of the tank. The dip tube goes down to the bottom of the tank and directly delivers the gas, where it then bubbles through any liquid already in the tank.

The gas impurities were tested by the oxygen supplier prior to delivering the trailers to NASA. The impurity test results are shown in Table 5. THC is the total hydrocarbon (i.e., methane, ethane, propane) within the system. Tracking impurities allows for future evaluation of the data as we gain a better understanding of how low-level impurities can impede the liquefaction process. There are two different impedances: solidification and gas dynamics. The solidification is relevant to impurities that solidify within the system and either coat the tank surface, increasing the thermal resistivity between the cryocooler flow and the fluid to be liquefied or become free blocks that either float or sink in the liquid, depending on the relative density. Within gas dynamics, as noncondensable impurities increase, they prevent the condensing fluid (in this case, oxygen) from coming into contact with the condensing surface (Ref. 21).

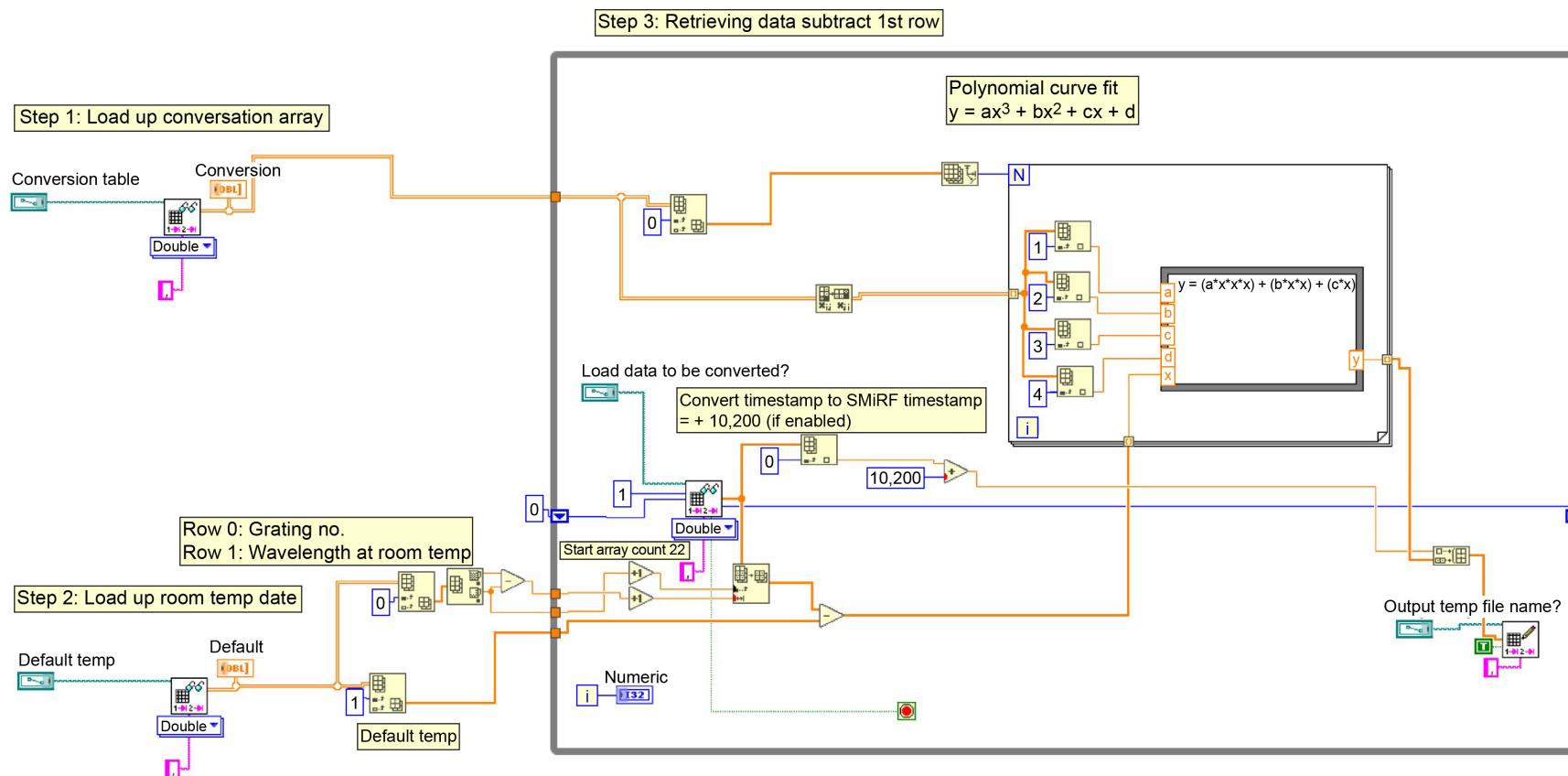


Figure 23.—LabVIEW® code that converts wavelength shift data into third-order polynomial linear curve fit.

TABLE 5.—IMPURITIES FOR GO₂ USED FOR INJECTIONS DURING LIQUEFACTION^a

Impurity	ppm
Nitrogen	266.88
Argon	357.96
Moisture	0.563
THC.....	25.37
CO	<LDL ^b 0.065
CO ₂	3.942

^aDate GO₂ trailer tested: 4/25/22; test dates used 7/19/22 to 11/7/22.

^bLow detection limit.

3.0 Test Matrix

The test matrix was split into three different parts. The first part was the Nominal Performance Determination Test Matrix (see Table 6), which was focused on understanding the impact of the variables within the neon cryocooler loop on the operation of the cryocooler loop. Variables investigated include the neon loop heater power, the cryofan speed, and the GO₂ injection method. Additionally, a boil-off test was completed to help determine the passive heat load on the system. An autogenous pressurization test was run to help separate liquid-vapor interface condensation phenomena from tank wall condensation phenomena.

The second part was the Constant Liquefaction Operations Test Matrix. In this part, constant liquefaction tests were completed at different pressures, fill levels, and flow rates. For several pressures and fill levels, the tank pressure was held constant while the liquefaction flow rate was allowed to vary. Based on the nominal settings determined during the first section of testing, the GO₂ flow rates were very close to the desired nominal flow of 1.1 kg/h.

The third part was the Transient Liquefaction Test Matrix. It built on the operational learning of the first two parts and allowed the flow rate, the environmental temperature, and the cryocooler effective heat removal to be varied independently, one at a time, while the pressure response was observed. The transient test cases were the most stressing on the test operations team, as well as the numerical model predictions that were performed. The full Test Matrix is also shown in Appendix B.

During the Nominal Performance Determination series (see Table 6), the test matrix started with a boil-off test to characterize the passive heat load into the system. The initial boil-off test was completed at 50 percent full and was immediately followed by an autogenous pressurization test. The autogenous pressurization test was intended to allow separation

between condensation on the liquid-vapor interface and tank wall without the cryocooler operating. Operations later in the test matrix had active cooling applied to the tank wall from the cryocooler. Because the temperature stratification in the ullage was low enough during the initial boil-off testing at 50 percent full, it was deemed sufficiently representative of the heat load into a 90-percent-full tank. During Test 2, a zero-boil-off (ZBO) test was run by adjusting both the heaters on the tank wall and on the neon loop until no additional GO₂ flow was required to keep the tank pressure constant while running the cryocooler system. ZBO conditions were achieved when the tank had a constant pressure, no incoming GO₂ flow, and no vent flow from boil-off. During Test 2a to 2g, additional ZBO tests were run at three different pressures and the tank pressure was controlled via heater setting with the cryocooler system operational but no incoming GO₂. Every time the thermal load on the neon flow was changed, a new subtest was started. Test 3 was used to determine the nominal heater settings required with the cryocooler system running with the incoming GO₂ flow rate at 1.1 kg/h. Test 3a varied the neon loop heater settings and observed the GO₂ flow rate changes to maintain tank pressure with the different heater settings. Test 4 observed impacts of variations of the neon flow rate on the oxygen flow rate and temperature and pressure changes in the cryocooler neon loop. Test 5 observed the effect of changing from vent line injection of the GO₂ to dip tube injection and Test 5a observed the differences at different heater settings via dip tube insertion. These tests set the nominal system operations that were used for the rest of the testing.

During tests with constant liquefaction (see Table 7), three sensitivities were experimentally evaluated: fill level, pressure, and flow rate. Tests 6 to 8 tested liquefaction rate at three different fill levels, <10 percent, 50 percent, and 90 percent, at 207 kPa (30 psia) tank pressure and 1.1 kg/h oxygen flow rate. The goal was to see if there were any significant variations at essentially 0 percent full and then determine at what fill level the liquefaction rate would slow down as the tank filled up. Tests 8 to 10 tested liquefaction rate at three different tank pressures: 138 kPa (20 psia), 207 kPa (30 psia), and 276 kPa (40 psia), all at <10 percent full and 1.1 kg/h oxygen flow rate. Tests 11 to 13 tested pressure rise and fall rate at three different oxygen flow rates: 0.5, 1.1, and 2.2 kg/h; all at <10 percent full and 207 kPa (30 psia). Additional oxygen flow rate tests at 1.6 and 0.6 kg/h were also completed. At the end of Test 7, the oxygen flow controller failed. During the ensuing 2 weeks, Tests 2a to 2g were run. For all tests, the vacuum chamber cold wall was maintained at 250 K ±5 K, the vacuum was maintained at <5×10⁻⁶ T, the heaters were set at 47 total watts, and the neon loop fan was set to 20 krpm. Tests 14 to 25 were optional tests

that could have been attempted in the Constant Liquefaction Test Matrix, but were not completed due to time allocations.

The Variable Liquefaction Test series (see Table 8) used the results from the Constant Liquefaction Test series to demonstrate the operations of the system at other conditions where a steady state was not expected to be achieved. In between each transient test, a constant liquefaction test was run to reset the system to nominal liquefaction conditions, so that one transient test did not affect the following transient. Test 27 stepped the GO₂ flow rate from 0.86 kg/h for 17 h to 1.6 kg/h for 7 h, averaging 1.08 kg/h over a 24-h period; the values used to calculate the flow rates and durations were from Tests 11 to 13. Test 29 varied the heater power into the system to simulate changing the cryocooler lift. Initially, results from Test 2a to 2g were used to calculate inputs of 94.4 W for 7 h and 15 W for 17 h; however, those did not yield consistent results, so the results from the initial Test 29 were used to update the heater settings to 93.4 W for 7 h and 0 W for 17 h and Test 29-2 showed more repeatable results. Test 31 varied the thermal vacuum chamber wall temperature. During the testing, a 1-h ramp duration between temperatures was assumed. For 6.5 h, the shroud was set at 290 K, and for the other 15.5 h, the shroud was set to 225 K. These values and durations were calculated by assuming

T³ (see Eq. (28) in Section 5.10), bringing the average heat input to the same as 250 K over the 24-h period. For all tests, the vacuum chamber cold wall was maintained at 250 K ±5 K, the vacuum was maintained at <5×10⁻⁶ T, and the neon loop fan was set to 20 krpm.

Several tests were completed interspersed within time gaps in the Variable Liquefaction test series as shown in Table 9. Test 4z was run three times at three different fill levels (<10, 15, and 90 percent). The intent of the test was to repeat Test 4 at the different neon loop speeds, but to control the oxygen flow to 1.1 kg/h and let the pressure vary, as opposed to the original Test 4, which had controlled the tank pressure and let the oxygen flow vary. This was easier to implement in the thermal modeling scheme. Test 6c was run to continue Test 6 but to attempt to get to higher fill levels to determine where the GO₂ flow rate for liquefaction would drop off. Test 40 was run to determine the maximum continuous liquefaction rate that could be achieved at constant pressure and no heaters on. Because previous testing showed considerable benefit of liquefying at the higher pressures, the test was run at 276 kPa (40 psia). Test 41 was run in an attempt to recreate pressure collapse events seen in Tests 2a to 2g. For all tests, the vacuum chamber cold wall was maintained at 250 K ±5 K, and the vacuum was maintained at <5×10⁻⁶ T.

TABLE 6.—NOMINAL PERFORMANCE DETERMINATION TEST MATRIX

Test no.	Test description	Fill level, %	Cold wall temperature, K	Initial tank pressure, kPa	GO ₂ flow, kg/h	Heaters, W	Neon loop fan speed, krpm	GO ₂ injection method
1	Boil-off test	50	250	207	n/a	n/a	n/a	n/a
1a	Autogenous pressurization test	50	250	207 to 276	1.1	n/a	n/a	Vent line
1a to 2	Autogenous pressurization test	15	250	185 to 253	1.1	n/a	n/a	Vent line
2	Zero boil-off	50	250	207	n/a	155	20	n/a
2a to 2g	Tank pressurization/depressurization	50	250	170 to 240 ^a	n/a	0 to 212	20	n/a
3	Initial liquefaction	50	250	207	1.1	47 ^a	20	Vent line
3a	Neon loop heater variations	50	250	207	^a 1.1	7 to 57 in 10-W increments	20	Vent line
4	Neon loop flow variations	50	250	207	^a 1.1	47	15, 17.5, 20, 22.5	Vent line
5	Effect of dip tube	50	250	207	^a 1.1	47	20	Dip tube
5a	Effect of heater settings with dip tube	50	250	207	^a 1.1	7, 17, 37	20	Dip tube

^aNominal value given, but test allowed this variable to respond to all other inputs.

TABLE 7.—CONSTANT LIQUEFACTION TEST MATRIX

Test no.	Test description	Fill level, %	Cold wall temperature, K	Initial tank pressure, kPa	GO ₂ flow, kg/h	Heaters, W	Neon loop fan speed, krpm	GO ₂ injection method
6	High fill level	90	250	207	^a 1.1	47	20	Vent line and dip tube
7	Medium fill level	50	250	207	^a 1.1	47	20	Vent line
8	Low fill, medium pressure	<10	250	207	^a 1.1	47	20	Vent line
9	Low fill, high pressure	<10	250	276	^a 1.1	47	20	Vent line
10	Low fill, low pressure	<10	250	138	^a 1.1	47	20	Vent line
11	Constant flow, nominal	<10	250	^a 207	1.1	47	20	Vent line
12	Constant flow, low	<10	250	^a 207	0.5	47	20	Vent line
13	Constant flow, high	<10	250	^a 207	2.2	47	20	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

TABLE 8.—VARIABLE LIQUEFACTION TEST MATRIX

Test no.	Test description	Fill level, %	Cold wall temperature, K	Initial tank pressure, kPa	GO ₂ flow, kg/h	Heaters, W	Neon loop fan speed, krpm	GO ₂ injection method
26	Set initial conditions	<10	250	207	^a 1.1	47	20	Vent line
27	Variable GO ₂ flow rate	<10	250	^a 207	0.9 to 1.6	47	20	Vent line
28	Set initial conditions	<10	250	207	^a 1.1 ^a	47	20	Vent line
29	Variable cryocooler lift	<10	250	^a 207	1.1	15 to 94.4	20	Vent line
29-2	Variable cryocooler lift	<10	250	^a 207	1.1	0 to 93.5	20	Vent line
30	Set initial conditions	<10	250	207	^a 1.1	47	20	Vent line
31	Variable environmental temperature	<10	225 to 290	^a 207	1.1	47	20	Vent line
32	Set initial conditions	90	250	207	^a 1.1	47	20	Vent line
33	Variable GO ₂ flow rate	90	250	^a 207	0.9 to 1.6	47	20	Vent line and dip tube

^aNominal value given, but test allowed this variable to respond to all other inputs

TABLE 9.—SUPPLEMENTAL LIQUEFACTION TEST MATRIX

Test no.	Test description	Fill level, %	Cold wall temperature, K	Initial tank pressure, kPa	GO ₂ flow, kg/h	Heaters, W	Neon loop fan speed, krpm	GO ₂ injection method
4z 4z-2 4z-3	Neon loop flow variations, control flow	<10 15 90	250	207 ^a	1.1	47	15, 16.25, 17.5, 20	Vent line
6c	Maximum fill level	95 to 100	250	207	^a 1.1	47	20	Vent line
40	Maximum liquefaction rate	0 to 5	250	276	^a 1.6	0	20	Vent line
41	Pressure collapse test	0 to 5	250	276 to 210 ^a	1.1	47	20	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

3.1 Steady-State Criteria

Multiple different steady-state criteria were used during testing. These criteria represent a quasi-steady state as a true steady state is not possible to achieve in cryogenic tank testing, where even something as minute as the fill-level change can cause unsteadiness. The steady-state criteria for the liquefaction testing were different from typical boil-off testing steady-state criteria due to the nature of testing. Two types of liquefaction steady-state criteria were used, depending on the control scheme: constant pressure and constant mass flow. The transient testing also was fundamentally different; although there is no steady state in these tests, stability was determined by the repeatability of the transient response to a transient input.

For all tests, two criteria were used. First, the chamber vacuum pressure had to be less than or equal to 5×10^{-5} T. Also, the chamber shroud temperature was maintained within ± 5 K of the value specified in the test matrix for the 24 h preceding declaration of stability. However, there were exceptions for tests that intentionally changed the chamber shroud temperature (Test 31).

For Test 1, two additional boil-off steady-state criteria were imposed. The tank pressure had to be maintained within ± 1.4 kPa (0.2 psia) over the 4-h period. The vented ullage gas temperature must increase with time (positive slope), indicating that the tank dome is in thermal equilibrium and no longer cooling down. The latter is a criterion that is regularly imposed on boil-off tests within NASA since at least the mid-1990s (Ref. 22).

For tests that were conducted under the constant pressure protocols, the following steady-state criteria were used. First, the tank pressure had to be maintained within 1.7 kPa (0.25 psia) of the setpoint over a 4-h test period. Also, the tank pressure had to vary by less than ± 1 percent over the same 4-h period. Finally, the bulk liquid temperature had to remain within ± 1 K of average over 4-h period (on all liquid sensors individually).

For tests that were conducted under the constant mass flow protocols, the following steady-state criteria were used over a single 4-h period. The average mass flow rate had to be within 0.25 slpm of setpoint. The mass flow had to vary by less than ± 2 percent. The bulk liquid temperatures had to be within ± 1 K of average (on all liquid sensors individually).

For transient tests (i.e., those in Table 8) the main criteria for successful test was stability between different cycles of response. This criterion was that three consecutive cycles had to have within 10 percent response (minimum and maximum peaks, but not rates of change) on pressures.

4.0 Test Data and Operations

4.1 LO₂ Nominal Performance Determination

Preliminary checkouts of system operations with nitrogen prompted confidence that the SMiRF and the integrated test article were ready for testing with oxygen. The first five tests and subsequent subtests progressively investigated the test system's performance with oxygen. These initial tests served as a basis for determining which parameters can be considered nominal, given the tank's response to the environment, and were instrumental in guiding operational decisions related to the constant and transient liquefaction tests. Nominally, the tank fill level was maintained near 50 percent full while exposed to an environmental temperature maintained within ± 5 K of 250 K for these initial oxygen tests. The following tests that maintained a constant tank pressure were held at ± 1.4 kPa (0.20 psia) at 207 kPa (30 psia). The saturation temperature for oxygen at 207 kPa is ~ 97.62 K. Later operational tests investigated the variance of these nominal parameters.

Test 1, the boil-off test, sought to characterize the parasitic heat loads nominally imposed onto the tank (Table 10). During this test, the forced convection neon loop was stagnant (the cryofan was off) but pressurized, GO₂ was not fed into the tank, and the tank vent was allowed to open freely as oxygen boiled off due to heat leak from the environment. The boil-off rate was measured by flow meter XO726. Flow meter XO727 was parallel to XO726 and would take over for higher flow rates. Figure 24, Figure 25, and Figure 26 capture Test 1's tank pressure, mass flow rates, and internal temperatures, respectively. The slight step function around hour 138.25 seen on the diode rake's temperature outputs are from EMI from the test facility lights. Section 4.2 discusses more about EMI issues experienced throughout testing.

TABLE 10.—BOIL-OFF TEST MATRIX

Test number 1	
Test description	Boil-off test
Fill level, %	50
Cold wall temperature, K	250
Initial tank pressure, kPa	207
GO ₂ flow, kg/h	n/a
Heaters, W	n/a
Neon loop fan speed, krpm	n/a
GO ₂ injection method	n/a

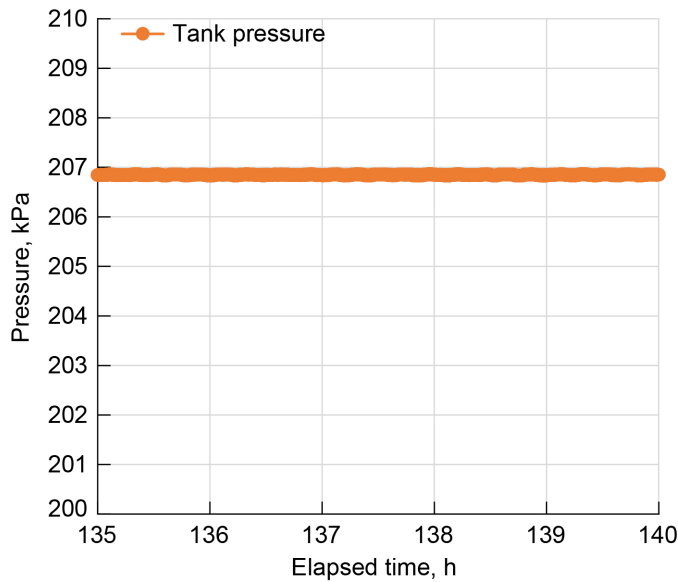


Figure 24.—Tank pressure for Test 1.

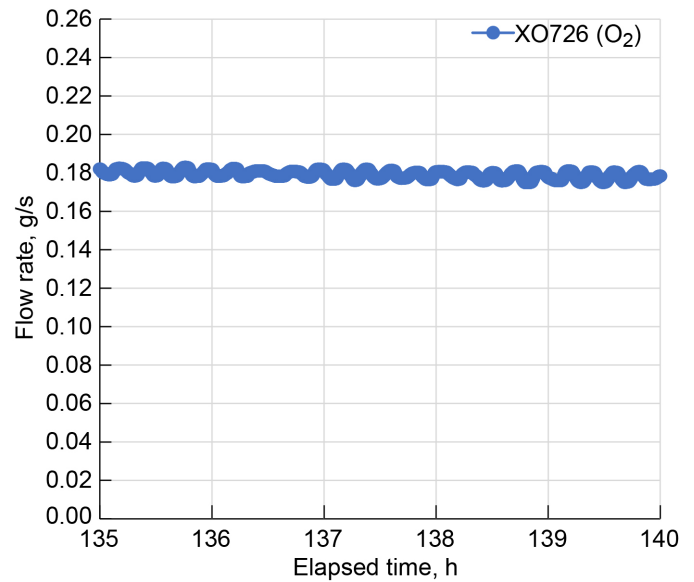


Figure 25.—Mass flow rates for Test 1.

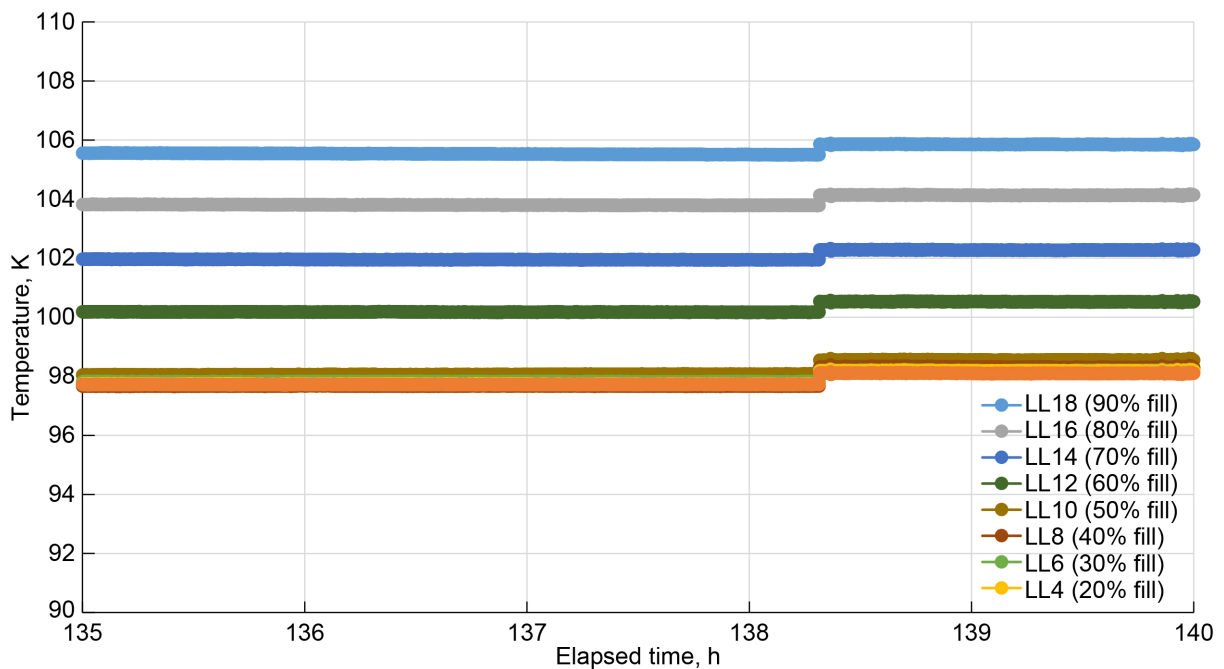


Figure 26.—Internal temperatures for Test 1.

An autogenous pressurization test, Test 1a, followed the boil-off test (Table 11). High pressure GO₂ near 300 K was introduced through the upper tank dome into the ullage space at a rate of 1.1 kg/h (0.30 g/s). The tank was around 50 percent full of LO₂. The only additional change from Test 1 was locking up the tank vent path to allow the tank to build pressure because of the incoming GO₂ mass flow. The tank was pressurized from 207 to 276 kPa (30 to 40 psia) over a 3.25-h period. This equated to a

pressurization rate of 21.23 kPa/h (3.08 psia/h). In Figure 27, the autogenous tank pressure variation over Test 1a is shown. The tank pressure decreased slightly once the GO₂ flow was terminated. Figure 28 tracks the mass flow rate of GO₂ introduced through the ullage. The internal temperatures of the oxygen in the tank increased with the tank pressure, as shown in Figure 29. Visually, the trend of the internal fluid temperatures increasing showed the saturation temperature adjusting with pressure.

TABLE 11.—AUTOGENOUS PRESSURIZATION TEST MATRIX

Test no.	Test description	Fill level, %	Cold wall temperature, K	Initial tank pressure, kPa	GO ₂ flow, kg/h	Heaters, W	Neon loop fan speed, krpm	GO ₂ injection method
1	Autogenous pressurization test	50	250	207 to 276	^a 1.1	n/a	n/a	Vent line
1a-2 ^a	Autogenous pressurization test	15	250	185 to 253	1.1	n/a	n/a	Vent line

^aA second run of Test 1a.

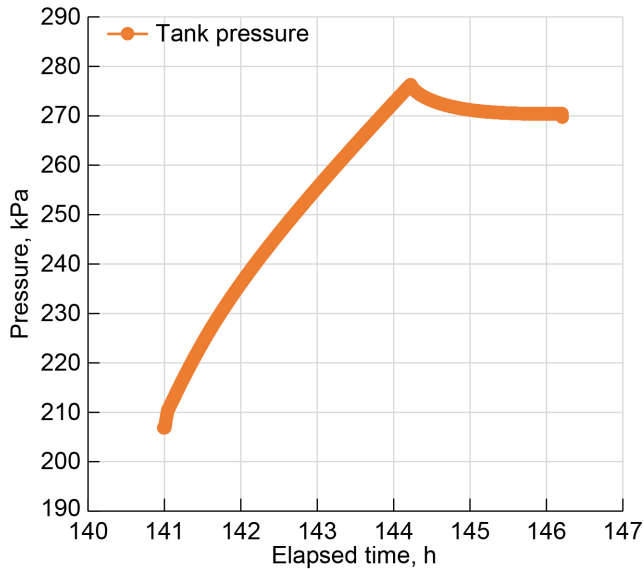


Figure 27.—Tank pressure for Test 1a.

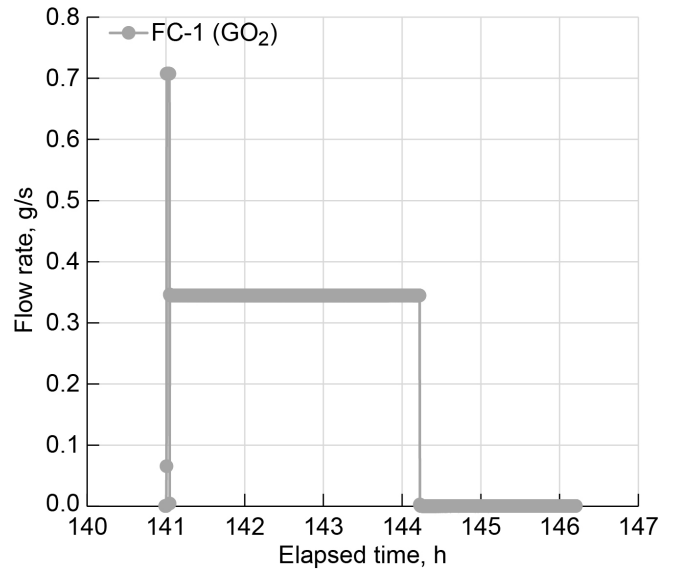


Figure 28.—Mass flow rates for Test 1a.

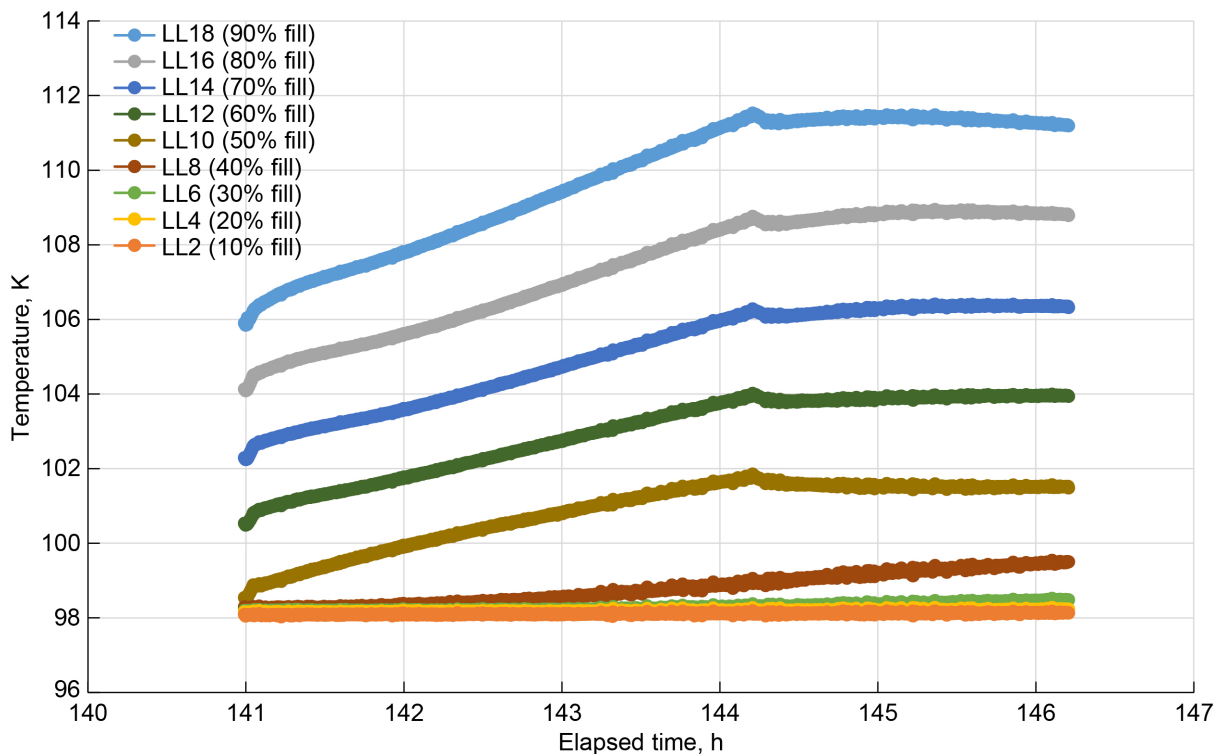


Figure 29.—Internal temperatures for Test 1a.

Towards the end of testing, enough time was available to perform an additional autogenous pressurization test. The test conditions for Test 1a-2 matched that of Test 1a. No external heaters, no use of the cryocooler, and a fixed GO_2 mass flow rate into ullage of 1.1 kg/h (0.30 g/s). However, Test 1a-2 was run at a fill level of 15 percent with an initial tank pressure of 184 kPa (26.7 psia). As shown in Figure 30, the tank was pressurized

to 253 kPa (36.7 psia) over a 6.5-h period. Test 1a-2 had an autogenous pressurization rate of 10.62 kPa/h (1.54 psia/h). The constant GO_2 flow that pressurized the tank is charted in Figure 31. Figure 32 contains the internal fluid temperatures from the diode rake during Test 1a-2. Greater stratification within the tank was present in Test 1a-2 when compared to Test 1a due to the lower fill level of LO_2 .

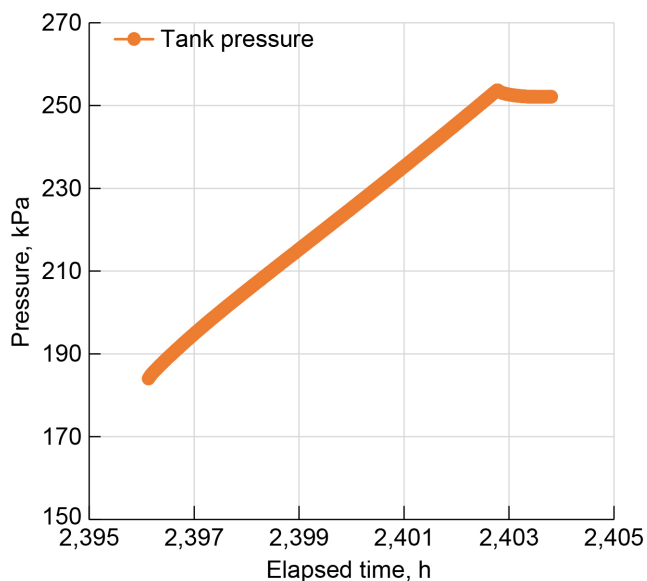


Figure 30.—Tank pressure for Test 1a-2.

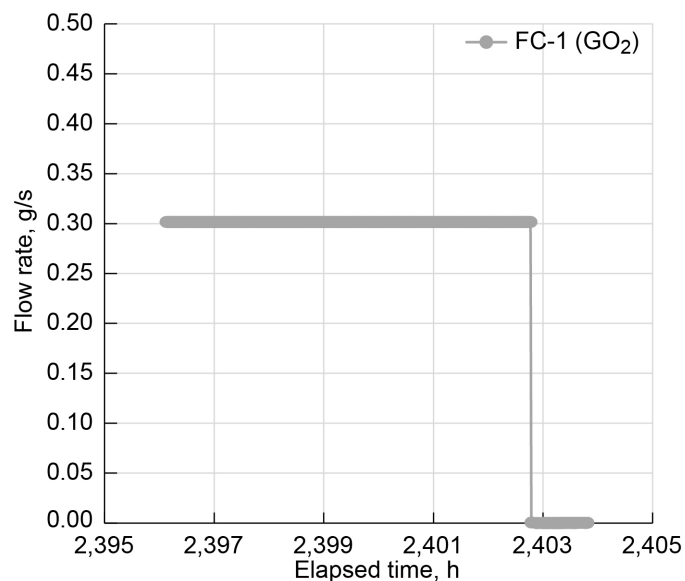


Figure 31.—Mass flow rates for Test 1a-2.

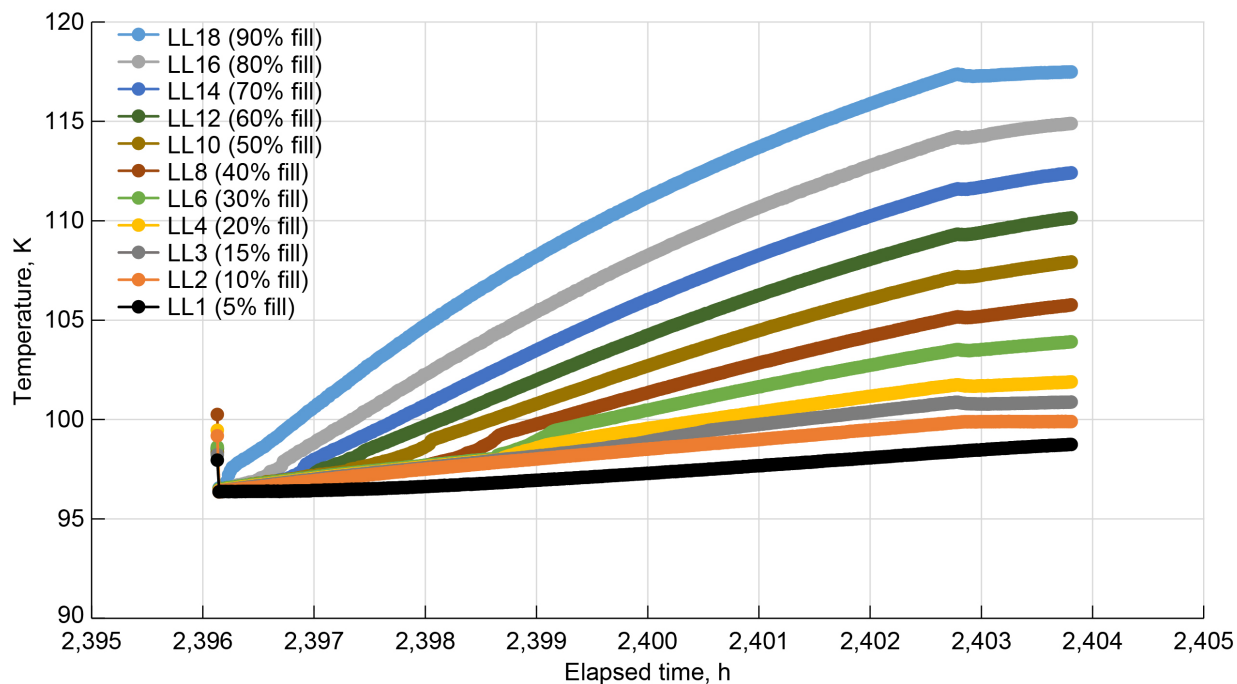


Figure 32.—Internal temperatures for Test 1a-2.

Test 2 captured the first zero boil-off (ZBO) test with LO₂ in the Prototype tank (see Table 12). To achieve ZBO, the test required active heat removal via the forced convection neon loop and heat rejection with the SMiRF integrated industrial cryocooler. The same initial conditions from Test 1 were recalled for Test 2 with the addition of the neon loop cryofan operating at 20 krpm to maintain an average neon mass flow rate of 8.83 g/s. It was discovered during Test 2 that the cryofan would shut off when making large changes to the fan speed, so 20 krpm became the nominal, operable fan speed by default. More details on the cryofan issue are highlighted in Section 5.6. Initially, tank pressure was controlled to 207 kPa (30 psia) by allowing the mass flow rate of GO₂ fed into the tank vary to maintain pressure via a flow controller. The restraint of the cryofan speed resulted in a net excess of cooling on the tank that required a continued flow of GO₂ to maintain tank pressure. ZBO was achieved by progressively increasing the heat load on the tank and neon loop with heaters until the oxygen flow went to zero. As more heat was added to the system, the thermal balance leveled out for ZBO to occur with the addition of 154 W of heat (90 W on the tank and 44 W on the neon loop) at ~191 h. Figure 33 shows the tank pressure remains within the steady-state criteria. Figure 34 contains the mass flow rates associated with Test 2. The neon flow stays relatively constant. FC-1 depicts the decrease in incoming GO₂ mass flow that eventually becomes steady at zero as a response to maintaining constant tank pressure. Figure 35 shows the oxygen temperatures inside the tank, which met the steady state criteria during the testing.

TABLE 12.—ZBO TEST MATRIX	
Test 2	
Test description.....	Zero boil-off
Fill level, %.....	50
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	207
GO ₂ flow, kg/h.....	n/a
Heaters, W.....	155
Neon loop fan speed, krpm.....	20
GO ₂ injection method.....	Vent line

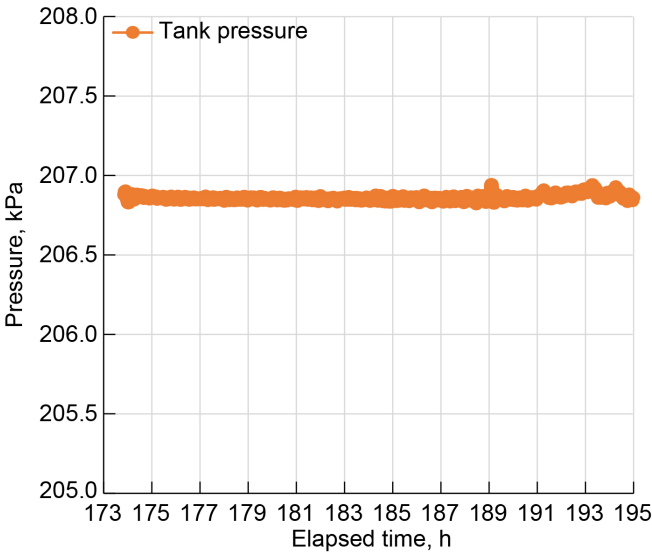


Figure 33.—Tank pressure for Test 2.

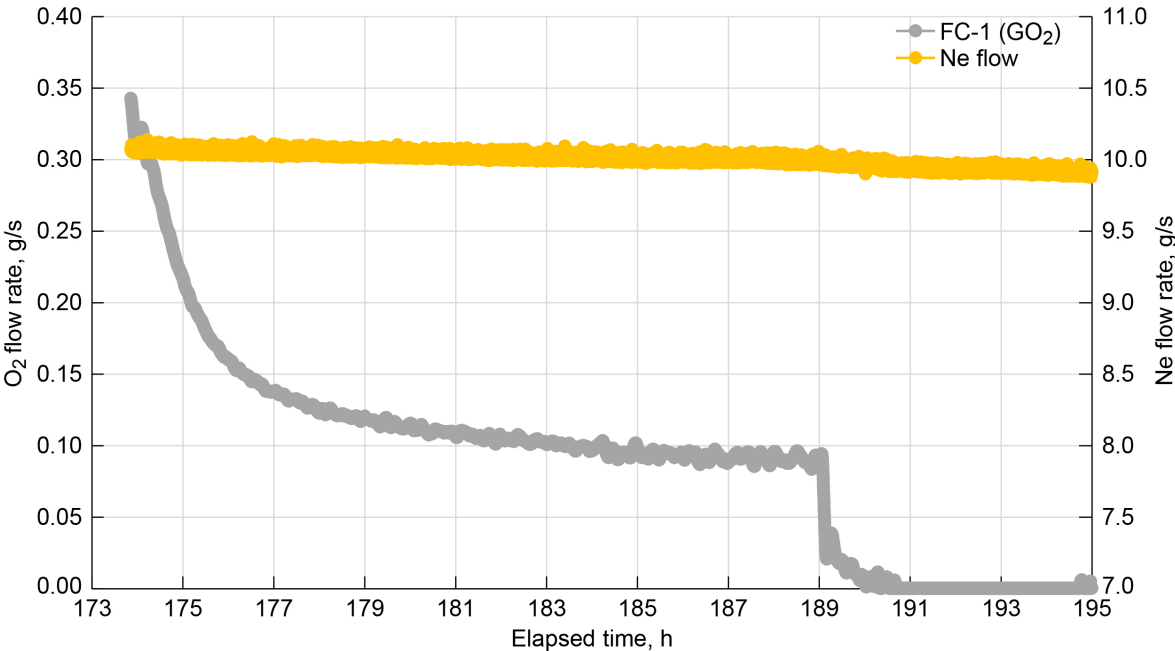


Figure 34.—Mass flow rates for Test 2.

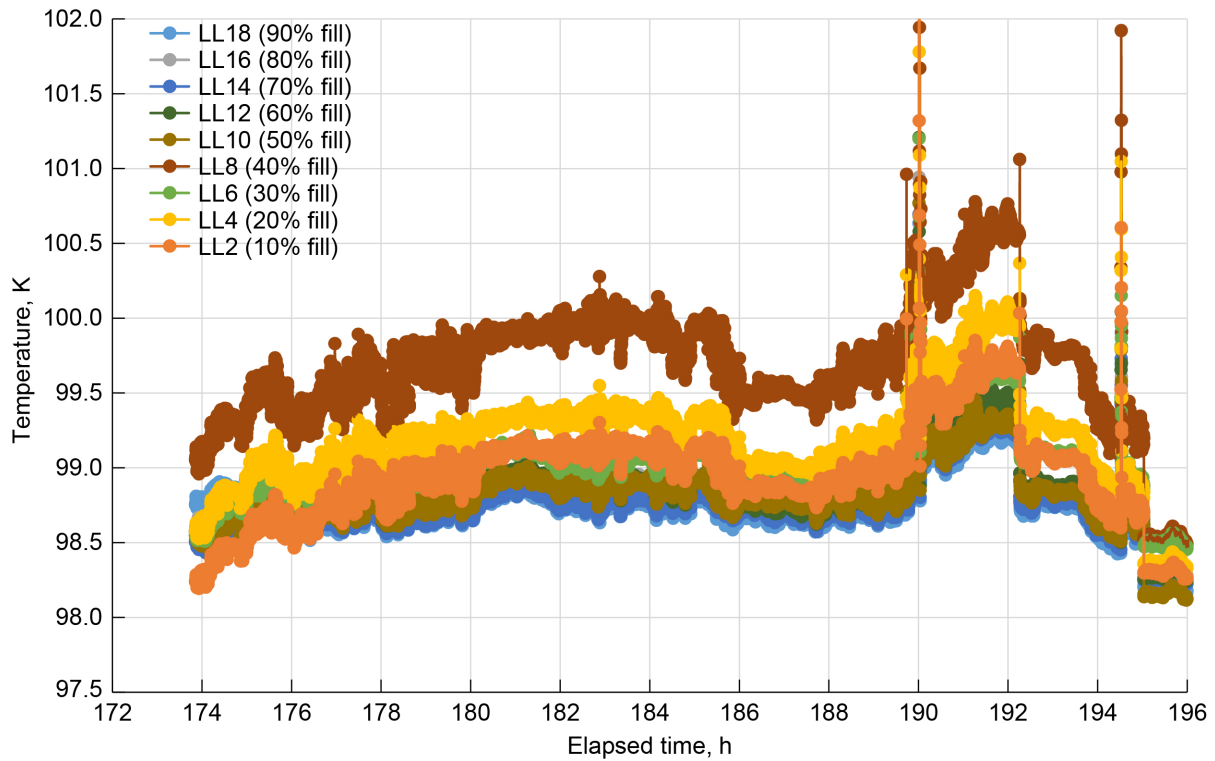


Figure 35.—Internal temperatures for Test 2.

TABLE 13.—TANK ZERO BOIL-OFF, PRESSURIZATION, AND DEPRESSURIZATION TEST MATRIX

Test no.	Test description	Fill level, %	Cold wall temperature, K	Initial tank pressure, kPa	GO ₂ flow, kg/h	Heaters, W	Neon loop fan speed, krpm	GO ₂ injection method
2a	ZBO	50	250	207	n/a	148.4	20	n/a
2b	Depressurization	50	250	207	n/a	0	20	n/a
2c	Pressurization	50	250	182	n/a	202.4	20	n/a
2d	ZBO	50	250	238	n/a	147	20	n/a
2e	Depressurization	50	250	236	n/a	47	20	n/a
2f	ZBO (neon heater controlled)	50	250	172	n/a	130-137	20	n/a
2g	Pressurization	50	250	176	n/a	175	20	n/a

During the constant liquefaction tests, the GO₂ flow controller failed and was out of service for at least 337 h. In an effort to maximize the test time available at SMiRF, additional tank pressure response tests were performed to further characterize the system's liquefaction operations while the GO₂ flow controller issue was being resolved. This test period can be broken down into three distinct sections for further characterization of the test system. Test 2a applied the same test conditions used during the ZBO test performed in Test 2 (Table 13). Test 2a demonstrated repeatability of the ZBO conditions found in Test 2. It also demonstrated the tank pressure, at 206.85 kPa (~30 psia), could be maintained relatively constant without the need for additional pressurization from GO₂ flow or depressurization from venting. Test 2x (which encompasses Tests 2a through 2g) covers a period where the tank and neon loop heater powers were varied multiple times to observe the tank's pressure response. Test 2x also demonstrated ZBO at three additional tank pressures and that tank pressure could be maintained with active heater control of the neon loop heater. Test 2g captured the tank pressurization rate with a singular variation of both the tank and neon loop heaters while maintaining the same total heater input into the system. These series of test were all performed near a 50 percent fill level and the previously mentioned EMI is noticeable on the diode LL8 in the following internal fluid temperatures figures.

The steady state ZBO period for Test 2a was considered between Hours 785 and 812. The tank pressure, mass flow rates,

internal fluid temperatures, and heater input powers for the repeat ZBO test, Test 2a, can be found in Figure 36, Figure 37, Figure 38, and Figure 39. Note how, near the start of Test 2a, the neon heater power in Figure 39 was incrementally lowered until the boil-off flow in Figure 37 began to trail off with little to no mass flow.

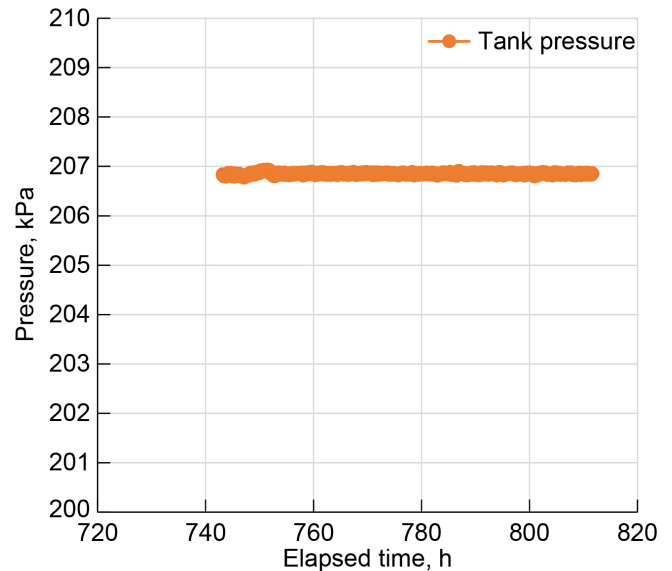


Figure 36.—Tank pressure for Test 2a.

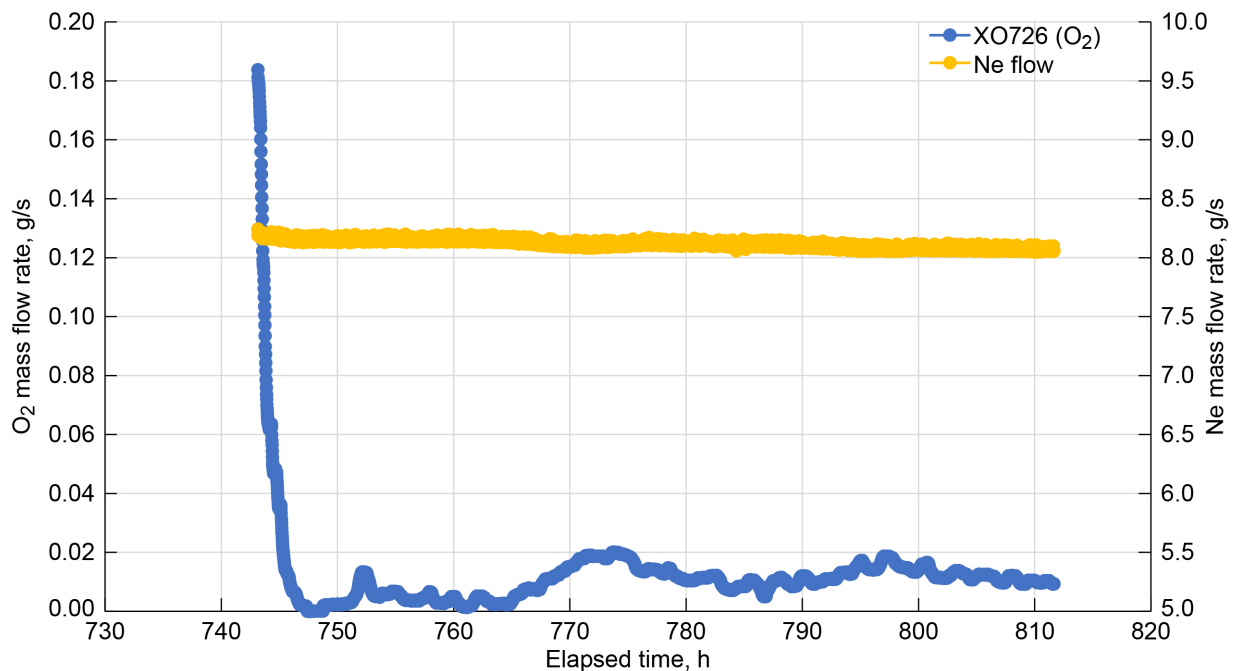


Figure 37.—Mass flow rates for Test 2a.

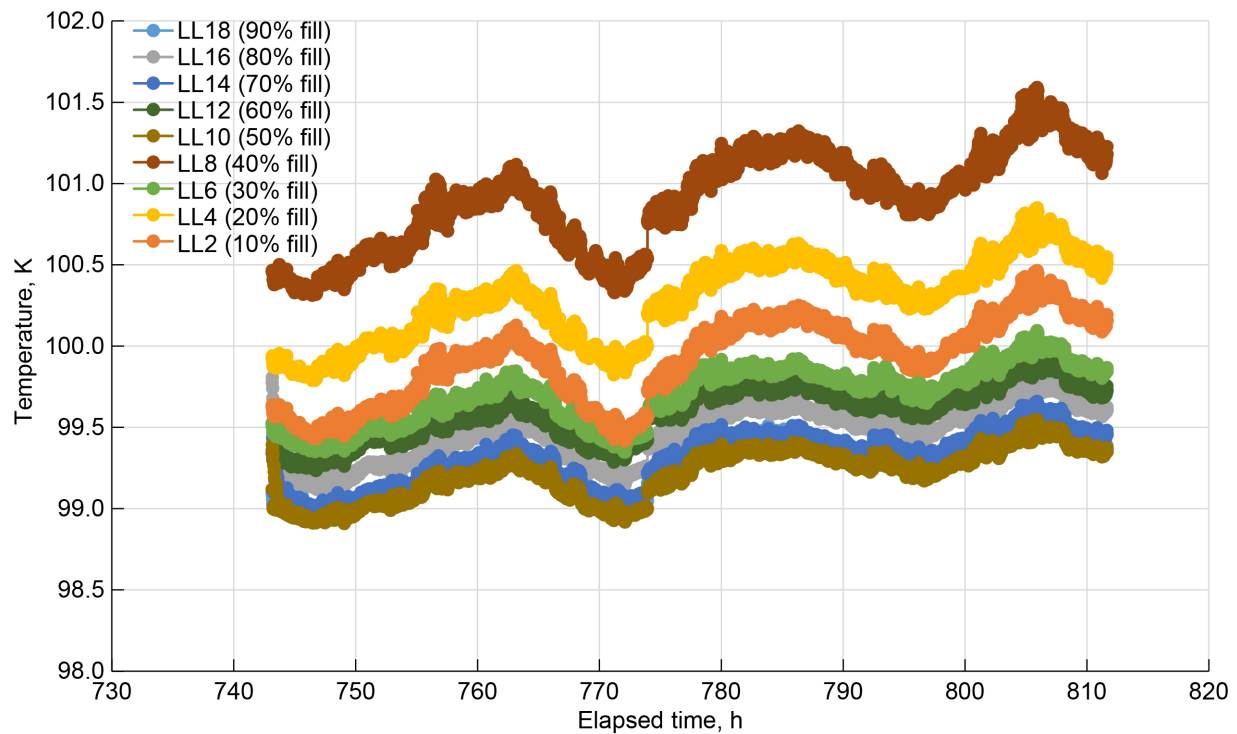


Figure 38.—Internal temperatures for Test 2a.

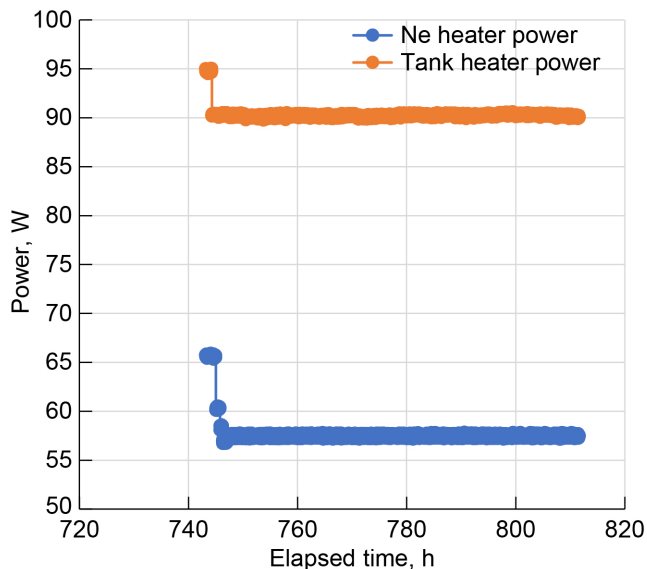


Figure 39.—Tank and neon loop heater power for Test 2a.

As noted previously, the tank and neon heaters were intentionally varied throughout Test 2x to characterize different pressurization and depressurization rates. Between variations in heater power input, three additional ZBO states were demonstrated at tank pressures of 183 kPa (26.5 psia), 238 kPa (34.5 psia), and 176 kPa (25.5 psia). Each period and its respective heater input power variation is tabulated in Table 14. Note that the constant pressure periods occurred when the tank was maintained in a ZBO state. The tank pressure fluctuations are in Figure 40. The first two ZBO tests maintained tank pressure with no boil off by adding a total of 147 W of heat into the system. The third ZBO test was achieved through controlling the tank pressure by allowing the neon loop heater input power to vary while the tank heater power was held constant at 120 W. This was the test system's first demonstration of tank pressure control using the neon loop heater. The neon loop heater's response to tank pressure was evident between Hours 911 and 980 in the heater input power plot of Figure 41. A similar variation of saturated internal fluid temperatures in response to the tank pressure changes is plotted in Figure 42. Figure 43 shows the neon mass flow was consistent throughout the test and there was no measured boil-off mass flow through the vent.

TABLE 14.—TANK AND NEON LOOP HEATER POWER FOR TEST 2X

Test no.	Tank condition	Start time, h	End time, h	Neon heater power, W	Tank heater power, W	Total heater power, W
2b	Depressurization	813.25	818.75	0	0	0
	ZBO	818.75	836.11	57	90	147
2c	Pressurization	836.11	866.87	65.5	137	202.5
2d	ZBO	866.87	884.17	57	90	147
2e	Depressurization	884.17	908.15	27	20	47
	Pressurization	908.15	911.56	65	100	165
2f	ZBO (neon heater controlled)	911.56	980	10 to 17	120	130 to 137
2g	Pressurization	980.7	1070.2	45 / 60	130 / 115	175

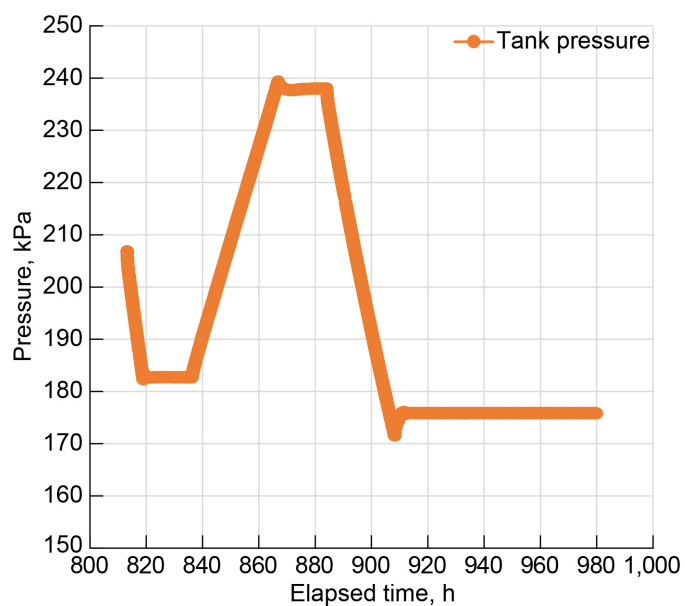


Figure 40.—Tank pressure for Test 2x.

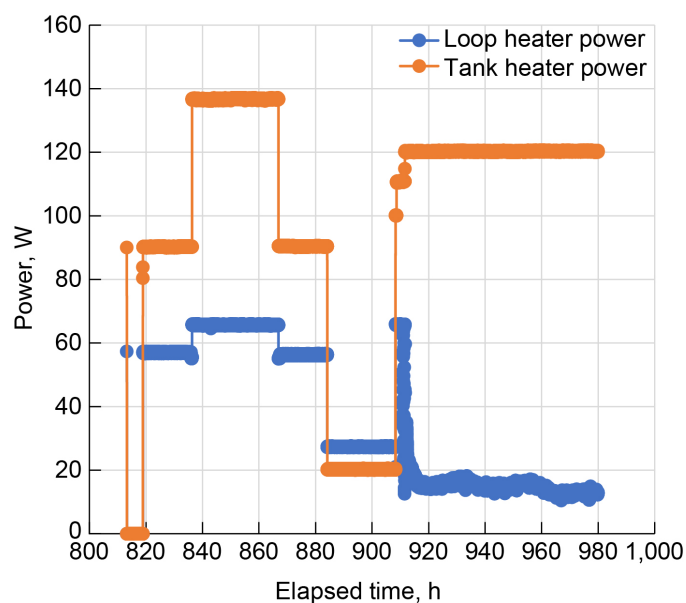


Figure 41.—Tank and neon loop heater power for Test 2x.

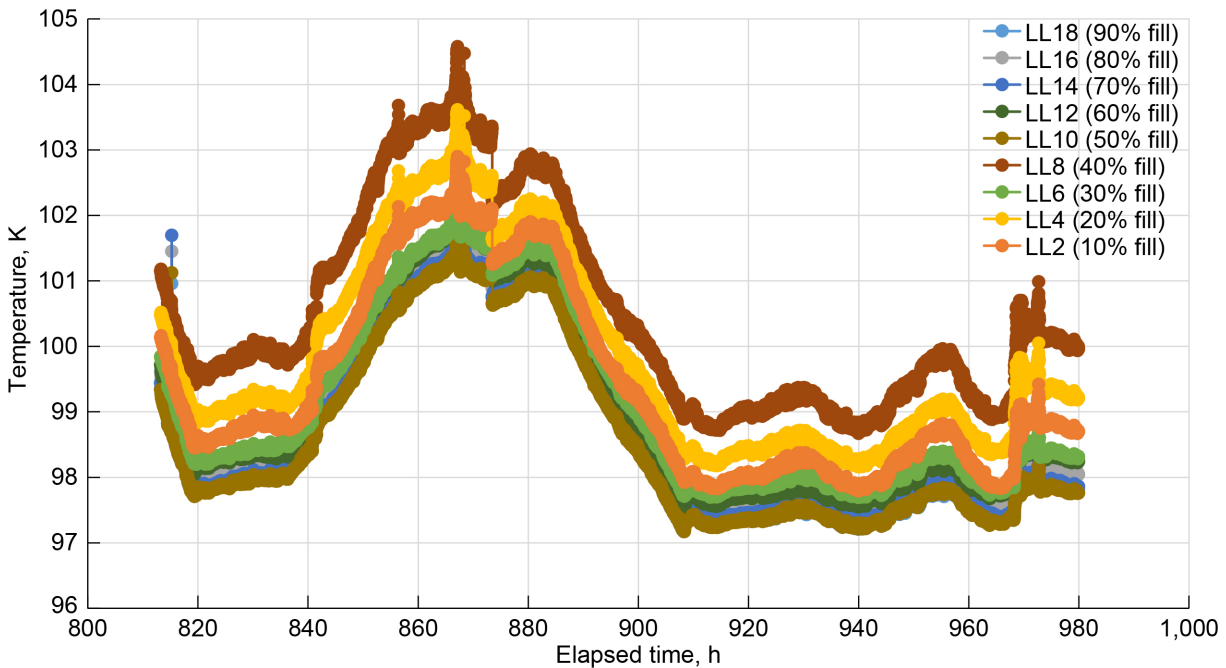


Figure 42.—Internal temperatures for Test 2x.

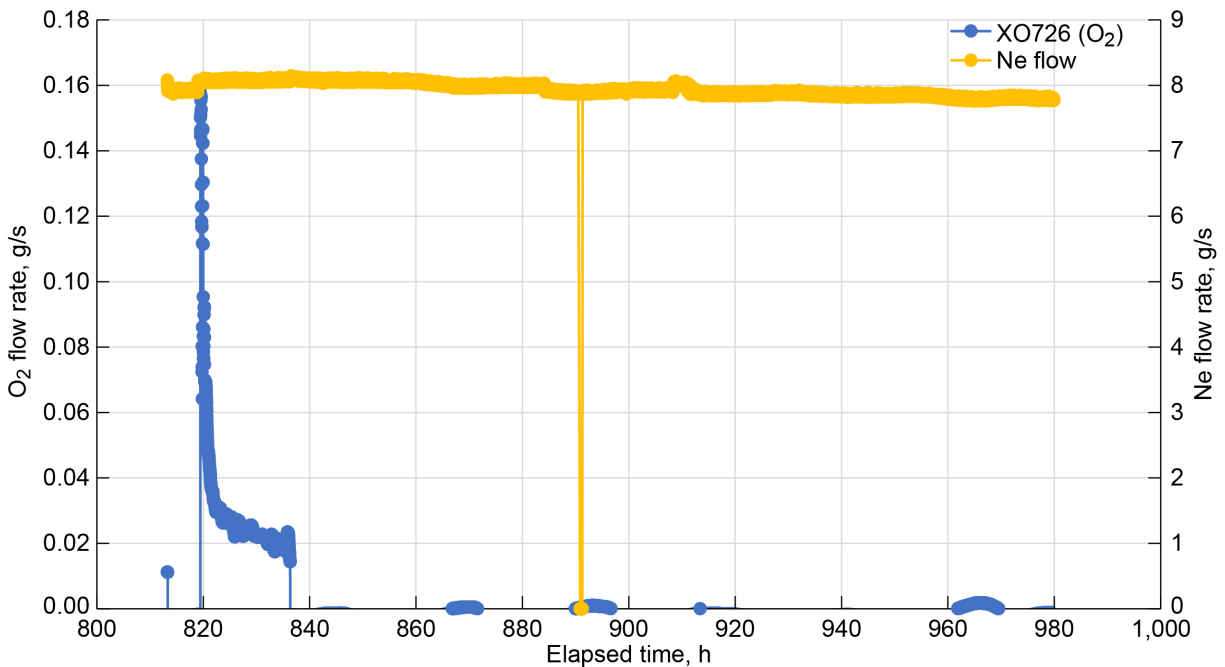


Figure 43.—Mass flow rates for Test 2x.

Test 2g was another tank pressurization test performed before the GO_2 flow controller was replaced and ready to continue constant liquefaction testing. The tank pressure increased from applying heater heat loads greater than the nominal heat input power values onto the closed-off tank. This varies from the pressurization test performed in Test 1a, which pressurized by introducing a GO_2 mass flow into the closed-off tank. The tank pressure

in Test 2g rose from 176 kPa (25.5 psia) to 280 kPa (40 psia) as depicted in Figure 44. When the heater input power was reduced after reaching a tank pressure of 280 kPa (40 psia), the tank pressure decreased slightly. This was also the case in Test 1a when the GO_2 flow into the tank was cut off. Figure 45 contains the mass flow rates associated with Test 2g; Figure 46 shows that the internal fluid temperatures at saturation increased with tank pressure.

This was also witnessed in Test 1a. Another notable finding from Test 2g was that the test system's pressure response does not appear to depend on whether heat was added through the tank heater or neon heater for the same total heat load. Figure 47 has the tank and neon loop heater powers from Test 2g. Throughout Test 2g, the total heat load imposed on the system was 175 W.

Initially, the tank heater was set to 130 W and the neon loop heater was set to 45 W. Around Hour 1,008, the tank heater was lowered to 115 W and the neon loop heater was increased to 60 W. The pressurization rate remained fairly constant even with this change. Further discussion of the tank pressure's response to the heaters can be found in Section 5.7.

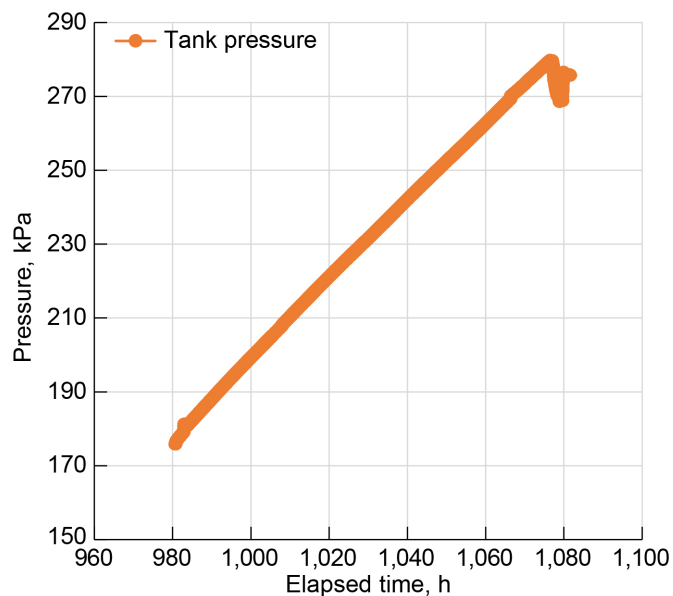


Figure 44.—Tank pressure for Test 2g.

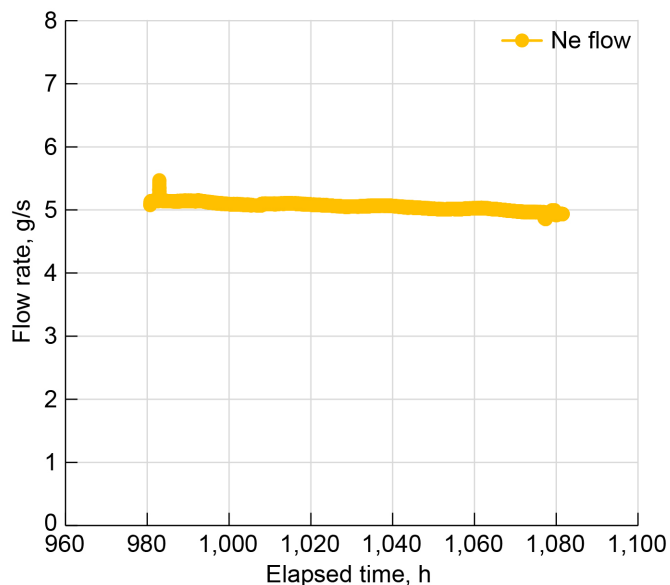


Figure 45.—Mass flow rates for Test 2g.

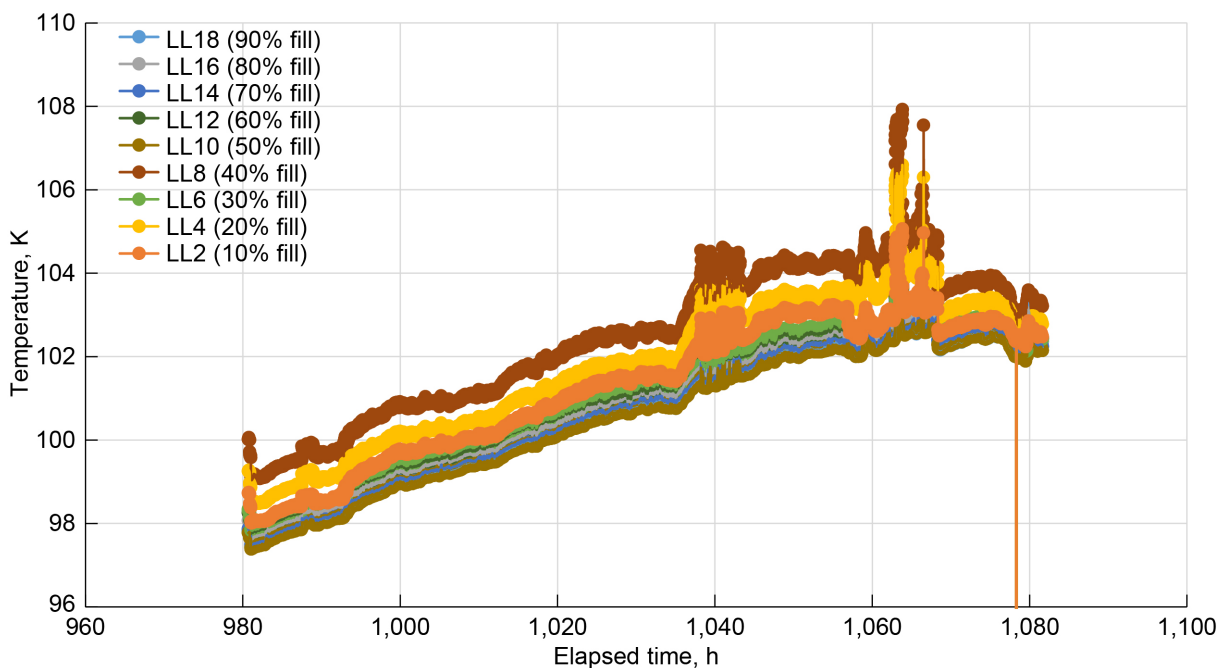


Figure 46.—Internal temperatures for Test 2g.

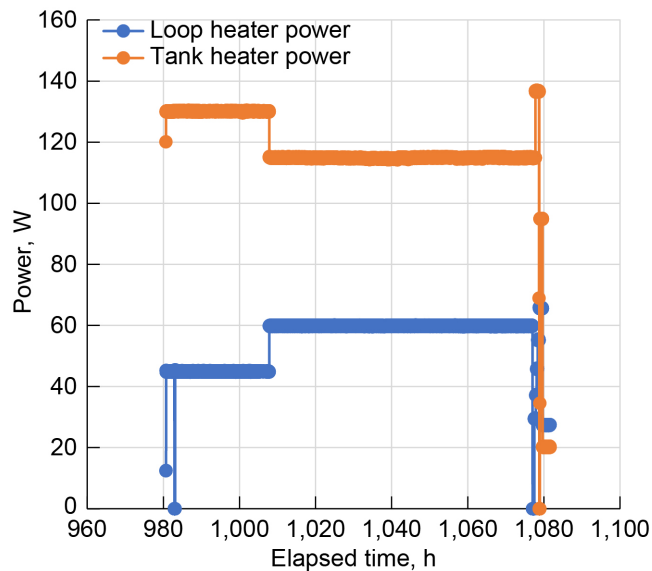


Figure 47.—Tank and neon loop heater power for Test 2g.

The initial oxygen liquefaction demonstration was conducted during Test 3 (Table 15). The GO₂ flow into the tank through the ullage was held constant at 0.31 g/s (1.1 kg/h) and the cryofan speed was operated at 20 krpm to circulate neon at a rate of 8.81 g/s (note that this rate has been adjusted per Section 5.0 compared to what is plotted). It was found that imposing a 20 W heat load onto the tank surface and a 27 W heat load onto the neon loop thermally balanced the test system to maintain a constant tank pressure of 207 kPa (30 psia) during oxygen liquefaction. These heat loads became the nominal heater powers used for the liquefaction tests. Figure 48 to Figure 50 contain the tank pressure, mass flow rates, and internal temperatures from the oxygen liquefaction in Test 3.

TABLE 15.—INITIAL LIQUEFACTION TEST MATRIX

Test 3	
Test description.....	Autogenous pressurization test
Fill level, %.....	50
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	207
GO ₂ flow, kg/h.....	1.1
Heaters, W	^a 47
Neon loop fan speed, krpm	2
GO ₂ injection method.....	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

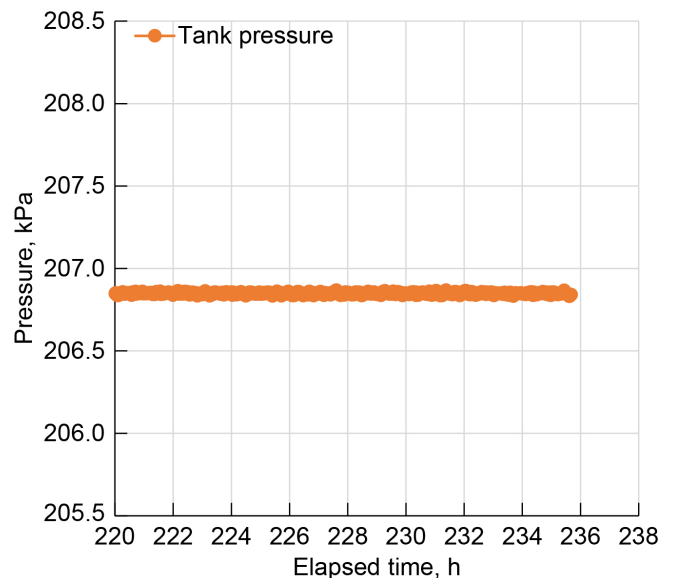


Figure 48.—Tank pressure for Test 3.

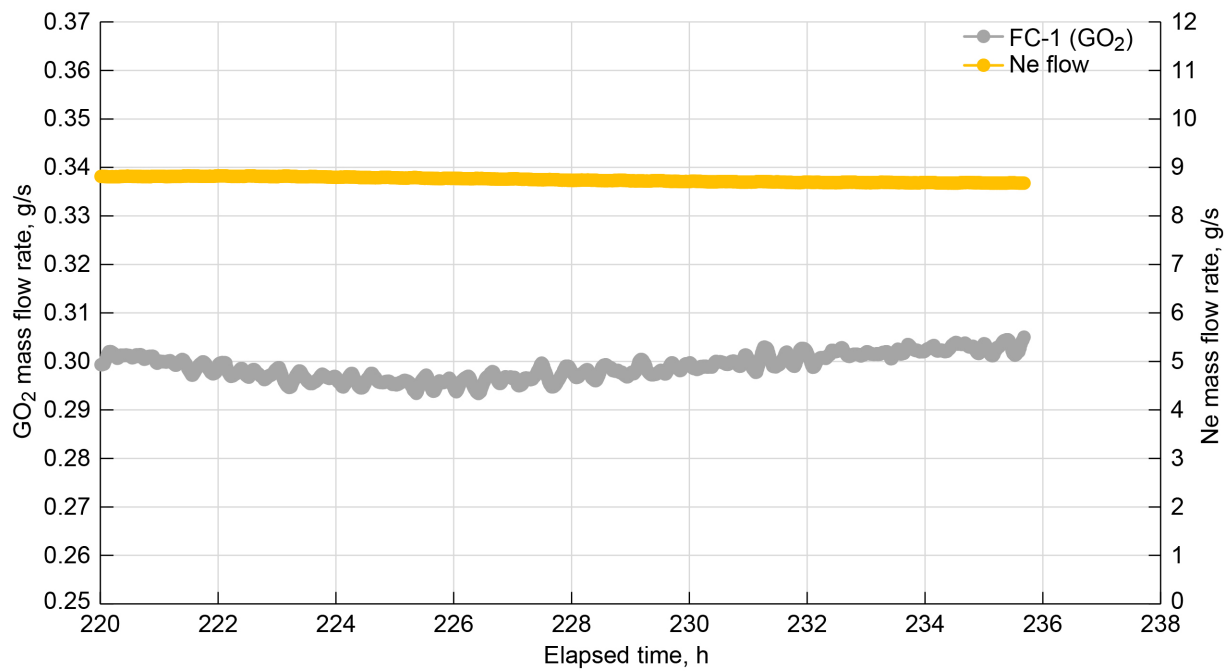


Figure 49.—Mass flow rates for Test 3.

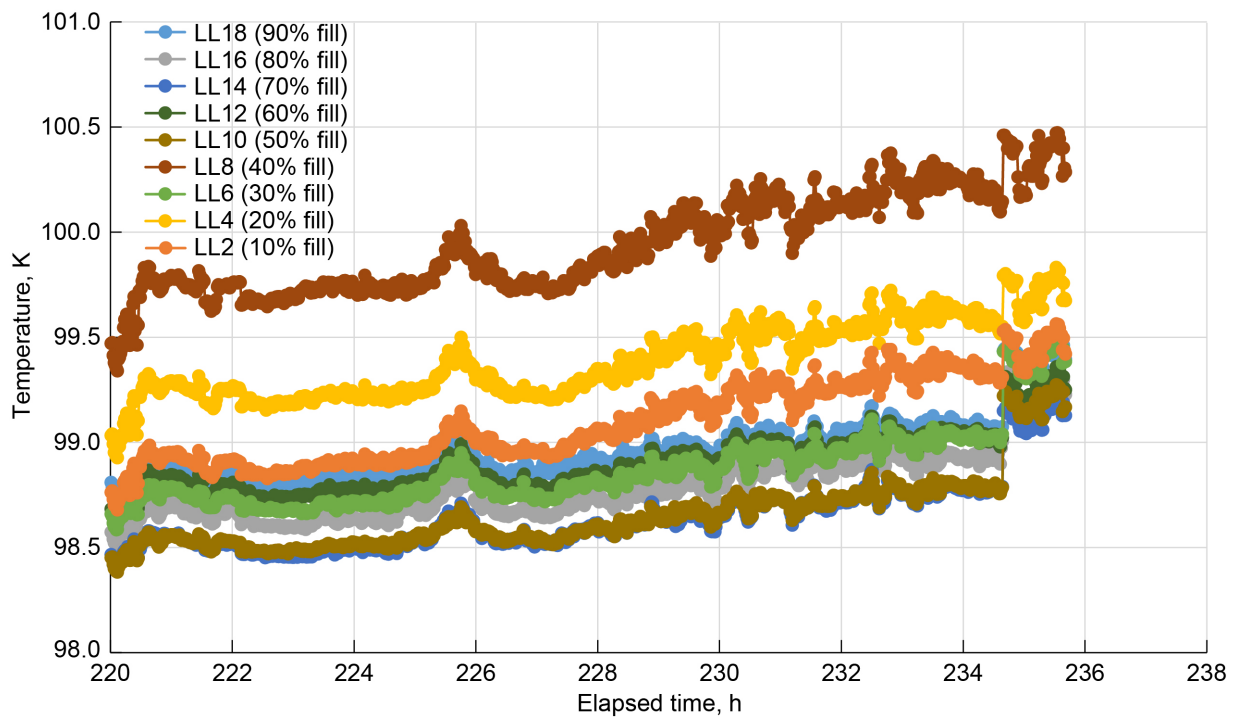


Figure 50.—Internal temperatures for Test 3.

Test 3a investigated how the liquefaction rate demonstrated in Test 3 would respond to variations of the heat load associated with the neon loop heater while maintaining a constant tank pressure (Table 16). All variables from Test 3 were held constant in Test 3a except the neon loop heater power. The neon loop heater heat load was changed from 27 W initially to 47, 57, 37, 17, and 7 W. Each heater setting was run for 1.5 to 2 h to allow the response of the liquefaction rate to stabilize. Figure 51 shows the essentially constant tank pressure and some slight pressure transients from each initial change of the neon loop heater power. Figure 52 has the mass flow rates from Test 3a. The liquefaction rate response to the heater changes is visible with the GO₂ mass flow rate (FC-1). Figure 53 contains the tank internal temperatures and the variations in neon loop heater power are in Figure 54.

TABLE 16.—NEON LOOP HEATER VARIATIONS
LIQUEFACTION TEST MATRIX

Test 3a	
Test description	Neon loop heater variations
Fill level, %	50
Cold wall temperature, K	250
Initial tank pressure, kPa	207
GO ₂ flow, kg/h	^a 1.1
Heaters, W	7 to 57 in 10-W increments
Neon loop fan speed, krpm	20
GO ₂ injection method	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

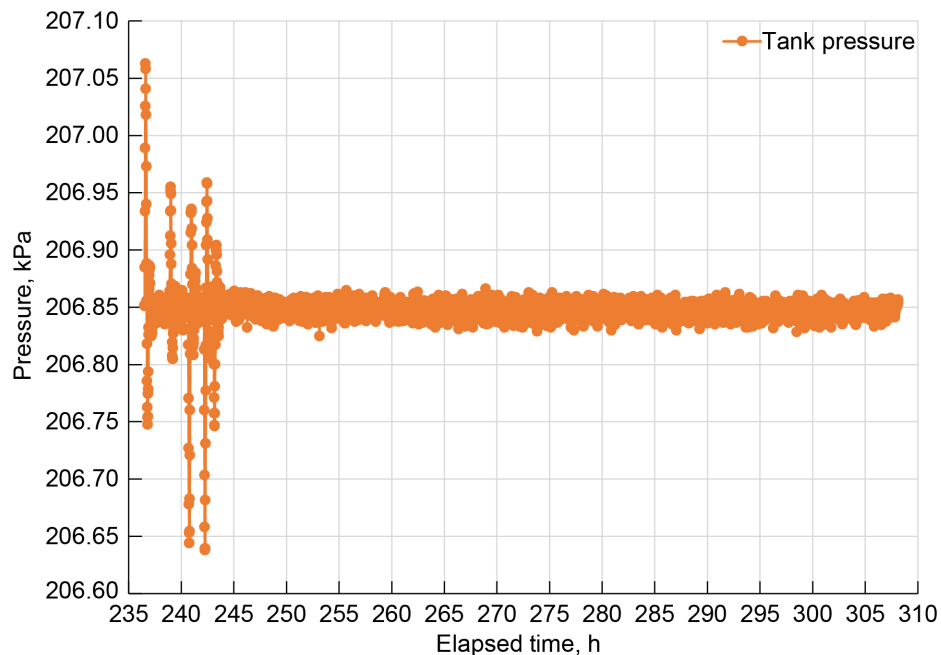


Figure 51.—Tank pressure for Test 3a.

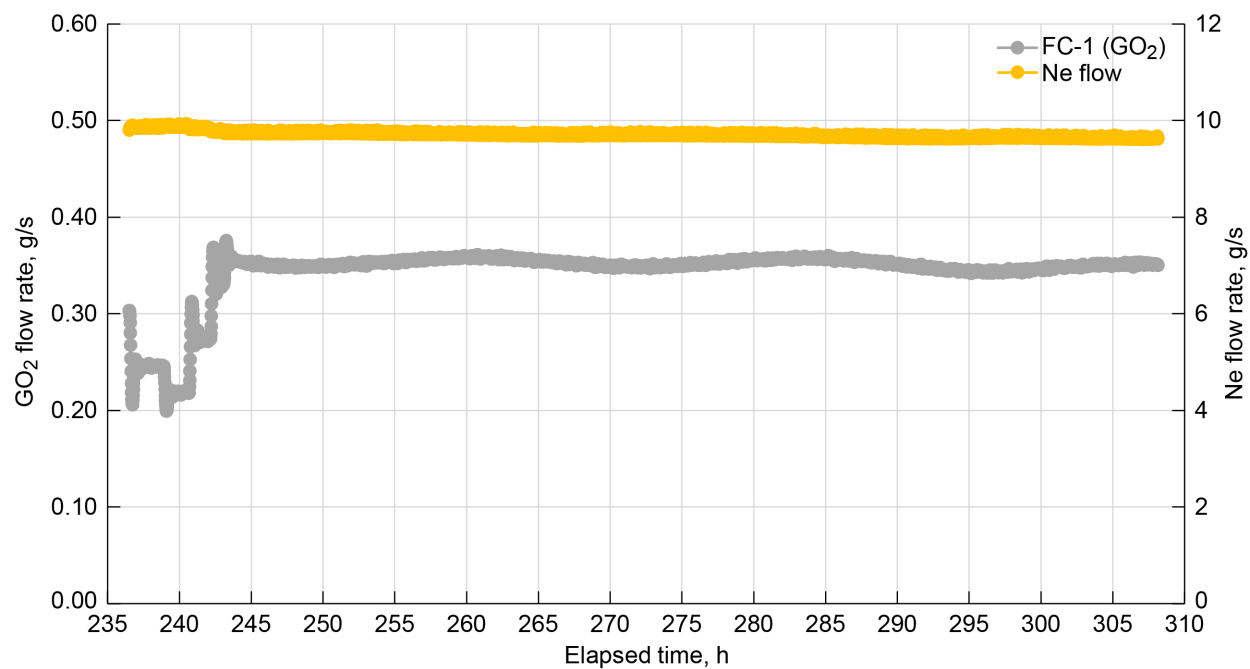


Figure 52.—Mass flow rates for Test 3a.

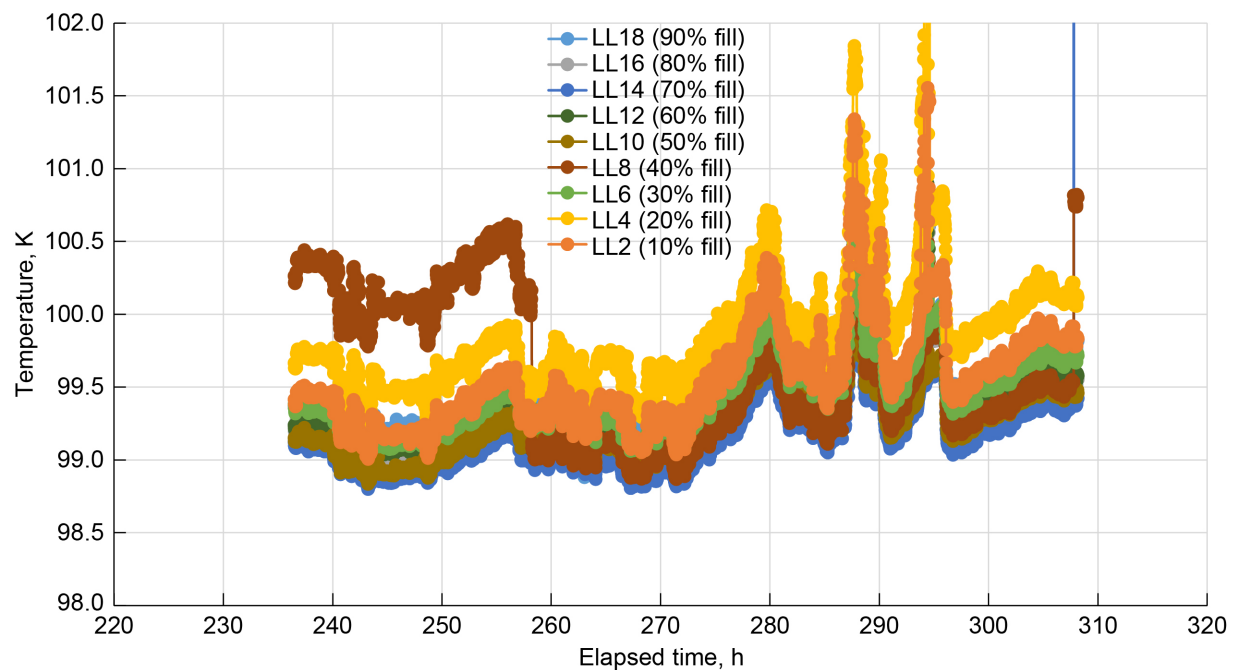


Figure 53.—Internal temperatures for Test 3a.

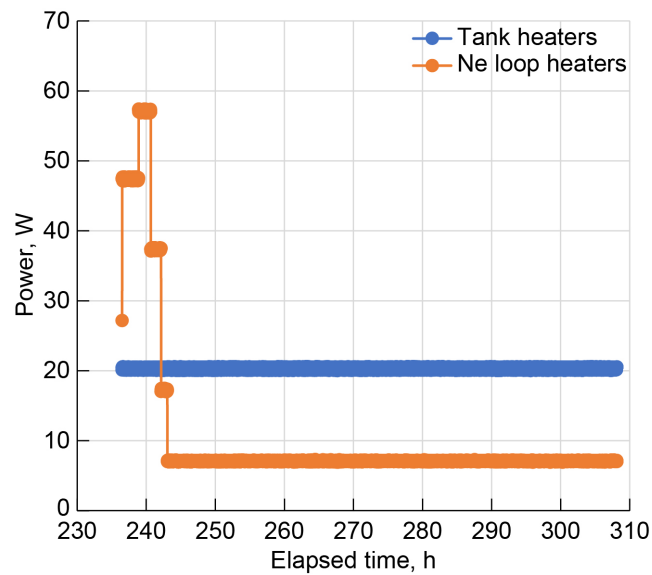


Figure 54.—Tank and neon loop heater power for Test 3a.

Further investigation of the cryofan speed limitations indicated the cryofan could handle smaller variations of fan speed at or slower than 22.5 krpm. Operated at the nominal constant liquefaction conditions detailed in Test 3, the cryofan speed was varied to see how the neon mass flow rate and tank pressure responded. The cryofan was operated at 15, 17.5, and 22.5 krpm, and nominally at 20 krpm. After a couple of hours of the cryofan at 22.5 krpm, the fan shut down, as did the GO_2 flow, but the tank still pressurized from the heat load coming into the LO_2 . This can be seen between Hours 318 and 335 of testing. Resetting the fan brought the tank back down to nominal operating conditions. Section 5.6 contains additional discussion on test conditions impacted by changing the cryofan's speed. Figure 55 to Figure 59 contain the tank pressure, mass flow rates, internal fluid temperatures, fan speeds, and cryocooler loop temperatures, respectively, for Test 4 (Table 17). An important finding from the fluid temperature plot is that, although the cryofan is operating and the circulating neon is removing heat from the tank, there is very little stratification in the fluid temperatures. However, when the fan shut down, the fluid stratified with a maximum fluid temperature difference of ~ 15 K.

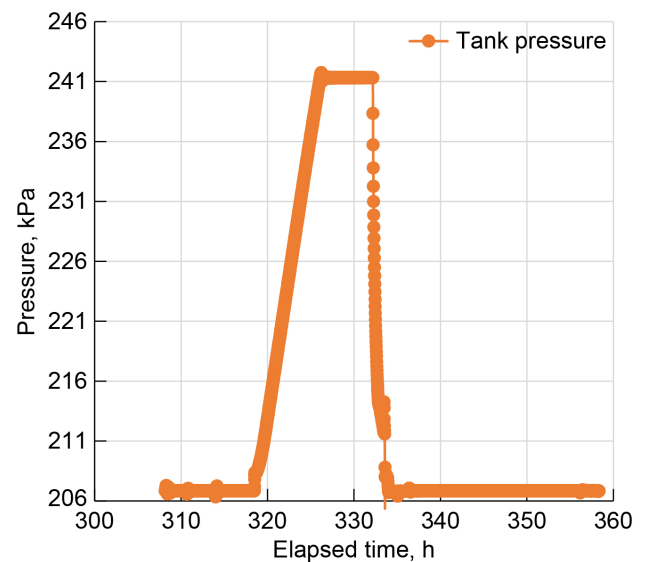
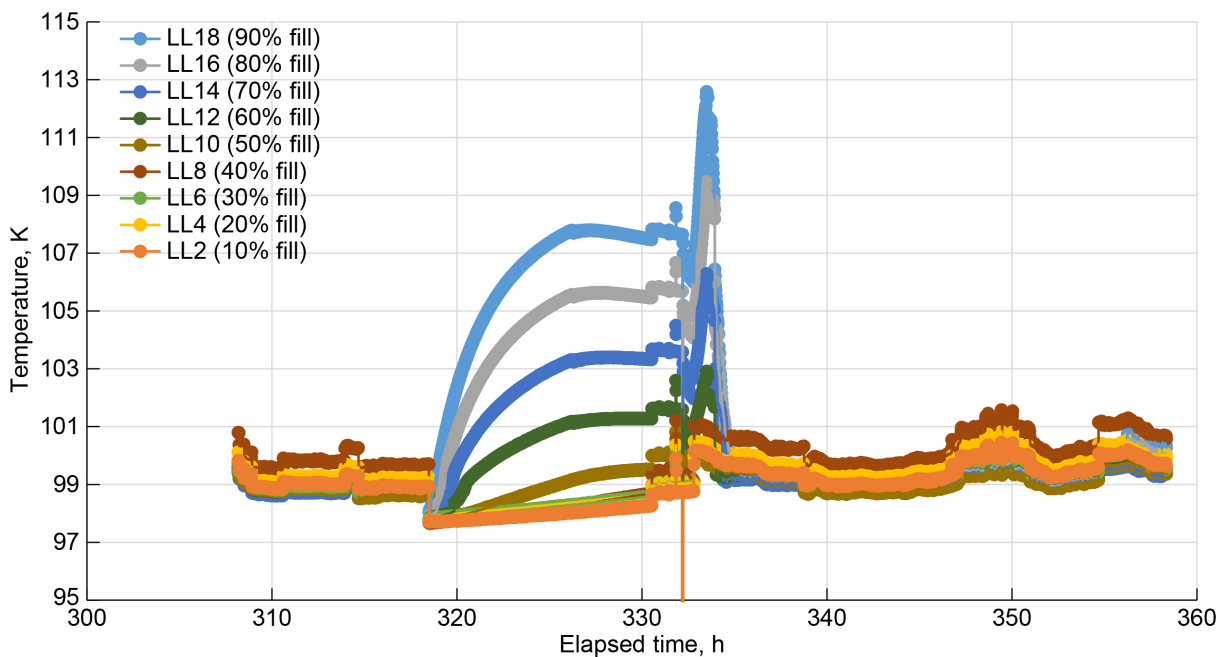
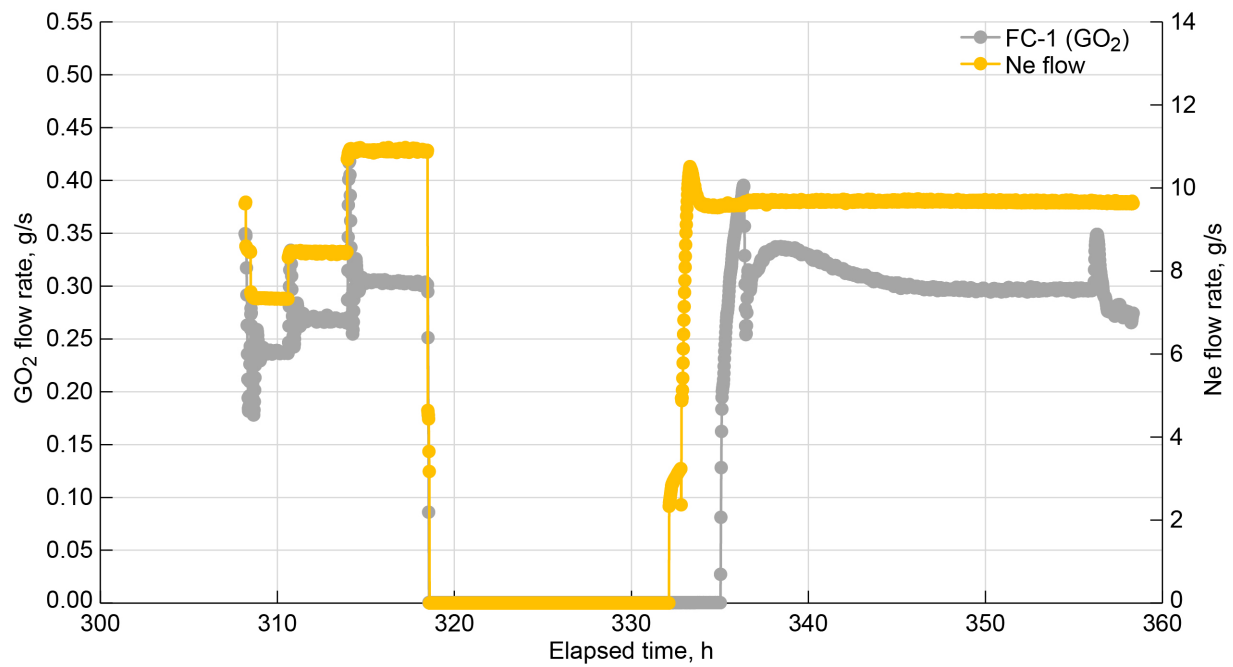


Figure 55.—Tank pressure for Test 4.



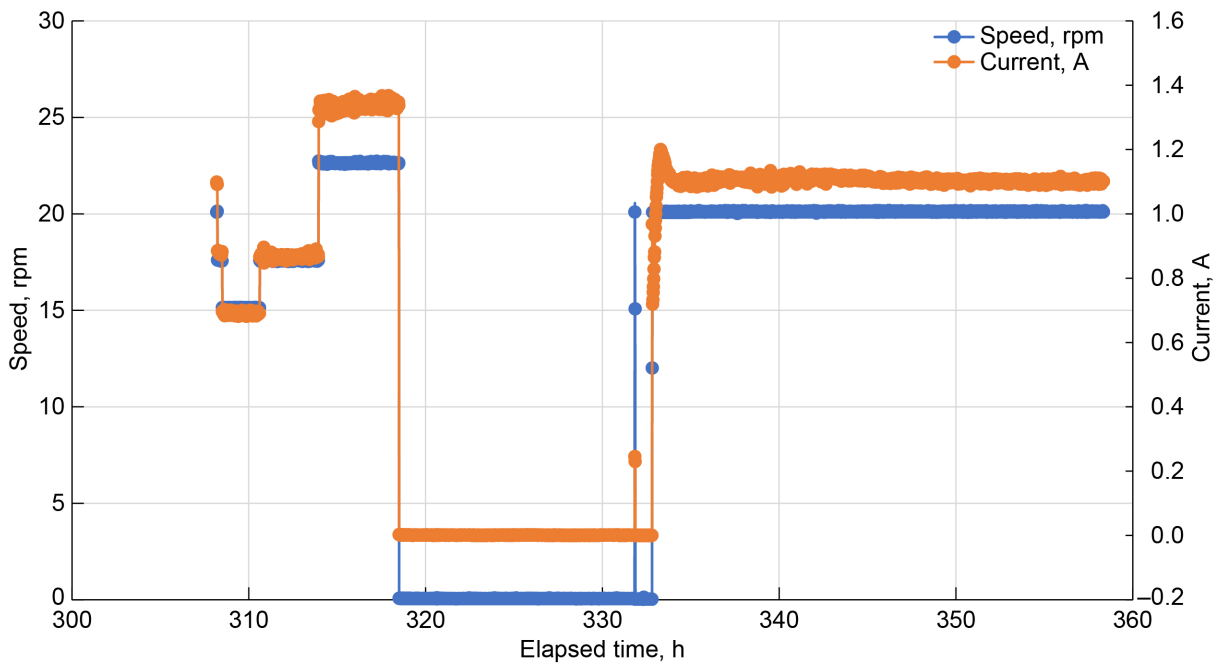


Figure 58.—Cryofan speeds for Test 4.

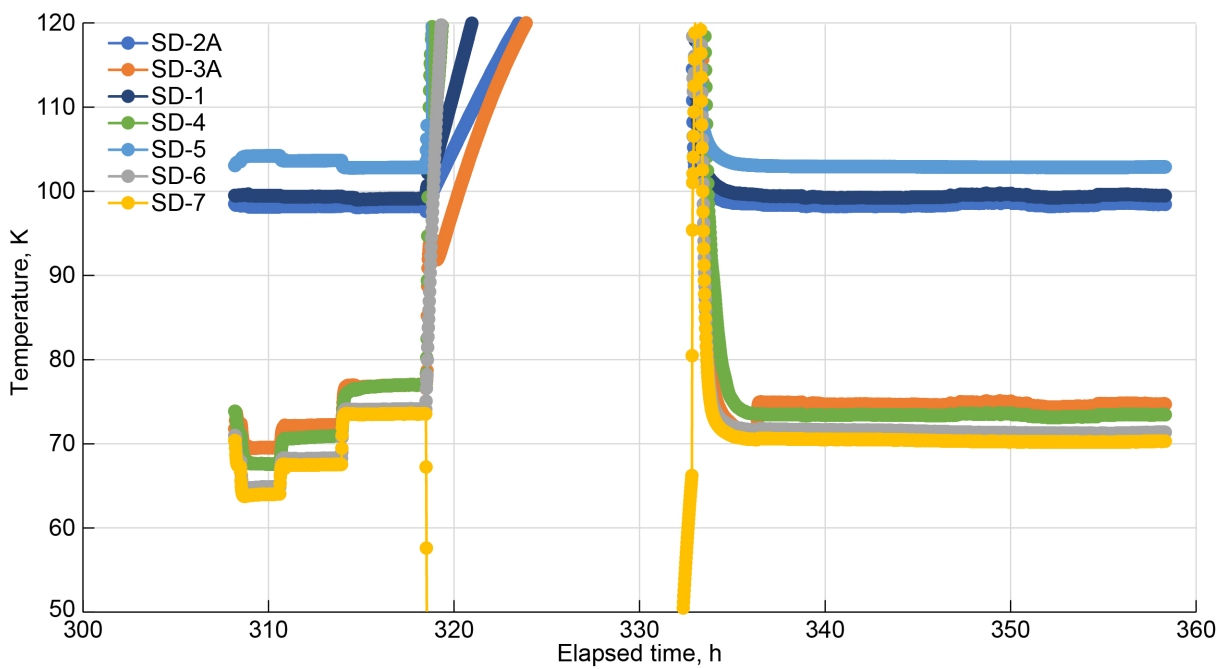


Figure 59.—Cryocooler loop temperatures for Test 4.

Test 5 (Table 18) and its Subtest 5a (Table 19) were run to determine the nominal method for introducing GO₂ mass flow to the tank. Test 5 repeated the constant liquefaction test performed in Test 3, except that the GO₂ mass flow was introduced to the tank via a dip tube into the liquid instead of

the ullage space near the top of the tank. The dip tube was a few inches above the bottom of the tank, allowing GO₂ to bubble up through the liquid before reaching the ullage. The tank pressure, mass flow rates, and internal fluid temperatures for Test 5 are in Figure 60 to Figure 62, respectively.

TABLE 17.—NEON LOOP FLOW VARIATIONS
LIQUEFACTION TEST MATRIX

Test 4	
Test description.....	Neon loop heater variations
Fill level, %.....	50
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	207
GO ₂ flow, kg/h.....	^a 1.1
Heaters, W.....	47
Neon loop fan speed, krpm.....	15, 17.5, 20, 22.5
GO ₂ injection method.....	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

TABLE 18.—EFFECT OF DIP
TUBE TEST MATRIX

Test 5	
Test description.....	Effect of dip tube
Fill level, %.....	50
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	207
GO ₂ flow, kg/h.....	^a 1.1
Heaters, W.....	47
Neon loop fan speed, krpm.....	20
GO ₂ injection method.....	Dip tube

^aNominal value given, but test allowed this variable to respond to all other inputs.

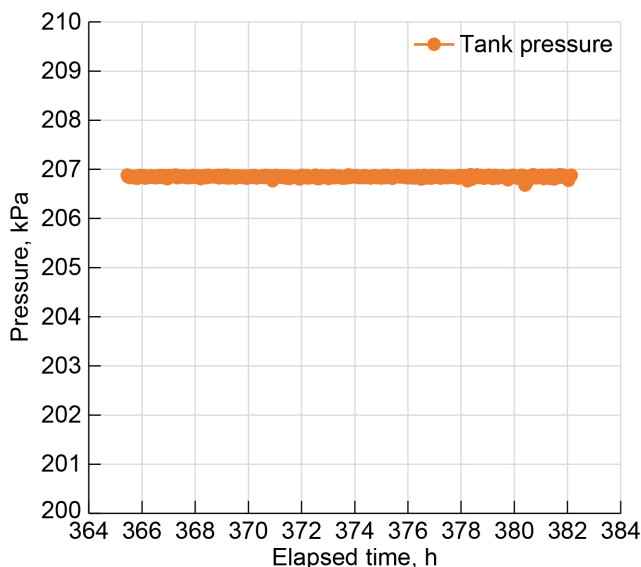


Figure 60.—Tank pressure for Test 5.

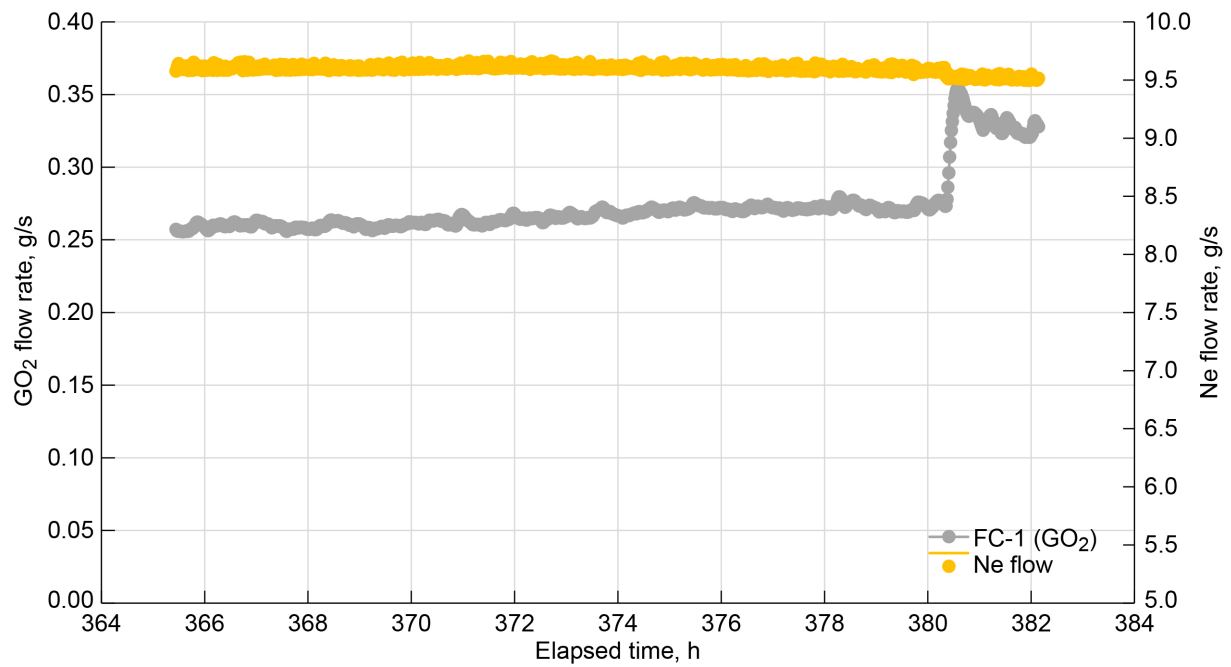


Figure 61.—Mass flow rates for Test 5.

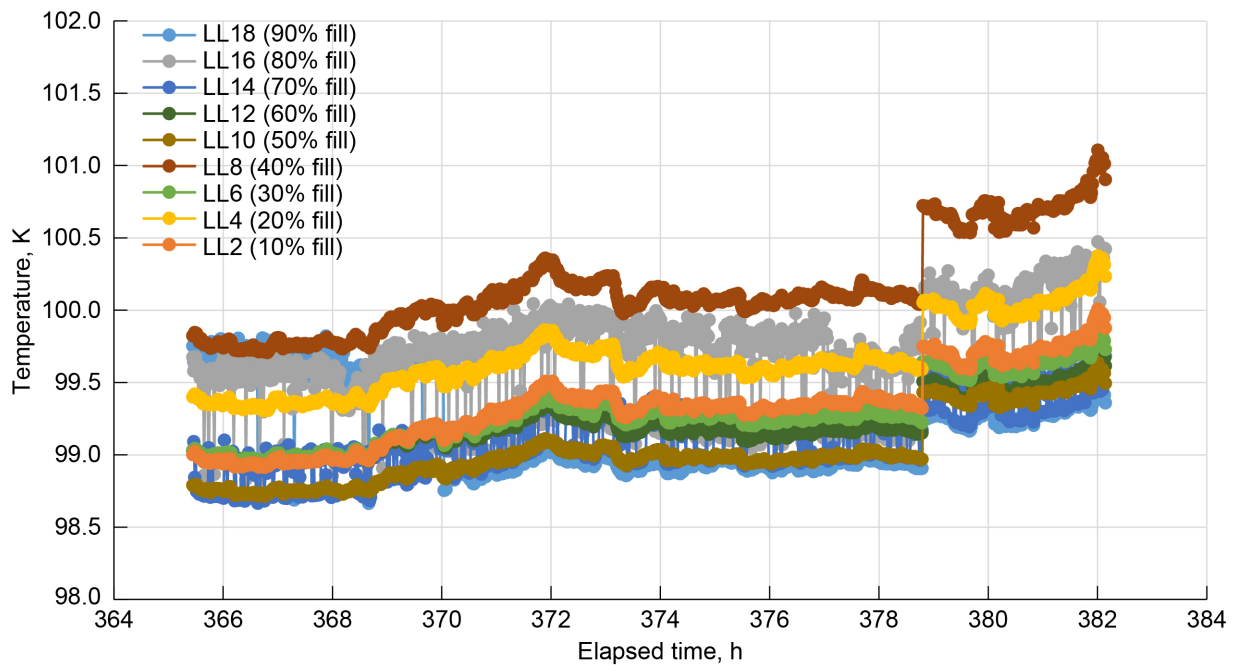


Figure 62.—Internal temperatures for Test 5.

Test 5a continued Test 5 by introducing GO₂ to the tank through a dip tube; however, the heater power input on the neon loop was varied, much as in Test 3a, to see how the liquefaction rate would respond while maintaining tank pressure. A more in-depth comparison of the GO₂ mass flow feed methods and the system's liquefaction rate response can be found in Section 5.4. Test 5a's (Table 19) tank pressure, mass flow rates, internal fluid temperatures, and neon loop heater input powers are shown in Figure 63 to Figure 66.

TABLE 19.—EFFECT OF NEON LOOP HEATER SETTINGS WITH DIP TUBE TEST MATRIX

Test 5a	
Test description.....	Effect of heater settings with dip tube
Fill level, %.....	50
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	207
GO ₂ flow, kg/h.....	^a 1.1
Heaters, W.....	7, 17, 37
Neon loop fan speed, krpm.....	20
GO ₂ injection method.....	Dip tube

^aNominal value given, but test allowed this variable to respond to all other inputs.

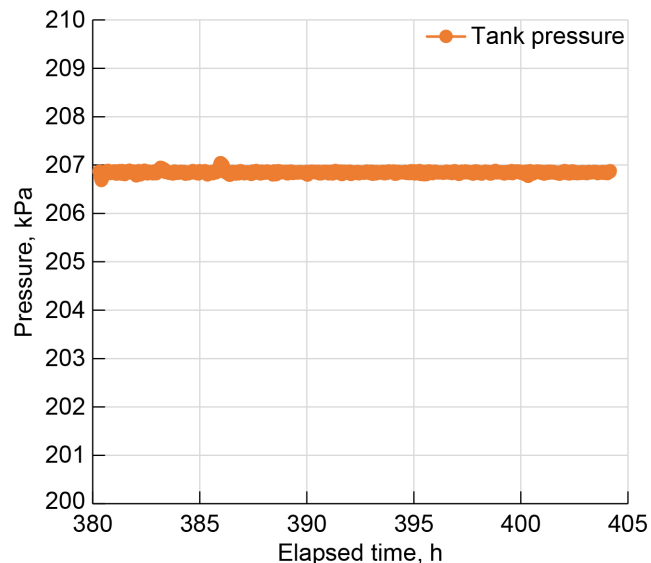


Figure 63.—Tank pressure for Test 5a.

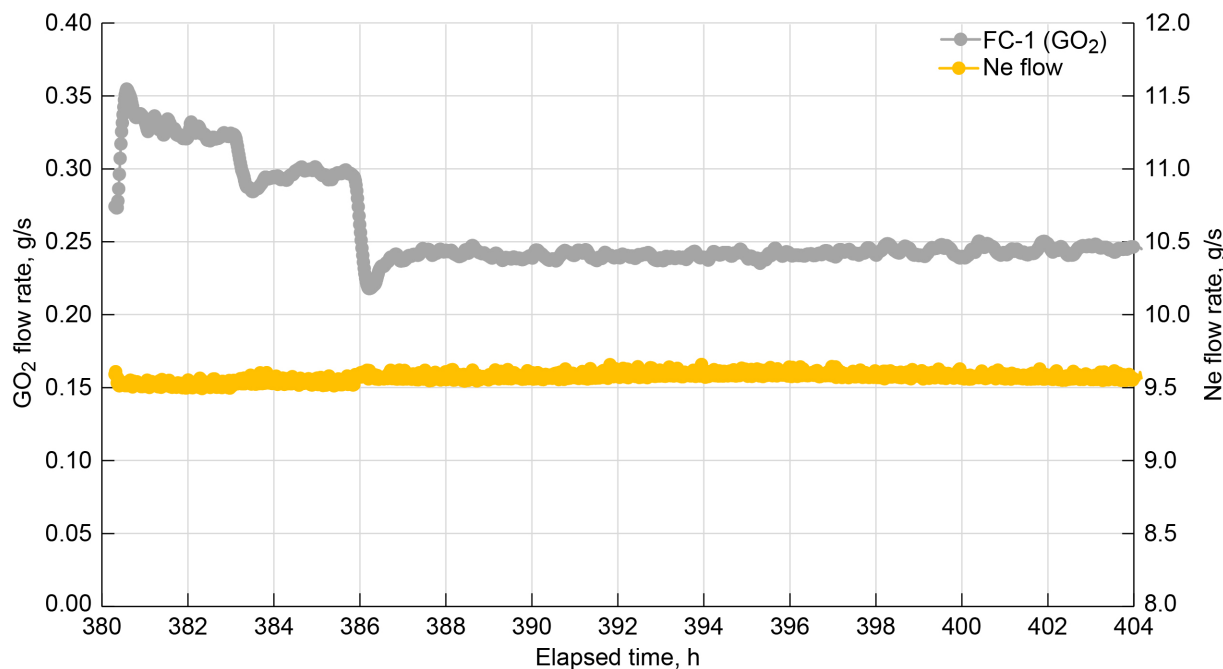


Figure 64.—Mass flow rates for Test 5a.

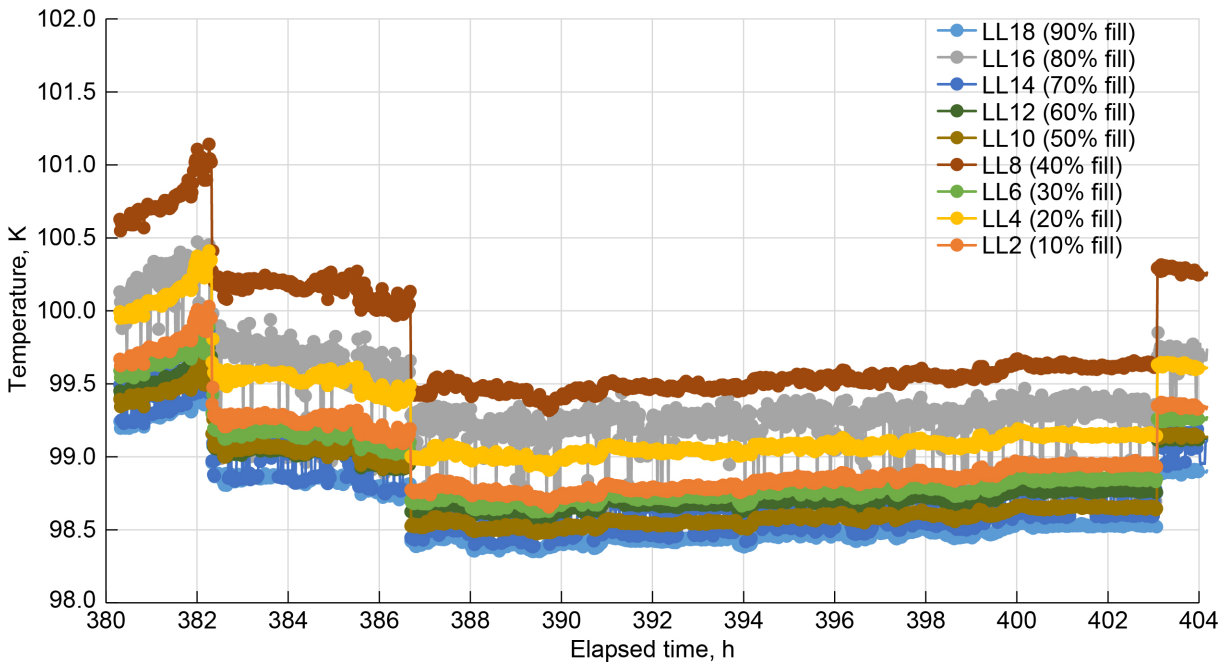


Figure 65.—Internal temperatures for Test 5a.

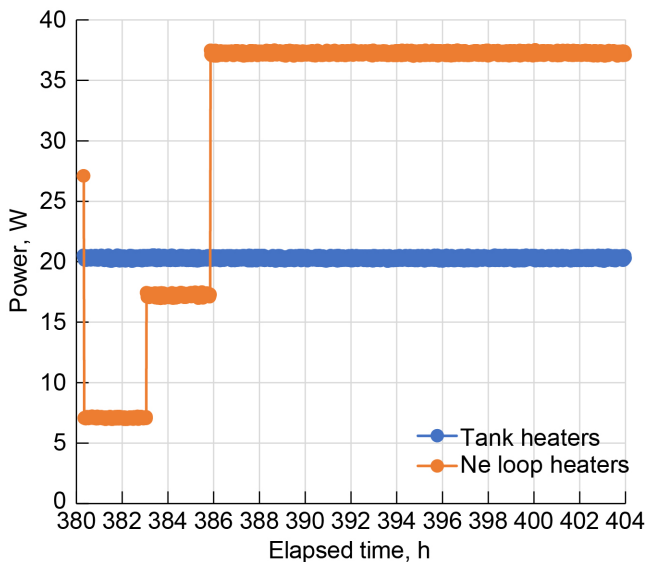


Figure 66.—Tank and neon loop heater power for Test 5a.

4.2 LO₂ Constant Liquefaction

The test matrix for the Constant Liquefaction Operations is shown in Table 7. During these tests, constant liquefaction was accomplished at different pressures, fill levels, and flow rates. Test 6 (Figure 67 to Figure 70), Test 7 (Figure 71 to Figure 74), and Test 8 (Figure 75 to Figure 78) were at a constant pressure of 207 kPa (30 psia), and starting fill levels of ~90 percent, ~50 percent, and <10 percent, respectively. During these tests (as well as all tests where the pressure was constant), the tank pressure was controlled and held constant while the liquefaction flow rate was allowed to vary and ultimately reach a steady state.

For tests at different pressures—Test 8 (Figure 75 to Figure 78): 207 kPa (30 psia), Test 9 (Figure 79 to Figure 82): 276 kPa (40 psia), and Test 10 (Figure 83 to Figure 86): 138 kPa (20 psia)—all with an oxygen flow rate of 1.1 kg/h, the starting fill level was ~5 percent. Note that the fill levels in the tests were never strictly constant. As liquefaction occurred, the fill level in each test increased. These tests were conducted in the following order chronologically: Test 9, Test 8, and Test 10. Also, Test 10 was conducted twice, once following Test 8, which was interrupted by a power failure in the facility that caused tank temperatures to rise and the tank liquid to be emptied, and a second time after recovering from the power outage. During the power outages, tank pressure was maintained by the facility's back pressure control system that would vent the tank when necessary.

Liquefaction tests were also performed by maintaining constant flow rates of GO₂ into the tank but allowing the pressure in the tank to respond to the oxygen flow. Note that the liquefaction rate is constant only when the system achieves a steady state and the tank pressure becomes constant. This was the case for Test 11 (GO₂ flow rate of 1.1 kg/h, tank pressure of 207 kPa (30 psia), starting fill level of ~2 percent). In Test 12, the GO₂ flow rate was reduced (0.5 kg/h), the starting fill level was ~8 percent, and all other conditions were the same as in Test 11. Because of the reduced GO₂ flow rate, the tank pressure decreased with time. Similarly, in Test 13, the GO₂ flow rate was increased to 2.2 kg/h (starting fill level of ~3.5 percent) and the tank pressure response increased with time.

Figure 67, Figure 71, and Figure 75 show the tank pressures for Tests 6, 7, and 8. In Test 6, the tank pressure was controlled from an elapsed time of ~430 h. The pressure was constant except for brief excursions just after Hour 500, when the cryofan was turned on, and around Hour 550, when the GO₂ was introduced into the tank via the dip tube. Figure 71 and Figure 75 show the pressure on an expanded scale. The pressure control was tight and the difference between the two pressure transducer readings is nearly 0.5 kPa.

Figure 68, Figure 72, and Figure 76 show the oxygen temperature distribution within the tank as measured by the diode rake. In Figure 68, disturbances to the fluid temperatures are seen at approximately Hour 475. Prior to this time, these disturbances were persistent and were a daily occurrence. It was finally discovered that these could be attributed to EMI from turning on certain lights inside the SMiRF. Shortly after the lights were turned off, these disturbances subsided, as is evident in Figure 68. The facility lights were never turned on for the remainder of the CryoFILL testing. Further noisiness was observed on SD-19, at the 95 percent fill level. The cause for this is not certain, but it was persistent throughout the duration of the testing.

Figure 69, Figure 73, and Figure 77 show the GO₂ flow rates for Tests 6, 7, and 8, respectively. For Test 6, the tank was filled up from 60 to 90 percent (Table 20). The tank pressure was ~110 kPa (16 psia) when the fill was completed. At approximately Hour 477 in Figure 69, oxygen was bubbled up through the liquid via dip tube injection for about 6 h to speed up the warming up of the tank. Oxygen gas was also injected through the dip tube at approximately Hour 573 for 5 h and 25 min to see what effect dip tube injection had on the system. In Figure 73 and Figure 77, the flows were steady for nearly the

entire time period shown. Note that the flow rate of neon and the fill-level percentage are displayed on the secondary axis and are on a logarithmic scale in Figure 69 and Figure 73.

Figure 70, Figure 74, and Figure 78 show the heater input powers for Tests 6, 7, and 8. Because the LO₂ was introduced into the tank at ambient pressure, the heater powers were varied in Test 6 to speed up the increase of the LO₂ temperature to achieve saturation conditions at the operating pressure. For Tests 7 and 8, the heater powers were kept constant for the duration of the tests (Table 21 and Table 22).

TABLE 20.—HIGH-FILL-LEVEL LIQUEFACTION TEST MATRIX

Test 6	
Test description.....	High fill level
Fill level, %.....	90
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	207
GO ₂ flow, kg/h.....	^a 1.1
Heaters, W.....	47
Neon loop fan speed, krpm.....	20
GO ₂ injection method.....	Vent line and dip tube

^aNominal value given, but test allowed this variable to respond to all other inputs.

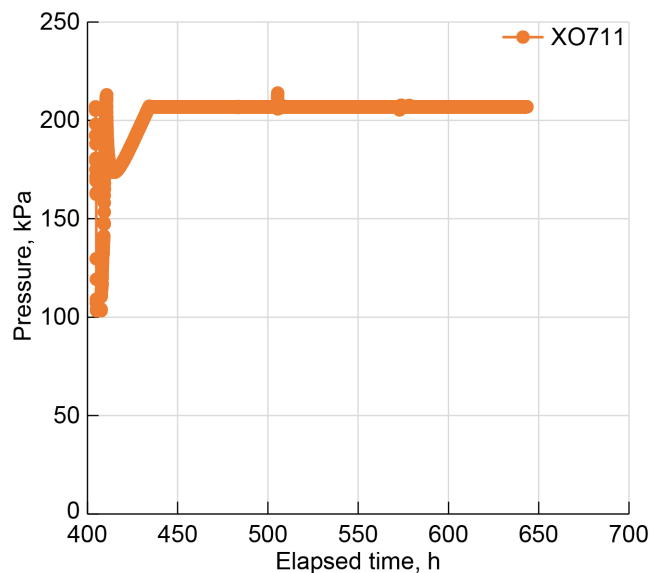
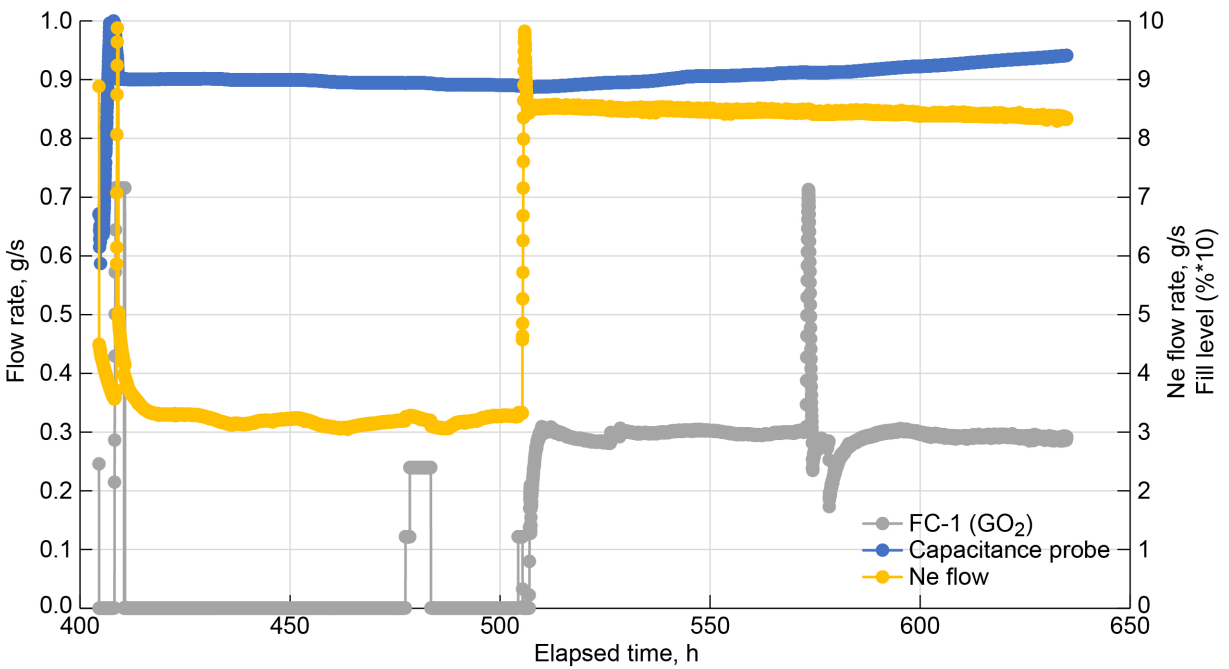
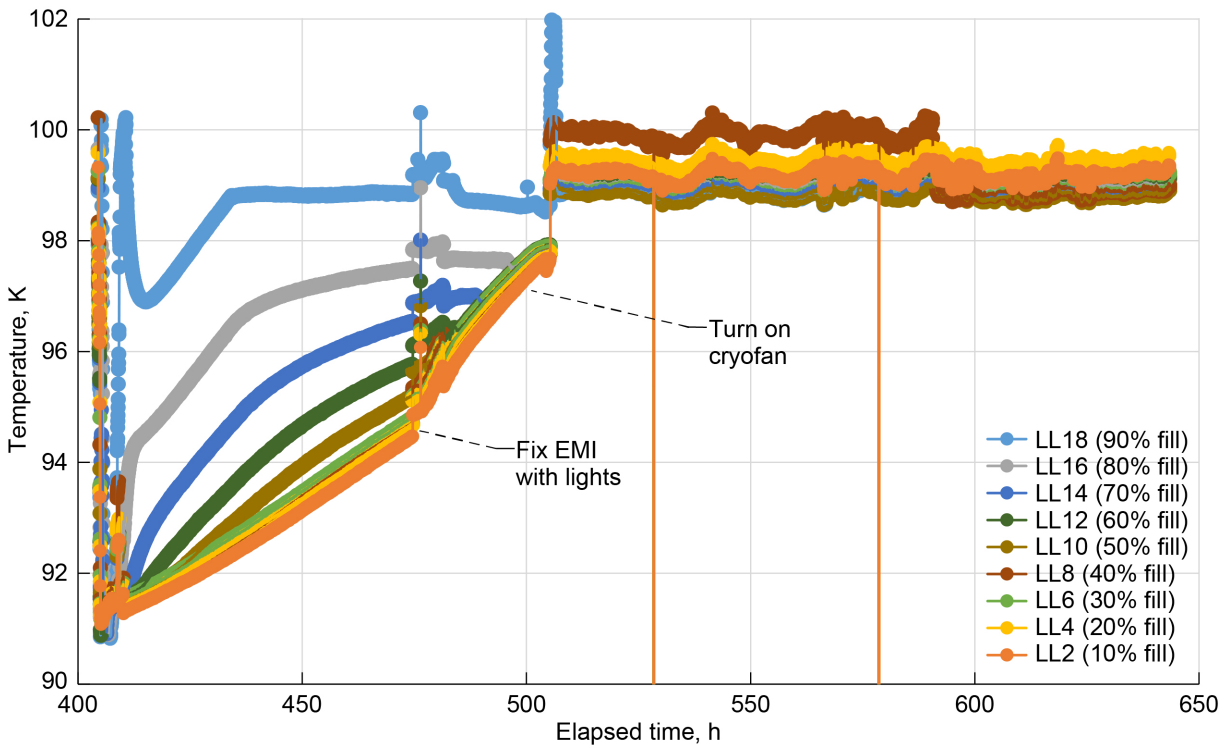


Figure 67.—Tank pressure for Test 6.



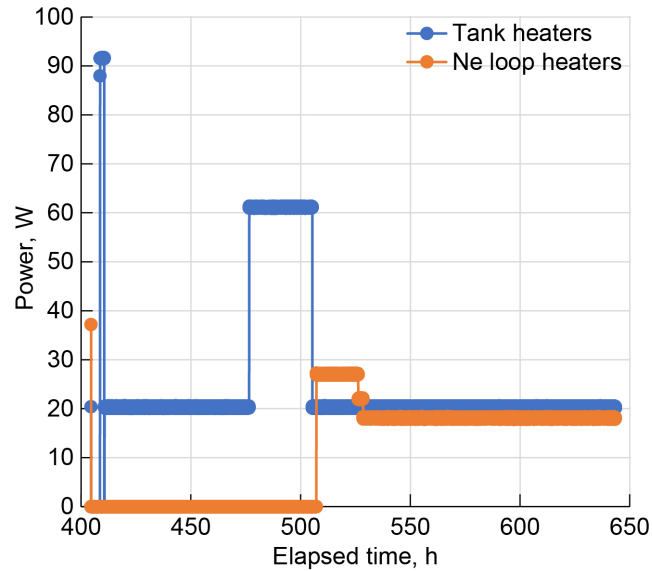


Figure 70.—Heater power for Test 6.

TABLE 21.—MEDIUM-FILL-LEVEL
LIQUEFACTION TEST MATRIX

Test 7	
Test description.....	Medium fill level
Fill level, %.....	50
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	207
GO ₂ flow, kg/h.....	^a 1.1
Heaters, W.....	47
Neon loop fan speed, krpm.....	20
GO ₂ injection method.....	Vent line and dip tube

^aNominal value given, but test allowed this variable to respond to all other inputs.

TABLE 22.—LOW-FILL-LEVEL AND MEDIUM TANK
PRESSURE LIQUEFACTION TEST MATRIX

Test 8	
Test description.....	Low fill, medium pressure
Fill level, %.....	<10
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	207
GO ₂ flow, kg/h.....	^a 1.1
Heaters, W.....	47
Neon loop fan speed, krpm.....	20
GO ₂ injection method.....	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

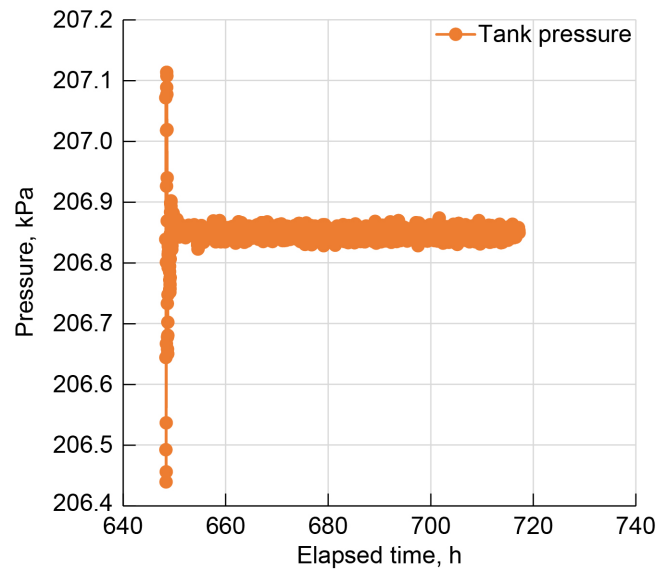


Figure 71.—Tank pressure for Test 7.

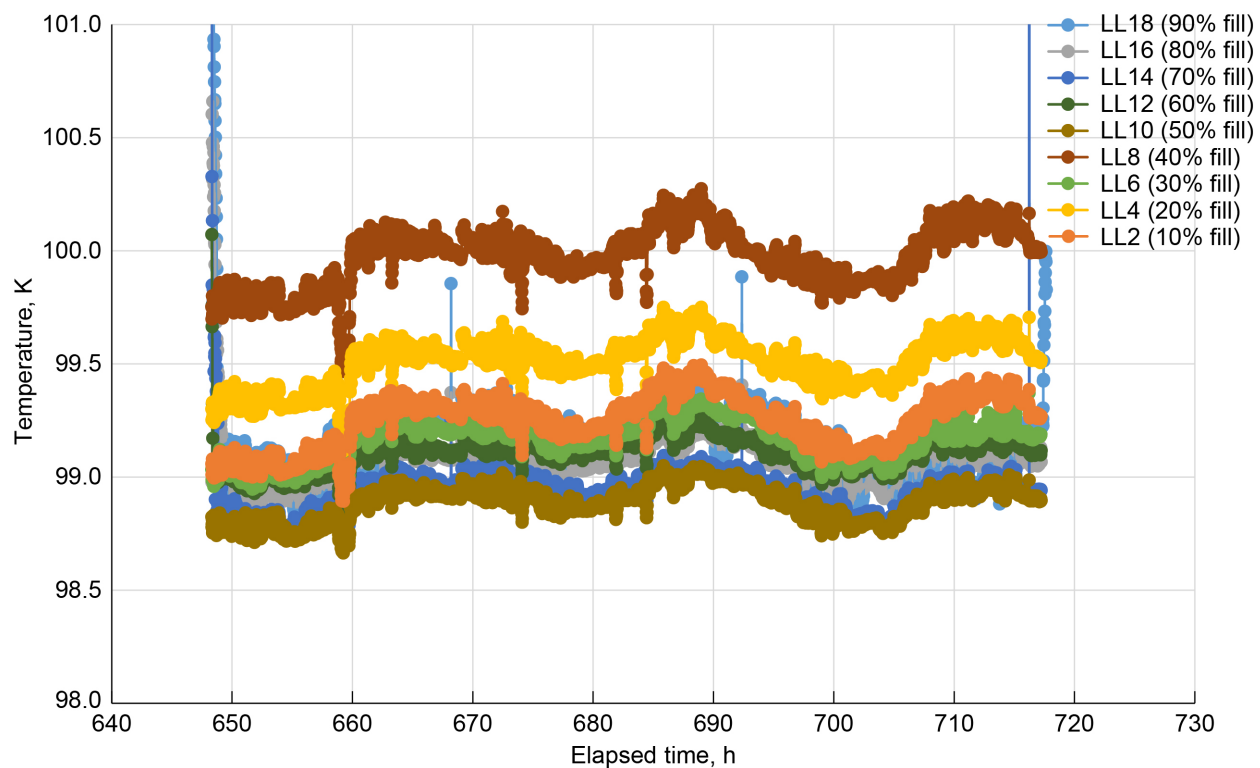


Figure 72.—Oxygen temperature distribution for Test 7.

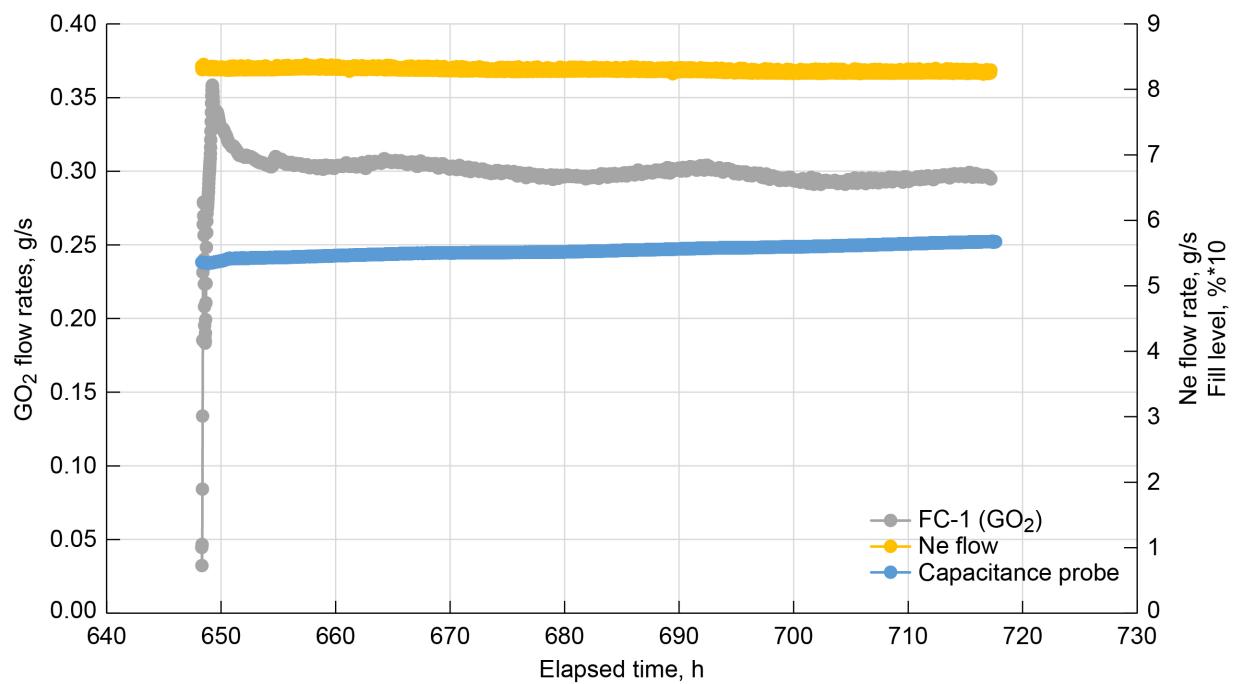


Figure 73.—Flow rates and fill level for Test 7.

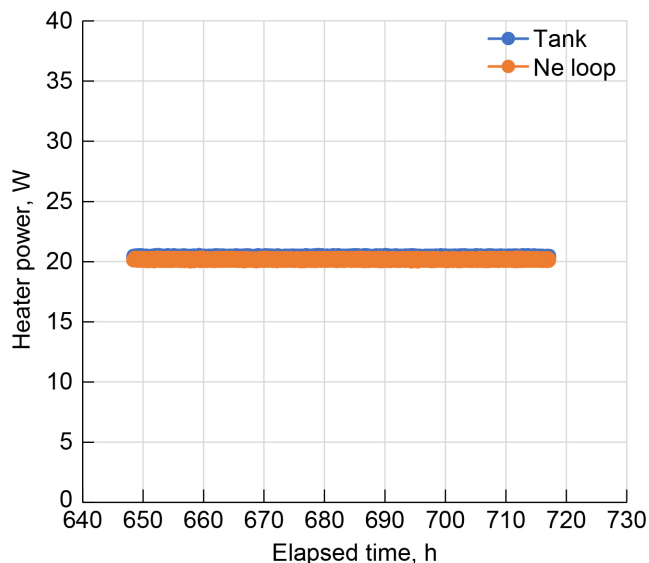


Figure 74.—Heater power for Test 7.

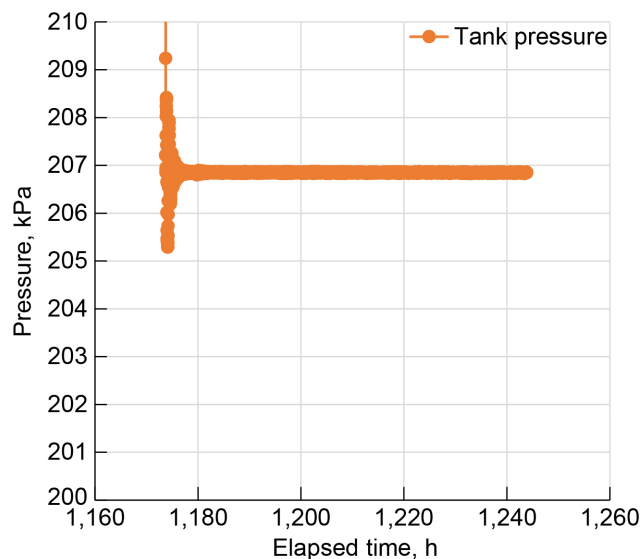


Figure 75.—Tank pressure for Test 8.

Figure 75, Figure 79, and Figure 83 show the tank pressure for Tests 8, 9, and 10, respectively. The tank pressure is constant, with the difference in the reading of the two pressure transducers being less than 1 kPa. Note that Test 10 was run twice; the first operation was interrupted by a power outage in the SMiRF, and it took several days to recondition the tank to saturation and resume the test. Also, the neon loop was recharged and the gas pressure in the loop was increased prior to the second time Test 10 was conducted. The effect of the varying GNe pressure is discussed later in Section 5.8.

Figure 76, Figure 80, and Figure 84 show the oxygen liquid and vapor temperatures measured by the diode rake within the tank for Tests 8, 9, and 10, respectively. The liquid and vapor temperatures are bunched up and there is very little stratification in the fluid, with the maximum temperature difference in the fluid being about 2 K.

Figure 77, Figure 81, and Figure 85 show the GO₂ flow rates and the tank fill level for Tests 8, 9, and 10, respectively. After initiation of the tests, a steady state for the flow of GO₂ into the tank was generally achieved in ~5 h. The second attempt of Test 10 took a longer time (~10 h) to get to a steady state of oxygen flow likely due to the extensive thermal disturbances the tank

was subjected to during the power outage. The vent flow rate of oxygen in Tests 8, 9, and 10 was zero. Therefore, when the GO₂ flow into the tank was steady, and the tank pressure was constant, the rate of liquefaction of oxygen was inferred to be constant. The tank fill level for Tests 8, 9, and 10 are also shown in Figure 77, Figure 81, and Figure 85. The starting fill level was ~5 percent for Test 8, Test 9, and the first Test 10. At the end of these tests, the fill level was less than 10 percent but was not the same, primarily because the test durations were different. The fill level increase is approximately linear, confirming that the rate of liquefaction was quite constant. The fill level behavior in the second Test 10 was a little different. The tank was close to empty at the start of this test and the capacitance probe did not detect any liquid until roughly Hour 1,375, by which time the test was in progress for more than 24 h. Beyond ~0.5 percent, the cap probe became active and subsequently showed a nearly linear increase in the fill level to about 2 percent at the completion of the test (roughly Hour 1,390).

Figure 78, Figure 82, and Figure 86 show the heater powers for Tests 8, 9, and 10, respectively. For the duration of each test, the tank and neon loop heater power were maintained nominally constant at 20 and 27 W, respectively.

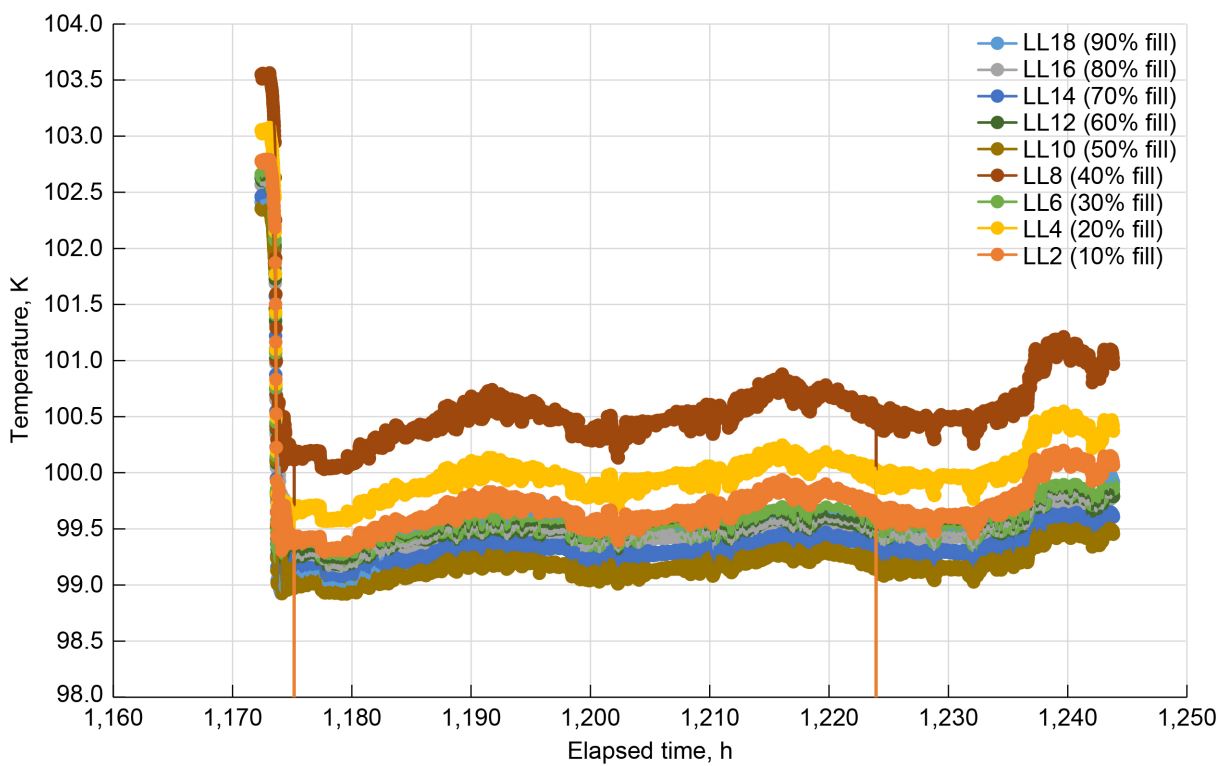


Figure 76.—Oxygen temperature distribution for Test 8.

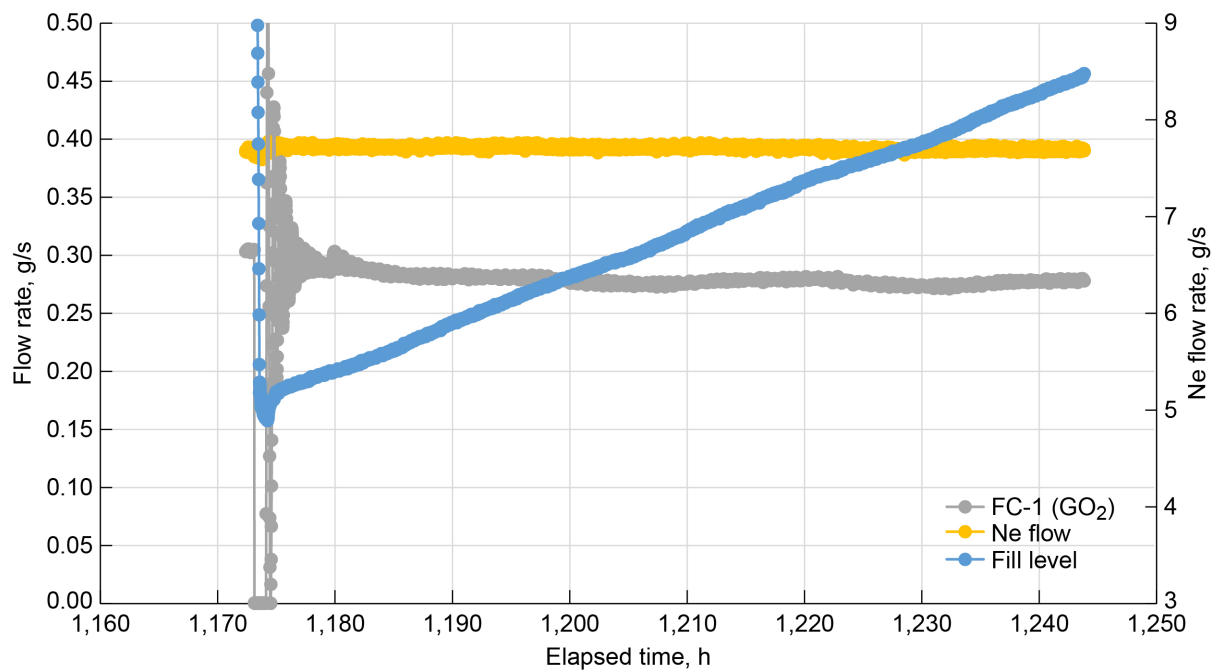


Figure 77.—Flow rates and fill level for Test 8.

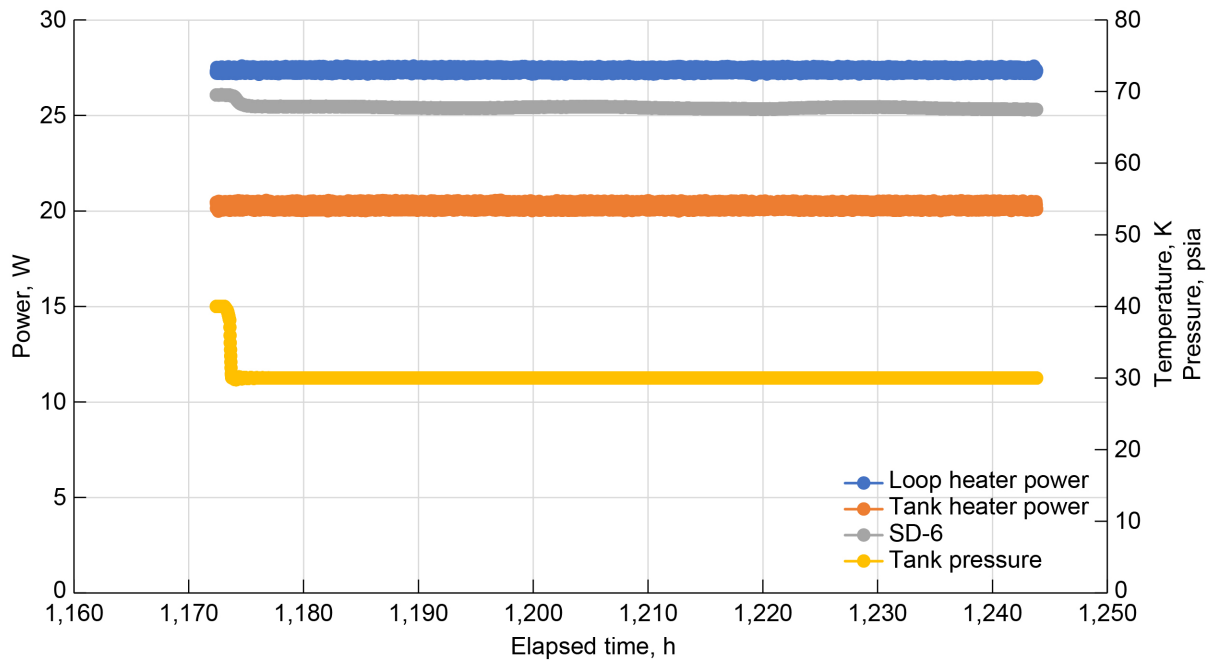


Figure 78.—Heater power for Test 8.

TABLE 23.—LOW-FILL-LEVEL AND HIGH TANK PRESSURE LIQUEFACTION TEST MATRIX

Test 9	
Test description	Low fill, high pressure
Fill level, %	<10
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	276
GO ₂ flow, kg/h.....	^a 1.1
Heaters, W	47
Neon loop fan speed, krpm.....	20
GO ₂ injection method	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

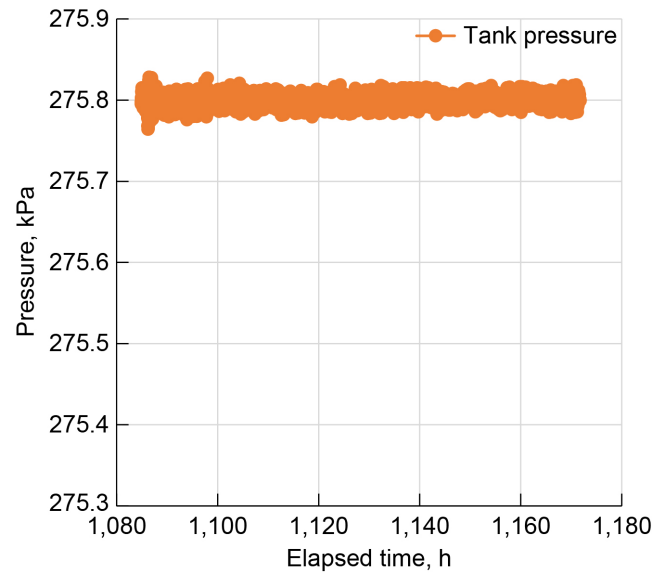


Figure 79.—Tank pressure for Test 9 (Table 23).

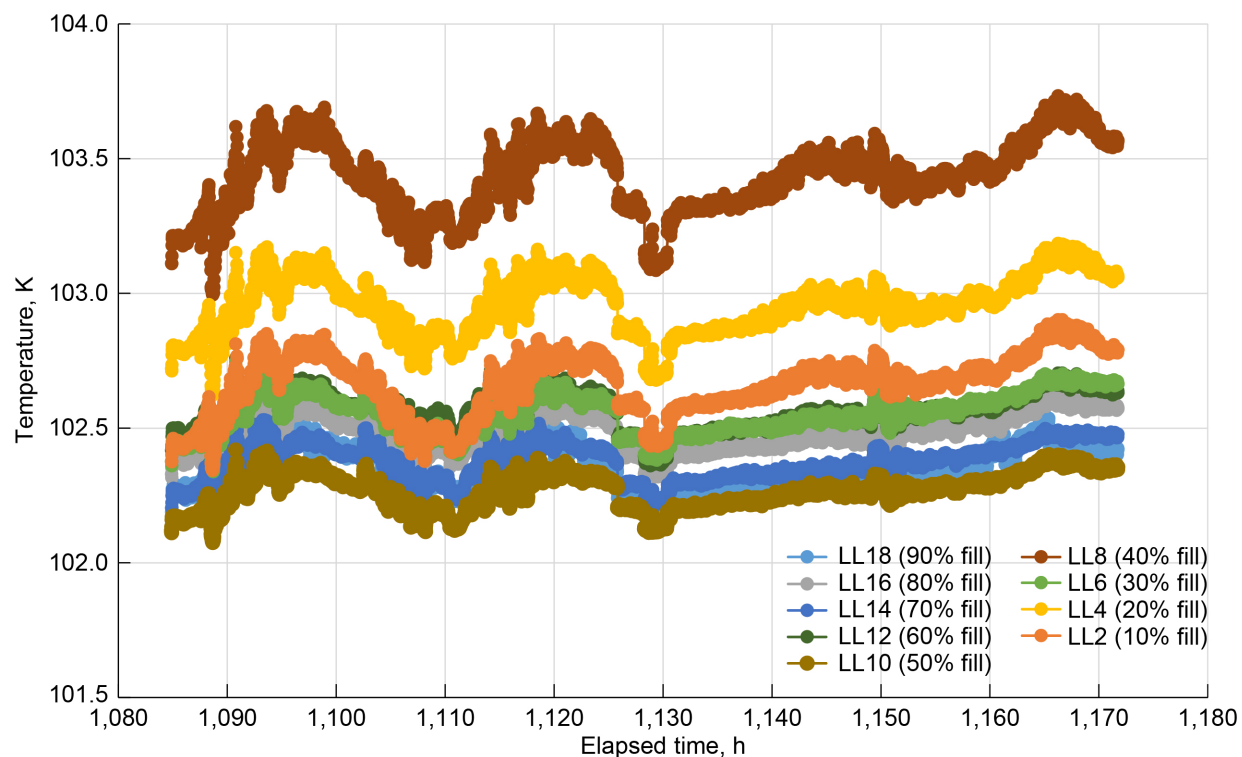


Figure 80.—Oxygen temperature distribution for Test 9 (Table 23).

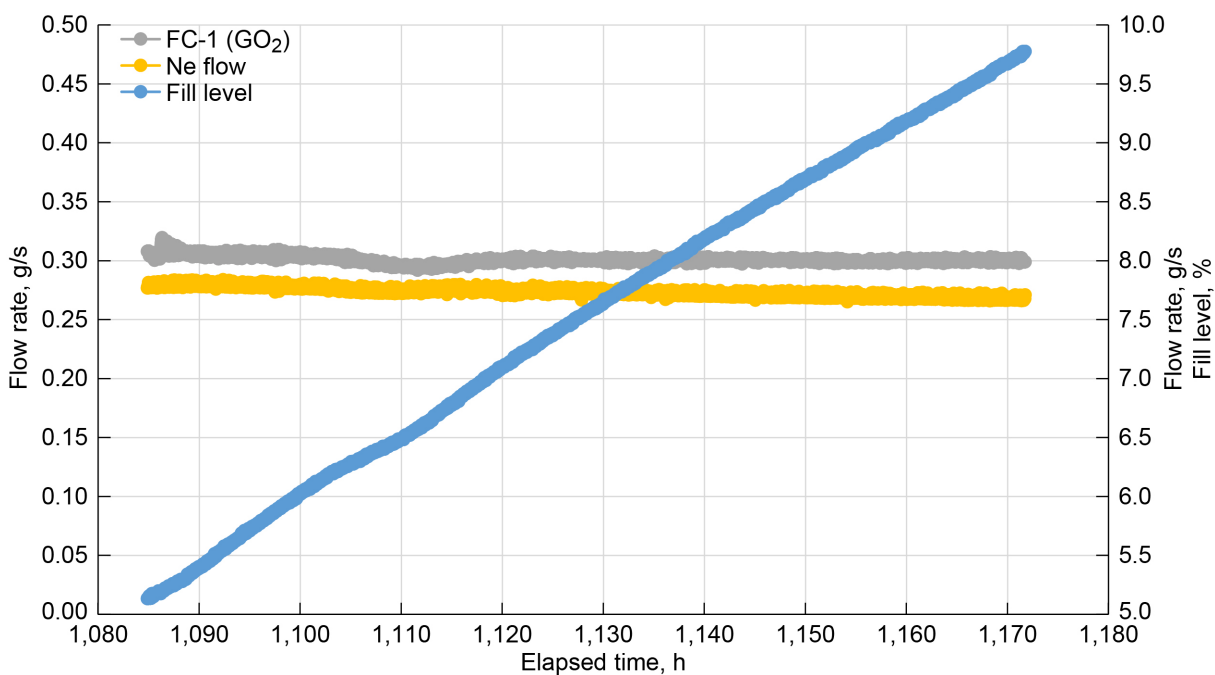


Figure 81.—Oxygen flow rates and fill level for Test 9 (Table 23).

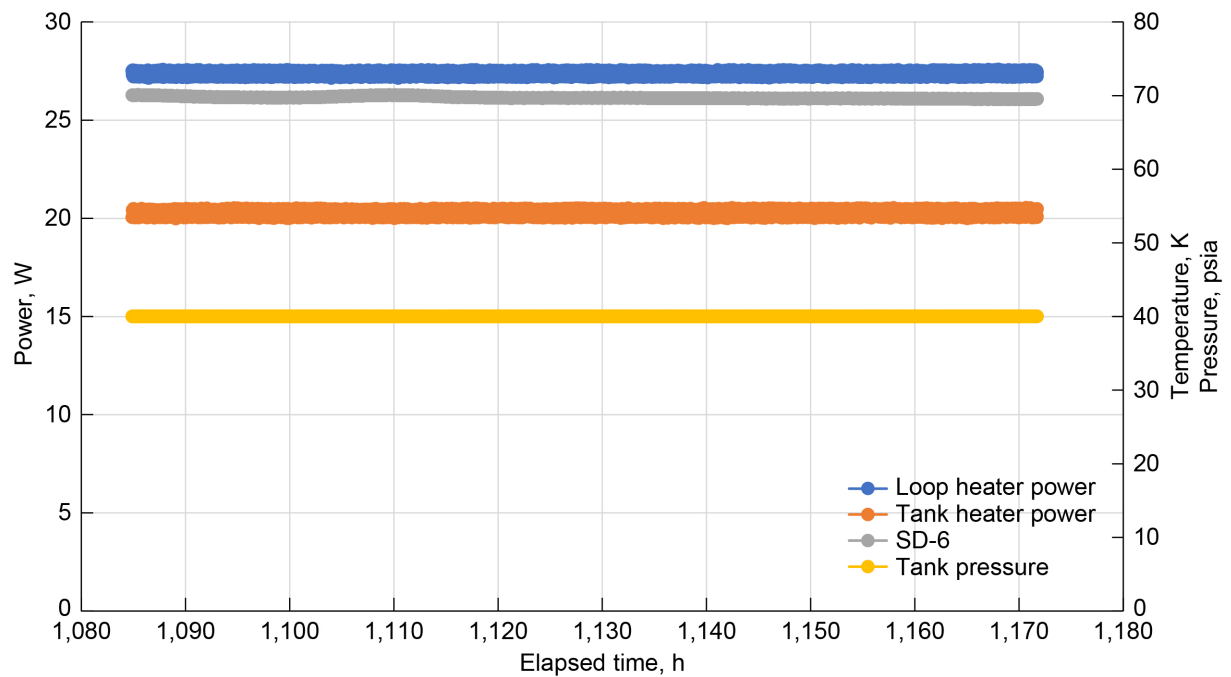


Figure 82.—Heater power for Test 9 (Table 23).

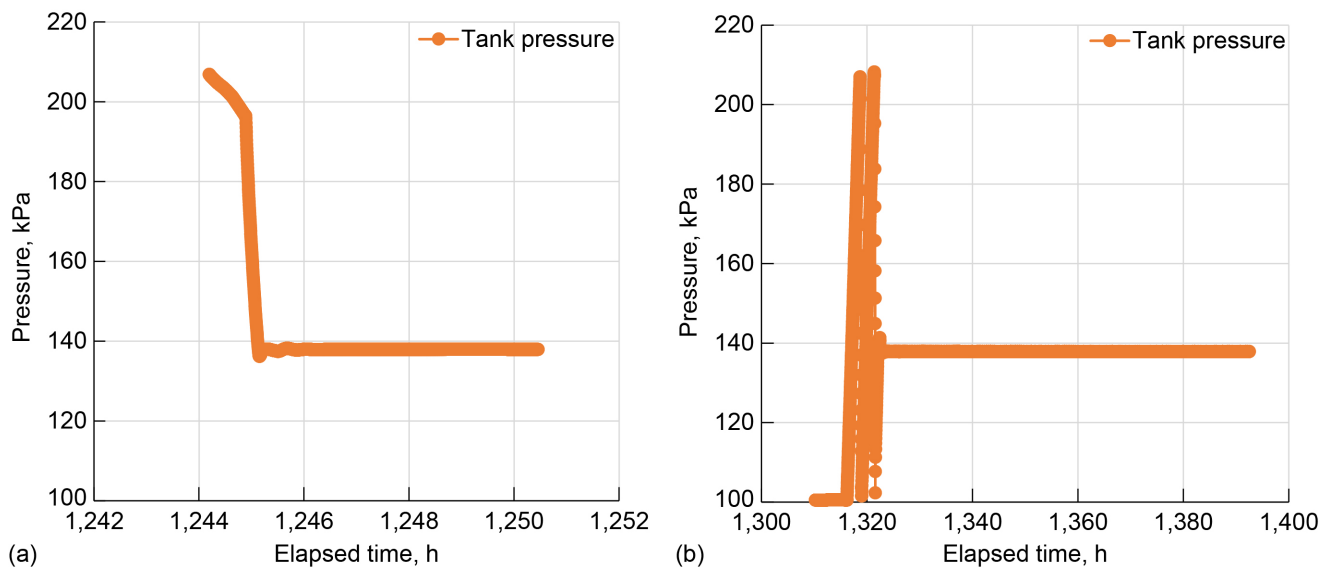


Figure 83.—Tank pressure for Test 10, both before and after the neon recharge (Table 24).

TABLE 24.—LOW-FILL-LEVEL AND LOW TANK
PRESSURE LIQUEFACTION TEST MATRIX

Test 10	
Test description.....	Low fill, low pressure
Fill level, %.....	<10
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	138
GO ₂ flow, kg/h.....	^a 1.1
Heaters, W	47
Neon loop fan speed, krpm	20
GO ₂ injection method	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

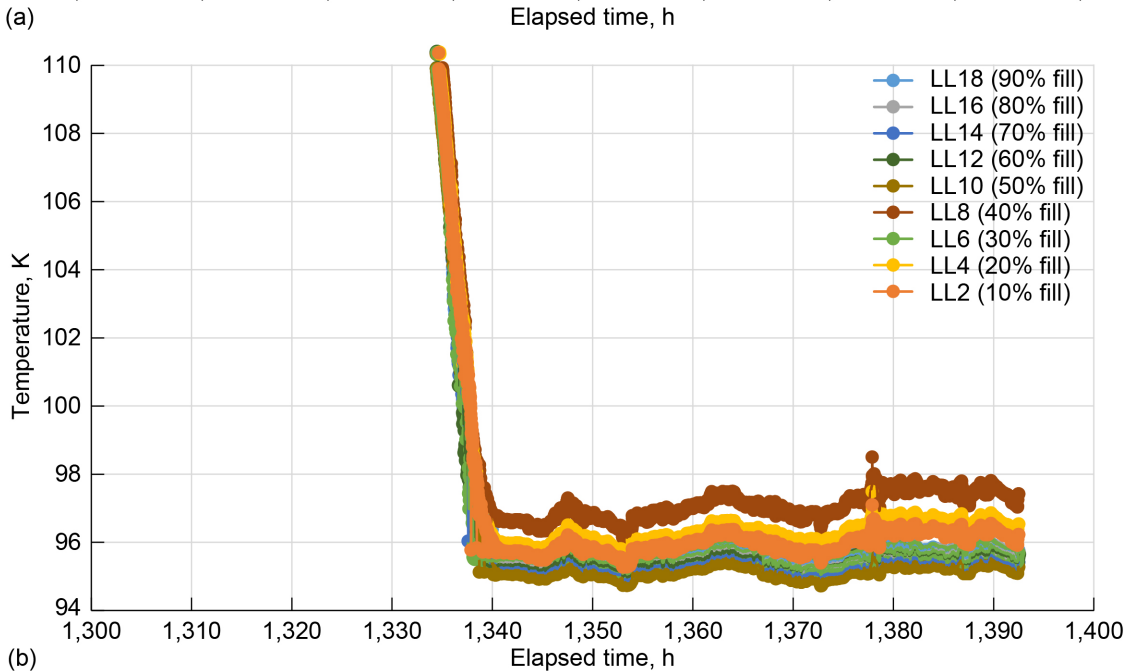
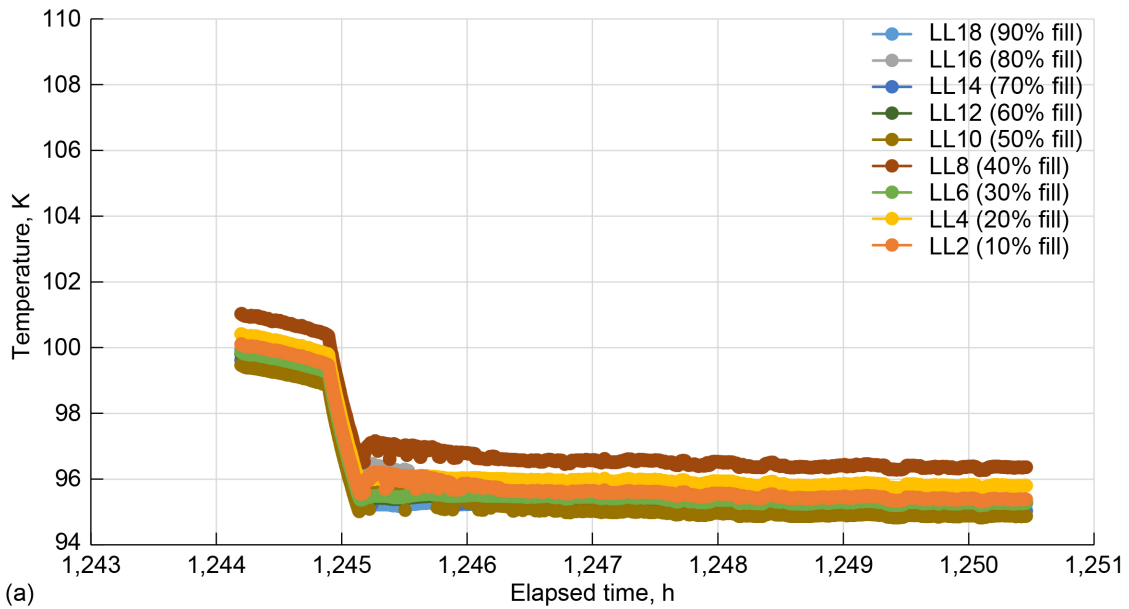


Figure 84.—Oxygen temperature distribution for Test 10, both before and after the neon recharge (Table 24).

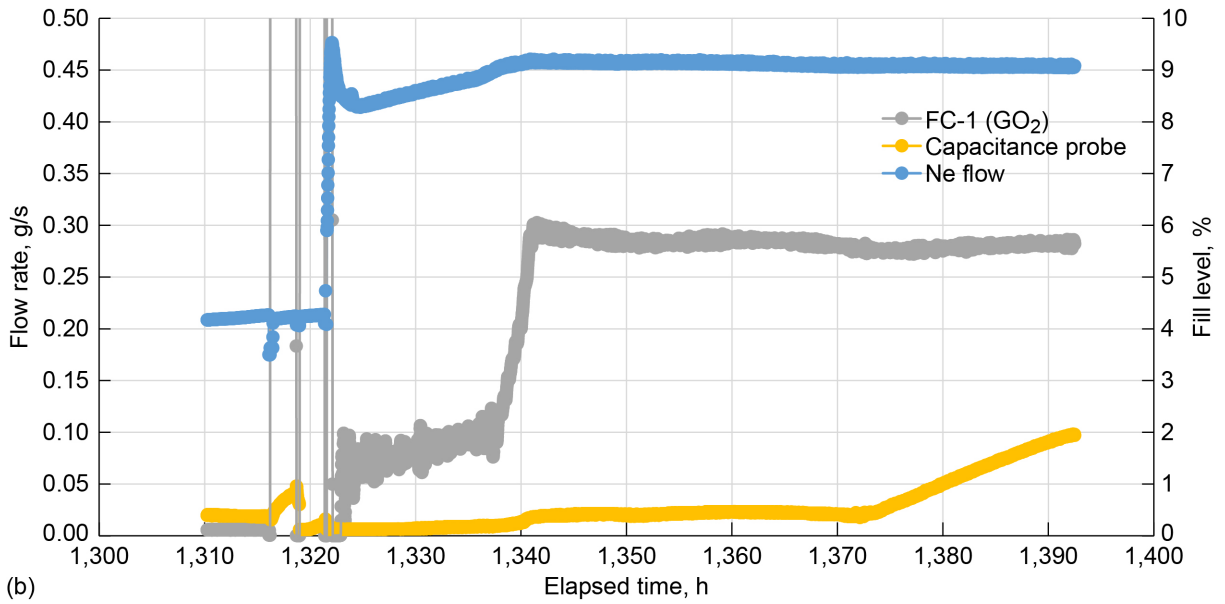
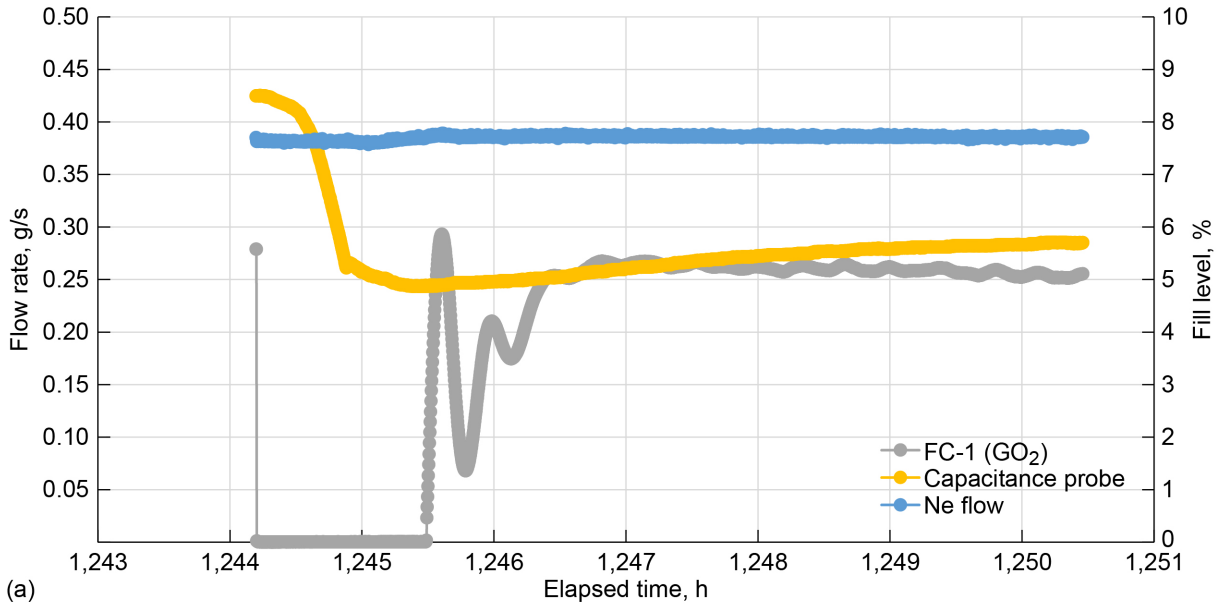


Figure 85.—Flow rates and fill level for Test 10, both before and after the neon recharge (Table 24).

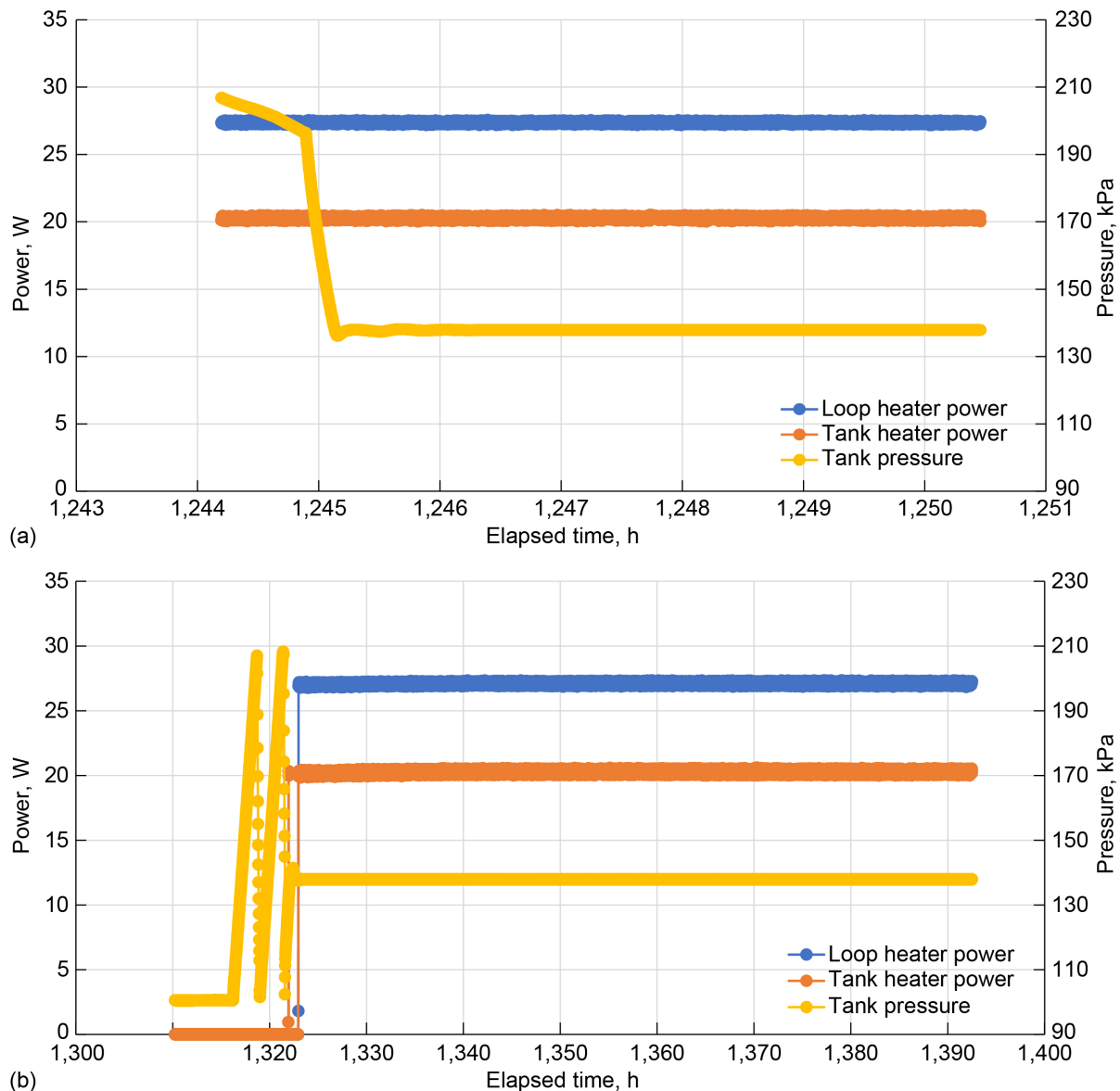


Figure 86.—Heater power for Test 10, both before and after the neon recharge (Table 24).

4.2.1 Liquefaction With Constant Flow of GO_2

As mentioned previously, Test 11 (Figure 87 to Figure 90), Test 12 (Figure 91 to Figure 94), and Test 13 (Figure 95 to Figure 98) were conducted while maintaining a constant flow of GO_2 into the ullage for the duration of each test, but the flow rate was varied across the tests. In Test 11, the GO_2 flow was 1.1 kg/h (Table 25). It was reduced to 0.5 kg/h for Test 12 (Table 26) and increased to 2.2 kg/h for Test 13 (Table 27). The tank pressure responded to the input oxygen flow. A steady state was achieved with the pressure becoming nearly constant for Test 11. The pressurization rate for Test 11 is approximately zero as seen in Figure 87. However, assuming saturated conditions, a slight

pressure rise is evident in the corresponding temperature plot shown in Figure 88. Therefore, Test 11 is also a test where the liquefaction rate is constant—all the input oxygen is condensed at a steady rate without a significant change in the tank pressure or being vented from the tank. The pressure steady state cannot be maintained for lower and higher rates of input GO_2 flow. As a result, the tank depressurized for the lower oxygen flow rate than the value at steady state (Test 12) and pressurized when the GO_2 flow rate was higher (Test 13).

Figure 87, Figure 91, and Figure 95 show the tank pressure for Tests 11, 12, and 13. The corresponding GO_2 flow rates and tank fill level are shown in Figure 89, Figure 93, and Figure 97.

The starting fill levels were ~2 percent, ~7.7 percent, and ~3.5 percent for Tests 11, 12, and 13, respectively. The heater power levels for these tests are shown in Figure 90, Figure 94, and Figure 98. The tank heater power was 20 W and the loop heater power was 27 W for all these tests.

Figure 87 shows that from approximately Hour 1,395.5 to Hour 1,412.5, the tank pressure was constant and the pressurization rate was zero. The corresponding flow rate from Figure 89 is 0.31 g/s (1.1 kg/h). In Figure 93, from Hour 1,484.2 to Hour 1,490.7, the GO₂ flow rate was reduced to 0.14 g/s (0.5 kg/h) compared with the nominal flow rate in Figure 89. The tank pressure decreased and the rate of depressurization was nearly constant. Similarly, in Figure 97 for Test 13, note that the GO₂ flow rate was higher than in Test 11, and it is seen from Figure 95 that the tank pressure increased, with the rate of pressurization being approximately constant.

Figure 88, Figure 92, and Figure 96 show the fluid temperature within the tank for Tests 11, 12, and 13, respectively. With the maximum fill level in these tests being less than ~8.5 percent (during the course of Test 12), almost all the

silicon diodes were measuring the temperature of GO₂. It is seen that the ullage temperature was nearly constant, and there was little to no stratification in the oxygen temperature. It should be noted that one of the diodes (LL19, located at 95 percent fill level on the internal rake) had sporadic excursions during all three of these tests. The reasons are not known.

TABLE 25.—CONSTANT NOMINAL FLOW LIQUEFACTION TEST MATRIX

Test 11	
Test description.....	Constant flow, nominal
Fill level, %.....	<10
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	^a 207
GO ₂ flow, kg/h.....	1.1
Heaters, W.....	47
Neon loop fan speed, krpm.....	20
GO ₂ injection method.....	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

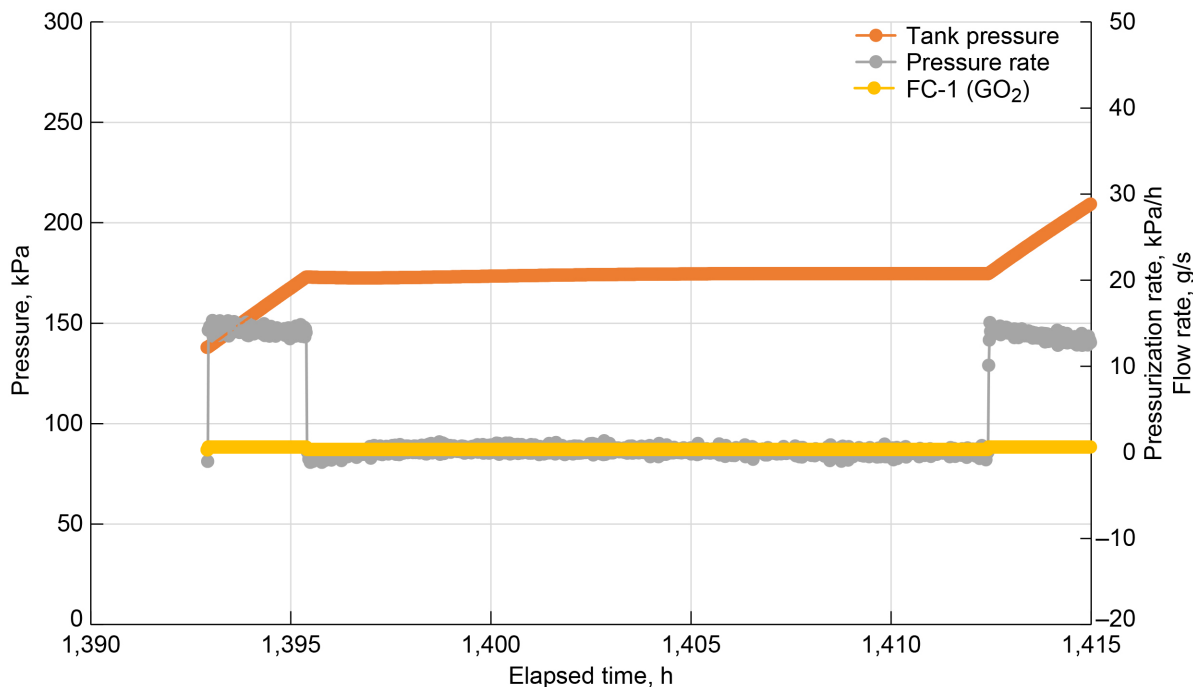


Figure 87.—Tank pressure for Test 11.

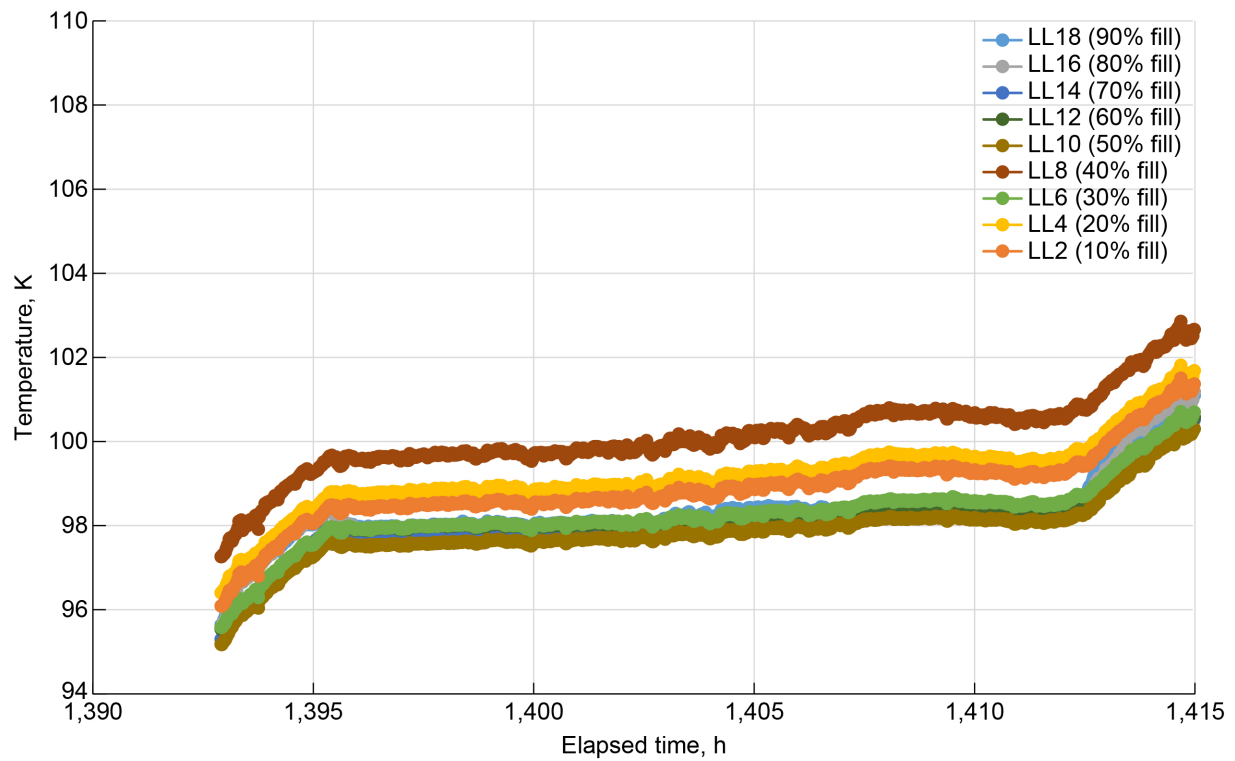


Figure 88.—Oxygen temperature distribution for Test 11.

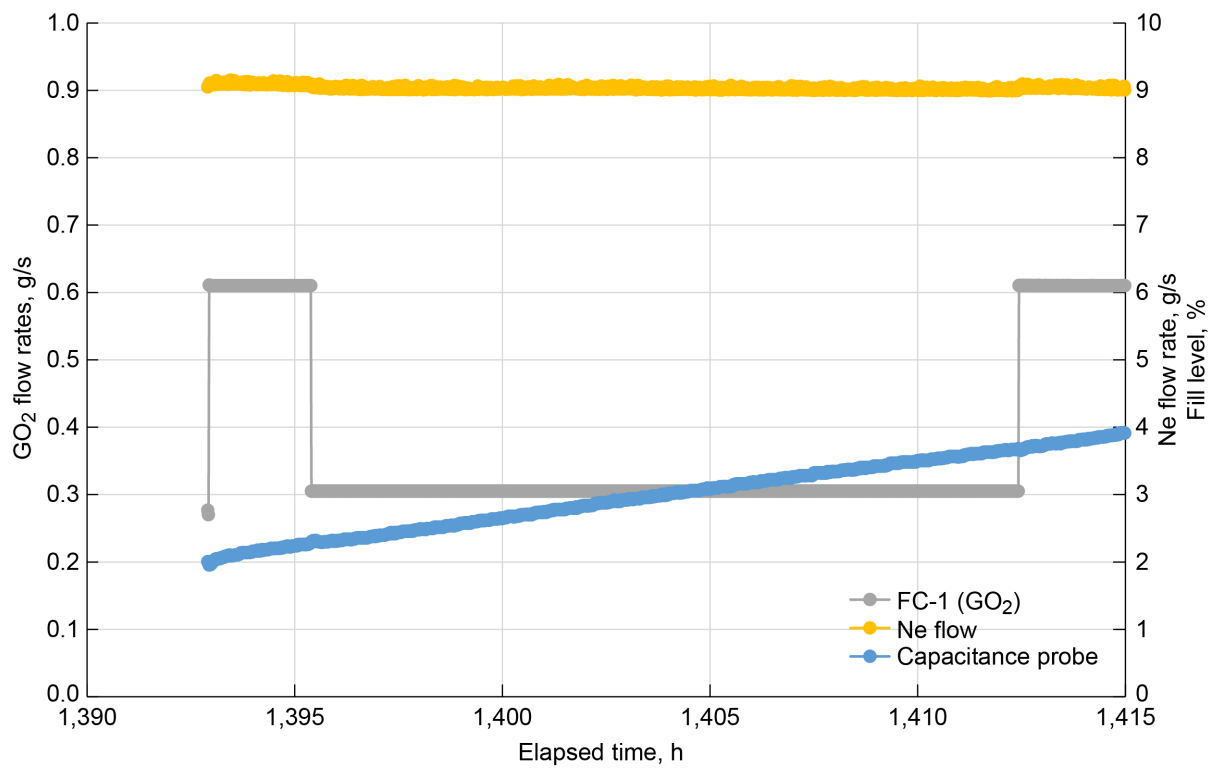


Figure 89.—Flow rates and fill level for Test 11.

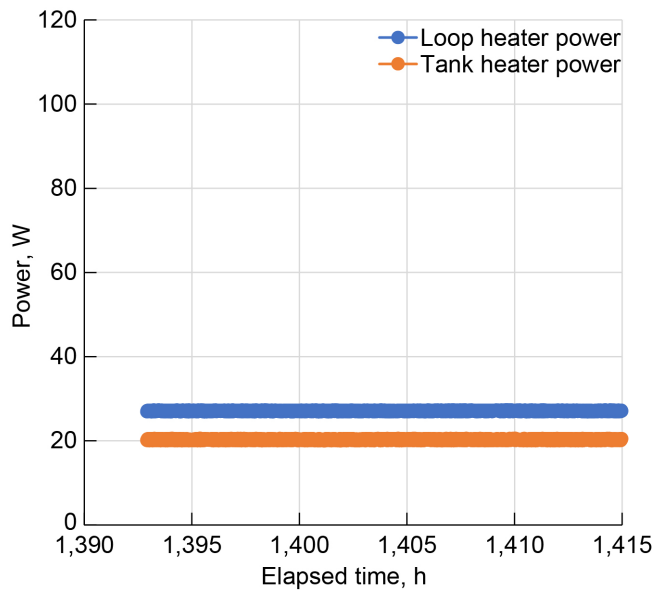


Figure 90.—Heater power for Test 11.

TABLE 26.—CONSTANT LOW FLOW LIQUEFACTION TEST MATRIX

Test 12	
Test description	Constant flow, low
Fill level, %	<10
Cold wall temperature, K	250
Initial tank pressure, kPa	^a 207
GO ₂ flow, kg/h	0.5
Heaters, W	47
Neon loop fan speed, krpm	20
GO ₂ injection method	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

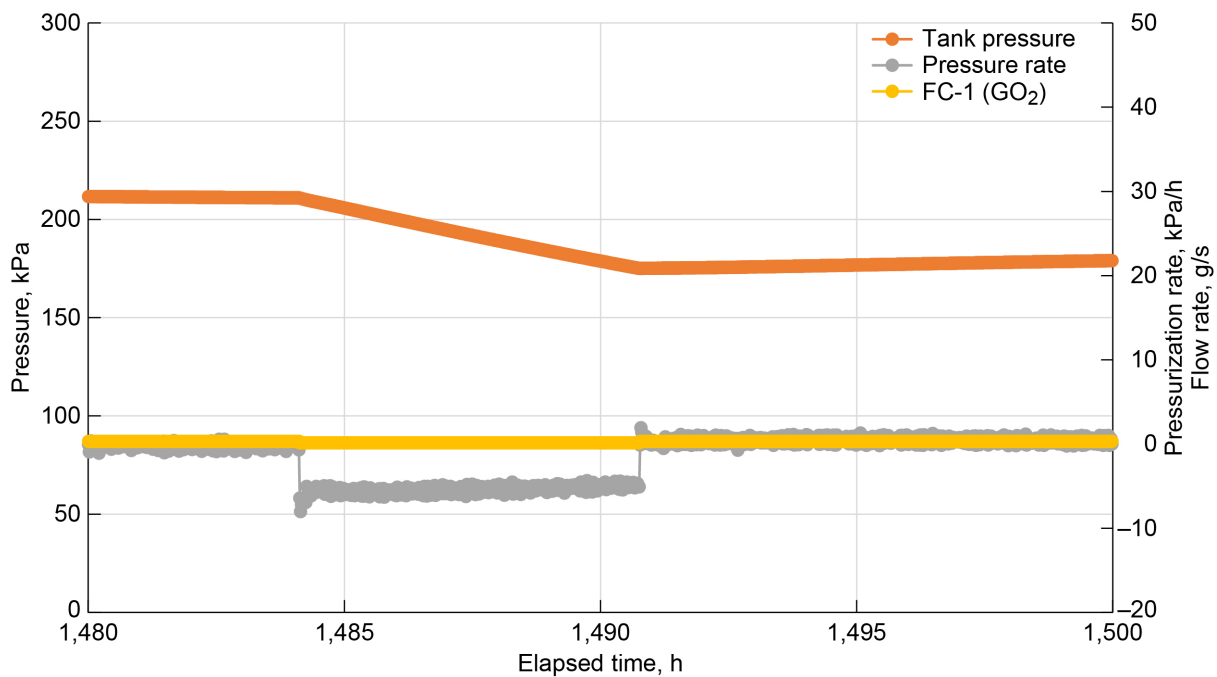
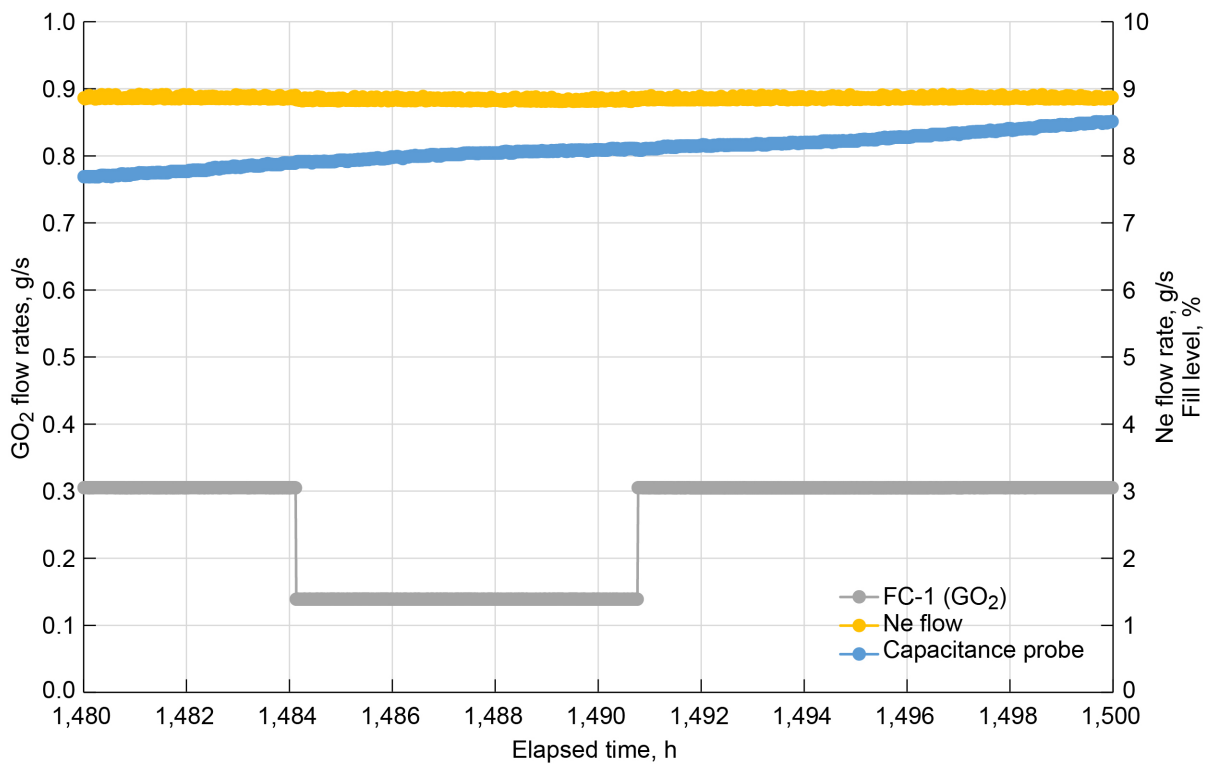
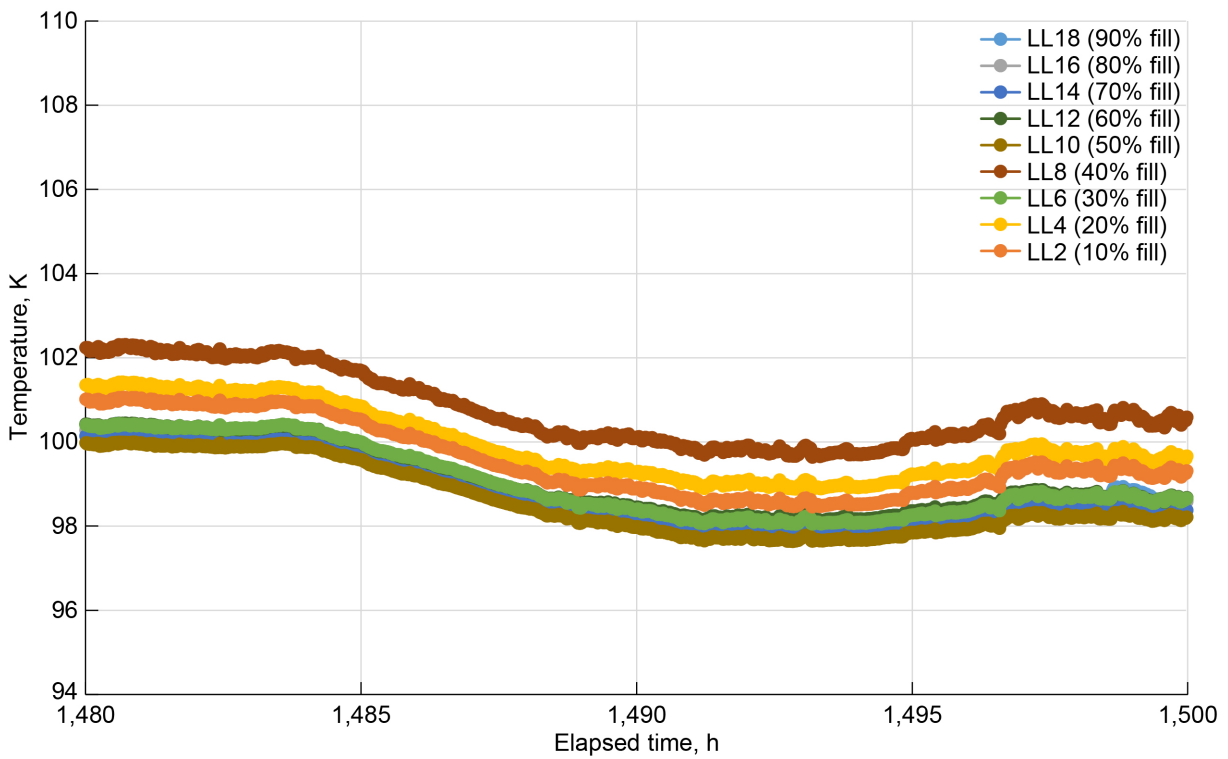


Figure 91.—Tank pressure for Test 12.



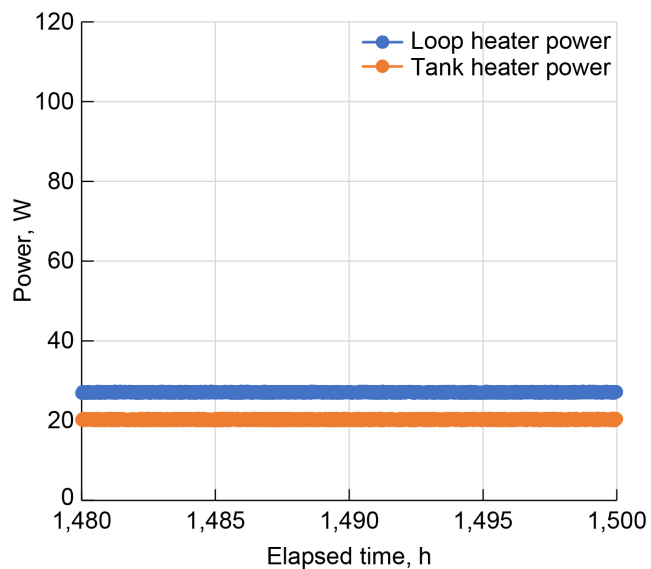


Figure 94.—Heater power for Test 12.

TABLE 27.—CONSTANT HIGH FLOW LIQUEFACTION TEST MATRIX

Test 13	
Test description	Constant flow, high
Fill level, %	<10
Cold wall temperature, K.....	250
Initial tank pressure, kPa	^a 207
GO ₂ flow, kg/h	2.2
Heaters, W	47
Neon loop fan speed, krpm.....	20
GO ₂ injection method	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

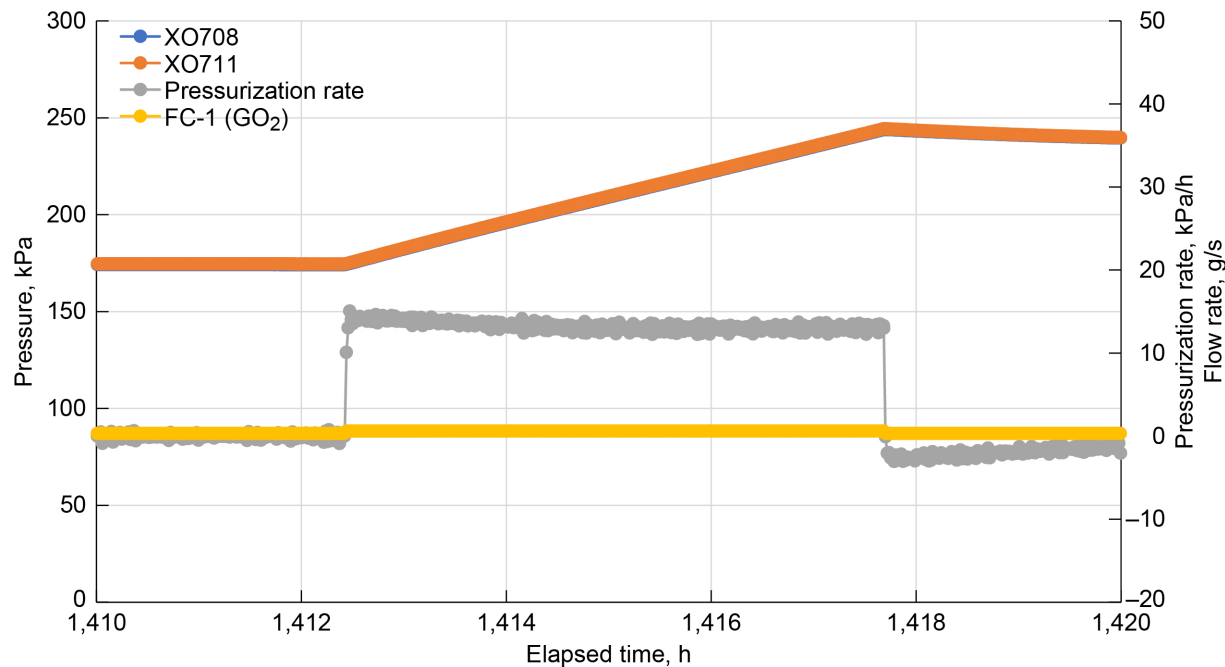


Figure 95.—Tank pressure for Test 13.

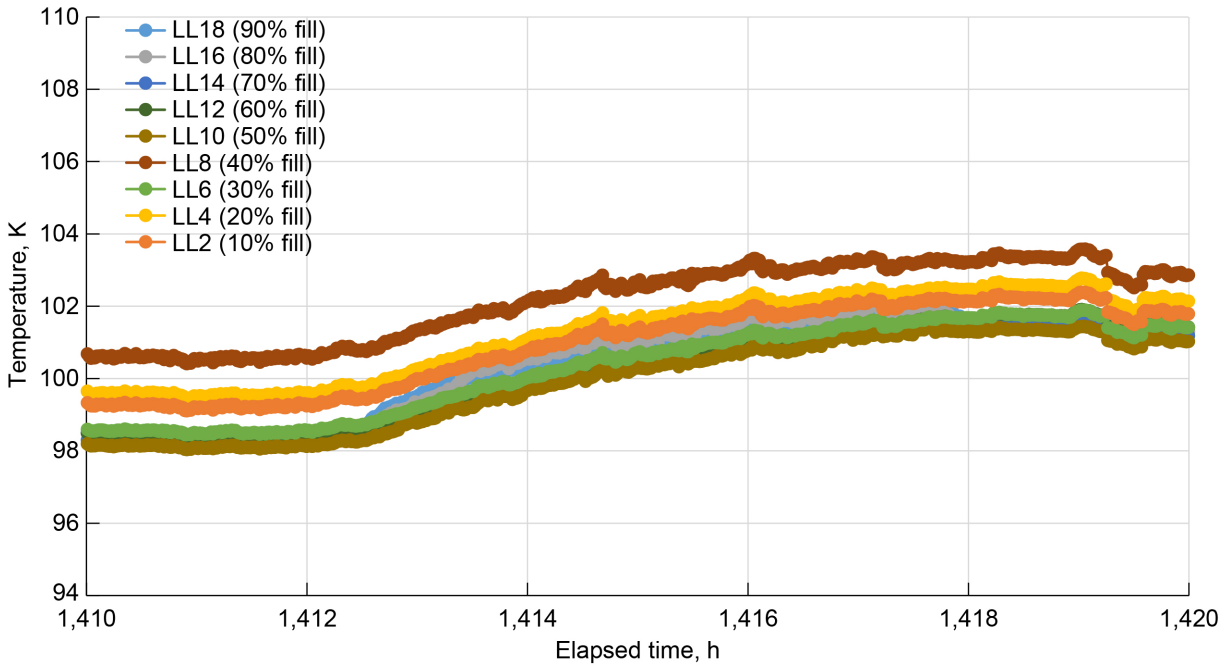


Figure 96.—Oxygen temperature distribution for Test 13.

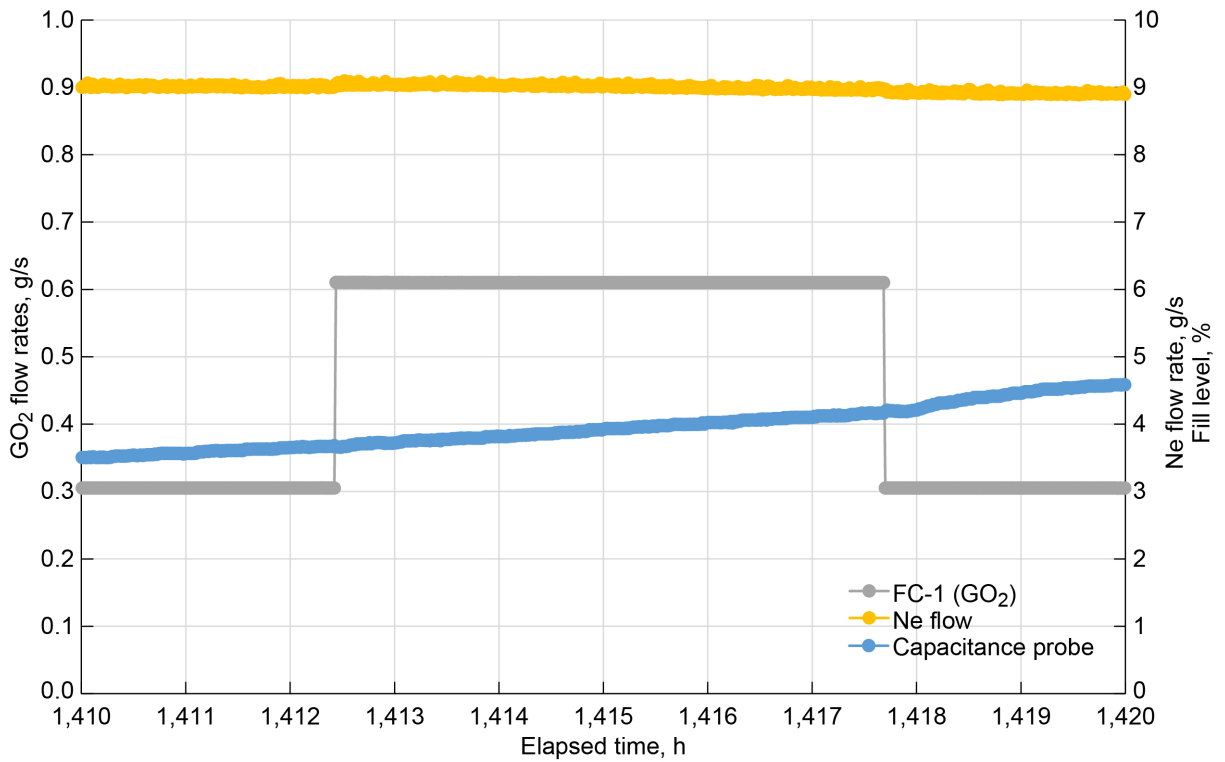


Figure 97.—Flow rates and fill level for Test 13.

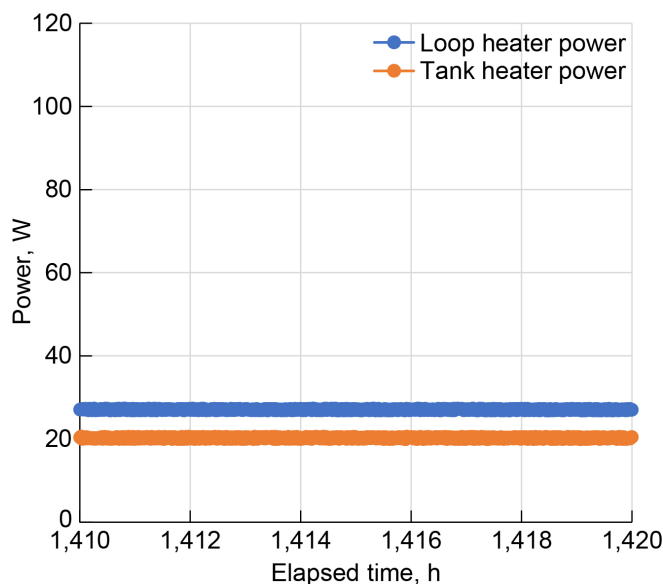


Figure 98.—Heater power for Test 13.

4.3 LO₂ Transient Liquefaction

The Variable Liquefaction Test series was run after the completion of the Constant Liquefaction Test series. At the end of the Variable Liquefaction Test series, several test repeats were performed. The tests were not completed in numerical order from the Test Matrix (see Table 7). Between each transient test, a constant liquefaction test was run to help reset the system to nominal liquefaction conditions so that one transient test did not affect the following transient. For all tests, the vacuum chamber cold wall was maintained at 250 K $\pm$ 5 K,

the vacuum was maintained at less than 5×10^{-6} T, and the neon loop fan was set to 20 krpm.

Test 28 and Test 29 (Table 28) were the first test pair completed in the Variable Liquefaction Test series. Test 29 varied the tank heater loads to simulate a cryocooler with the input value ramping up and down. Tank pressure and inlet GO₂ flow rates are shown in Figure 99 and internal tank temperatures are shown in Figure 100. System heater settings are shown in Figure 101 and neon loop temperatures are shown in Figure 102. Due to a power outage over the weekend, the initial portion of Test 28 was raising the tank pressure back to 207 kPa (30 psia) and cooling the tank down to temperature at saturation. The starting fill level was $\sim$ 1 percent and the ending fill level slightly higher than 4 percent on the capacitance probe. The tank was allowed to cool down and then the test was run for about 30 h for the system to stabilize with the tank heaters at the nominal setpoints (27 W on the neon loop and 20 W on the tank wall). At approximately Hour 1,700, the heater settings were raised to 64.4 W on the tank wall and 30 W on the neon loop; these heater settings were held for 7 h and then the heaters were set to 0 W on the tank wall and 15 W on the neon loop, which were held for 17 h. The following day, this was repeated: 7 h for the heaters at the higher settings and 17 h at the lower settings. The third day, which was a Friday, the 7 h of high power setting testing was run and the system was set to stabilize over the weekend for Test 30. However, another power failure occurred that weekend at approximately Hour 1,766 and the system once again safed itself (turned off all heaters and the cryocooler and opened the tank vent to atmosphere); at this point the pressure and temperatures within the tank ullage started increasing even as the heater power decreased.

TABLE 28.—VARIABLE CRYOCOOLER LIFT LIQUEFACTION TEST MATRIX

Test no.	Test description	Fill level, %	Cold wall temperature, K	Initial tank pressure, kPa	GO ₂ flow, kg/h	Heaters, W	Neon loop fan speed, krpm	GO ₂ injection method
28	Set initial conditions	<10	250	207	^a 1.1	47	20	Vent line
29	Variable cryocooler lift	<10	250	^a 207	1.1	15 to 94.4	20	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

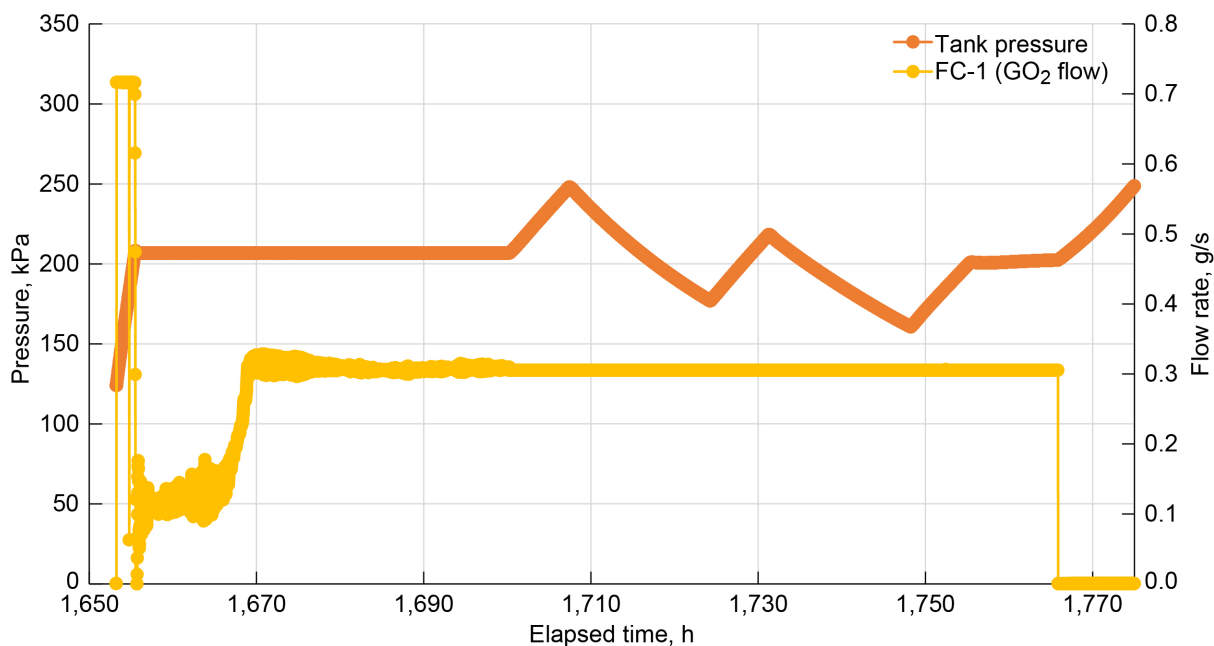


Figure 99.—Tank pressure and GO₂ inlet flow rate as function of time during Tests 28 and 29. Power failure occurred at Hour 1,766.

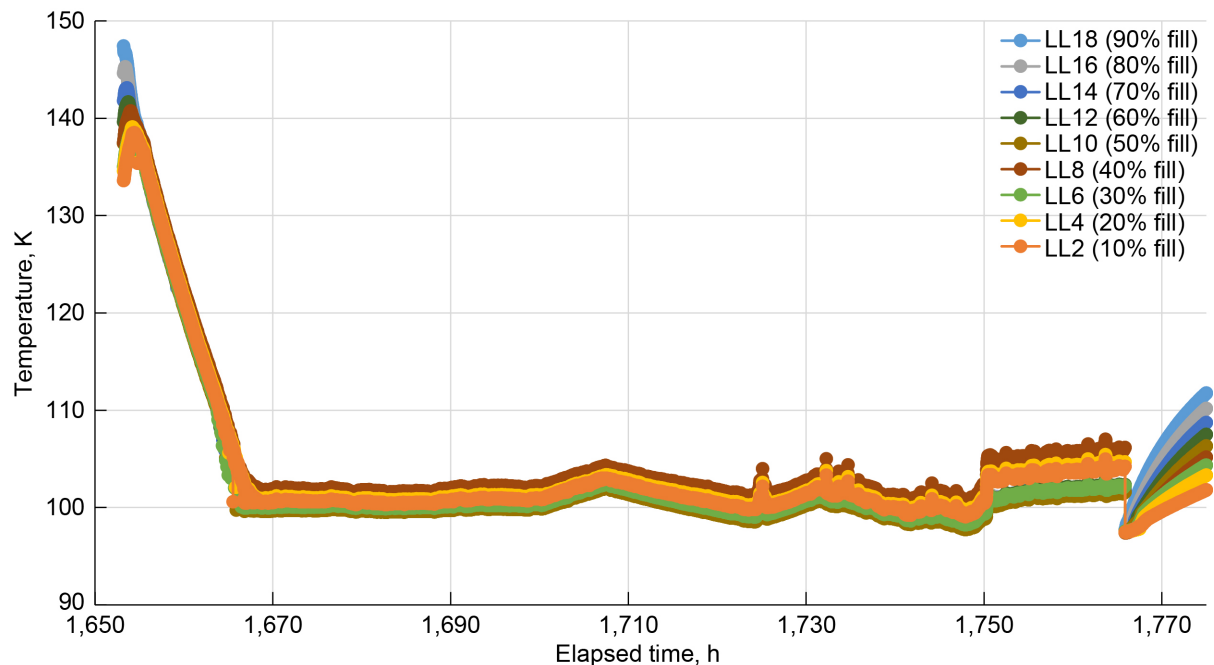


Figure 100.—Internal tank fluid temperatures as function of time during Tests 28 and 29. Power failure occurred at Hour 1,766.

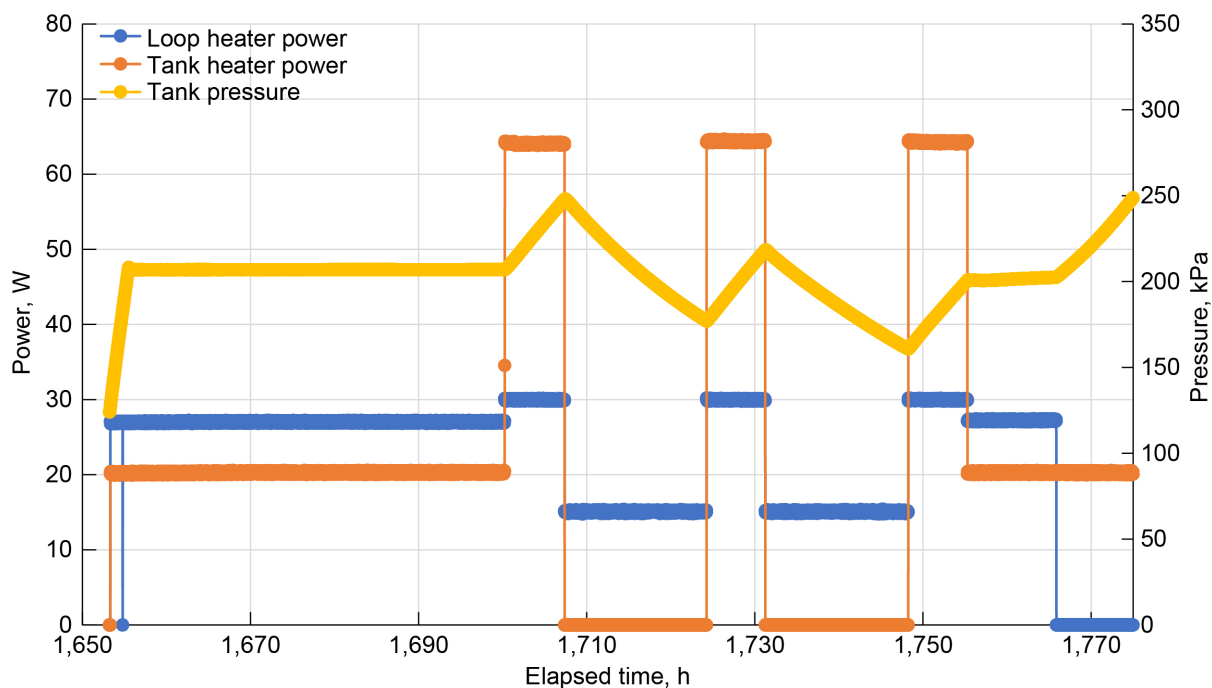


Figure 101.—System heaters and tank pressure as function of time during Tests 28 and 29. Power failure occurred at Hour 1,766.

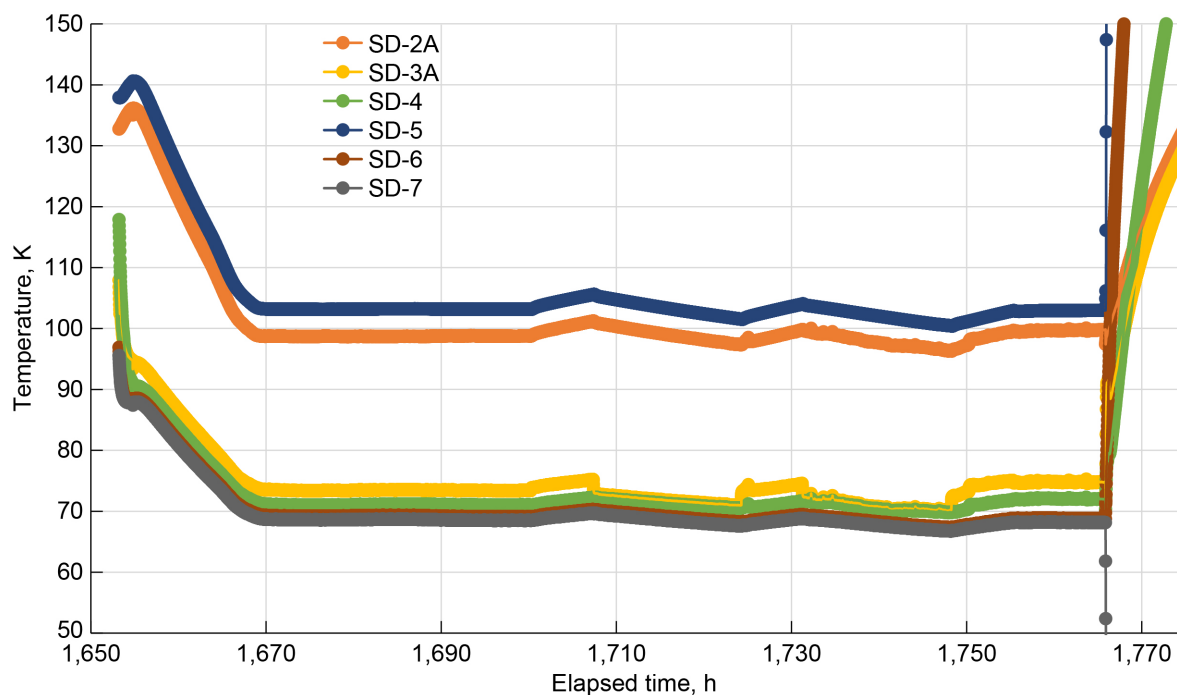


Figure 102.—Neon loop temperatures as function of time during Tests 28 and 29. Power failure occurred at Hour 1,766.

Test 30 started off once again with the tank temperature higher than 100 K and required the cryocooler to be used to chill the tank down to saturation (Table 29). Figure 103 shows the tank temperatures as a function of time after the cryocooler was turned on. Figure 104 shows the pressure control that was performed using the GO₂ inlet flow shown in Figure 105. Figure 105 also shows where the capacitance probe started reading as the tank started to fill up with LO₂. Test 30 moved directly into Test 31, which was a demonstration of the transient response to environmental transients (Table 29). Figure 106 shows the cold wall temperatures as a function of time. The cold wall was run at 290 K for ~6.5 h a day and 225 K for ~16 h a day. The rest of the duration was the transitions between temperature settings. A total of four warm and three cold portions of the cycle were run; at the end of the fourth warm cycle, the cold wall was reset to 250 K. However, at Hour 1,932.6, the power to the cryocoolers failed and the cryocoolers turned off. Figure 107 shows the tank pressure as a function of time. The periodic response to the temperature swings is evident. The first three warm portions and

two cold portions of the cycles repeat quite well; however, the third cold cycle did not allow the pressure of the tank to fall at all. Figure 108 shows the inlet flow rate held at 0.3 g/s (1.1 kg/h) and the increase of fill level within the tank on the capacitance probe. The cyclical behavior of the capacitance probe shows that during the hotter periods with the transitions to warm fluid temperatures, the liquefaction rate went down as expected. Furthermore, the decrease in the fill level suggests that the fluid evaporates during the transitions. However, the swings are much larger than would be expected and the total increase is more than it should have been at the rates tested. Figure 109 shows the internal temperatures and Figure 110 shows a zoomed-in view on the internal temperatures right after the cryocooler turned off. It becomes evident just how much the temperature sensors were being affected by the EMI caused by the cryocooling system by this point. After the failure, the temperature gradient with the 19 internal diodes is less than 1 K as the top-to-bottom flow of the neon cooling loop continued to eliminate stratification.

TABLE 29.—VARIABLE ENVIRONMENTAL TEMPERATURE LIQUEFACTION TEST MATRIX

Test no.	Test description	Fill level, %	Cold wall temperature, K	Initial tank pressure, kPa	GO ₂ flow, kg/h	Heaters, W	Neon loop fan speed, krpm	GO ₂ injection method
30	Set initial conditions	<10	250	207	1.1 ^a	47	20	Vent line
31	Variable environmental temperature	<10	225 to 290	207 ^a	1.1	47	20	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

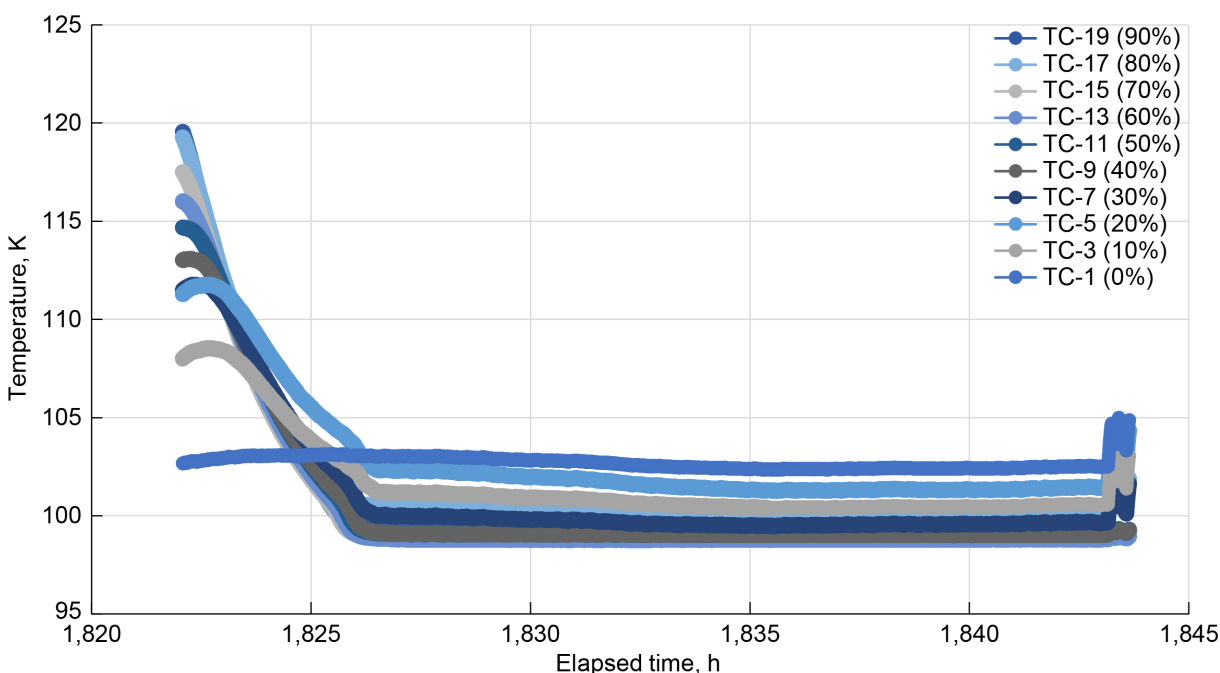


Figure 103.—Tank wall temperatures during Test 30.

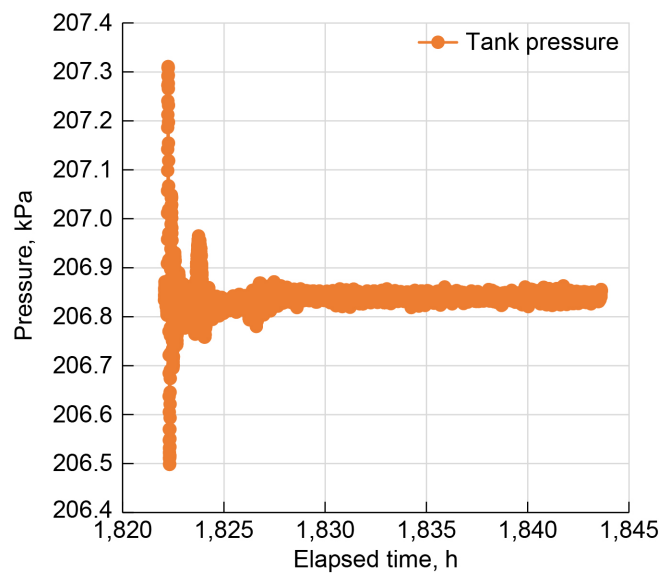


Figure 104.—Tank pressure during Test 30.

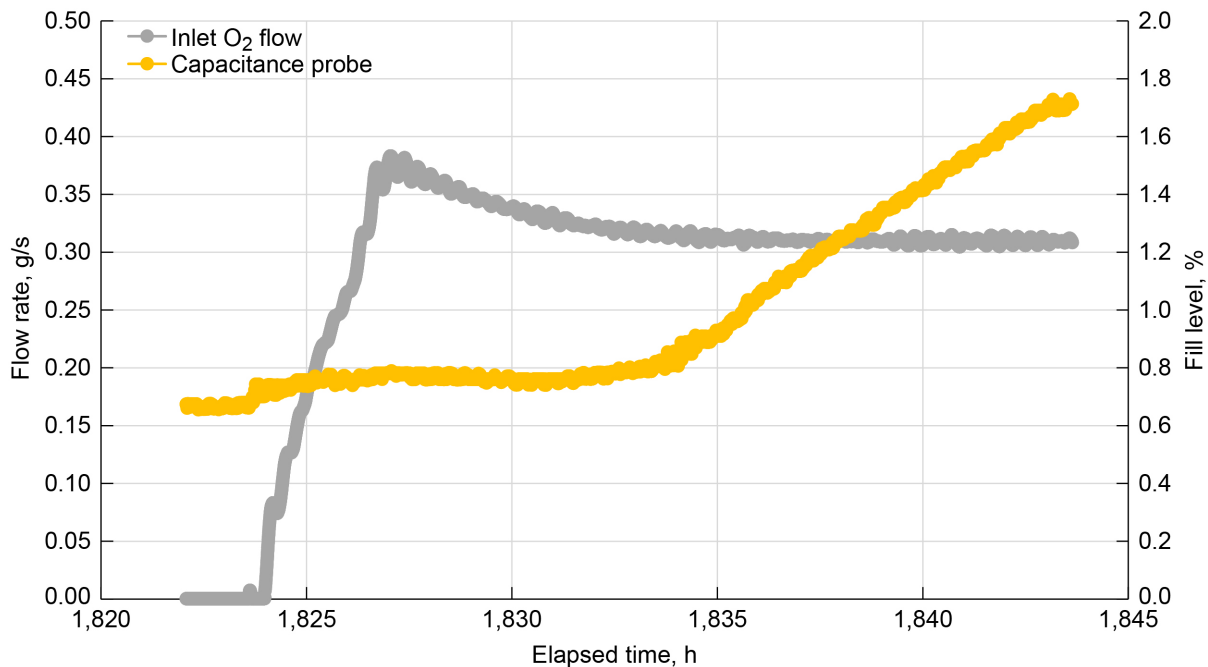


Figure 105.—Oxygen flow rate and tank fill level as function of time during Test 30.

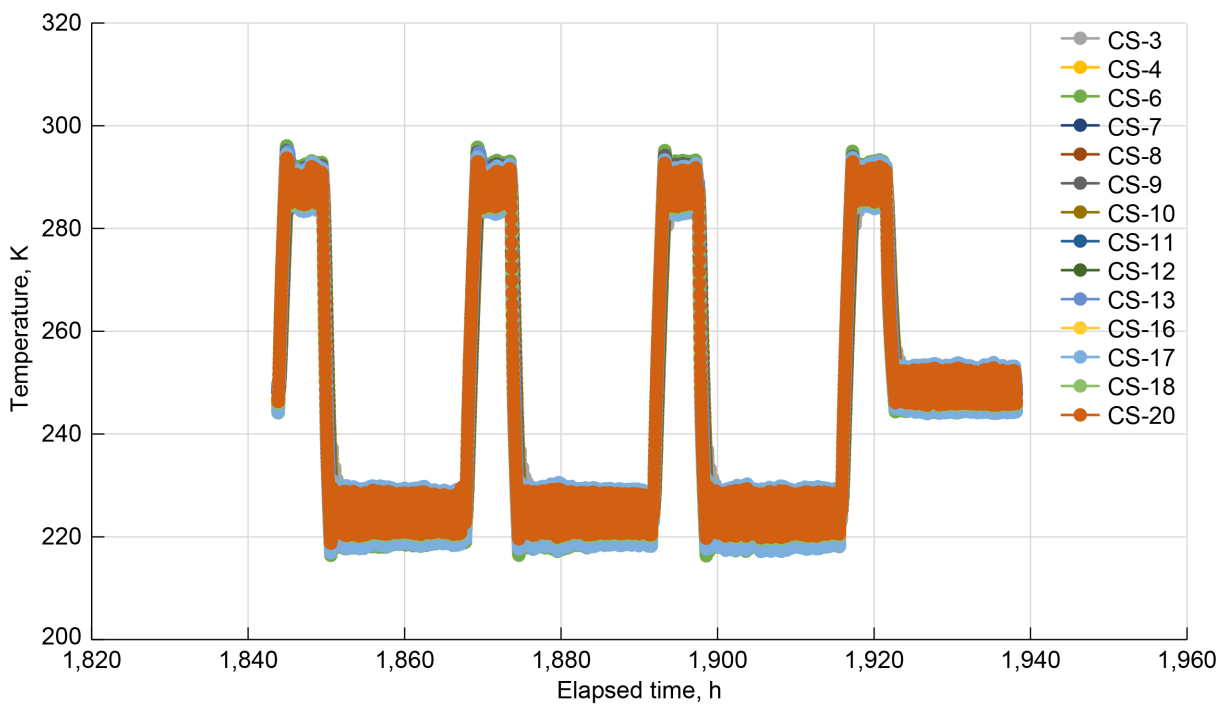


Figure 106.—Cold wall temperatures during Test 31.

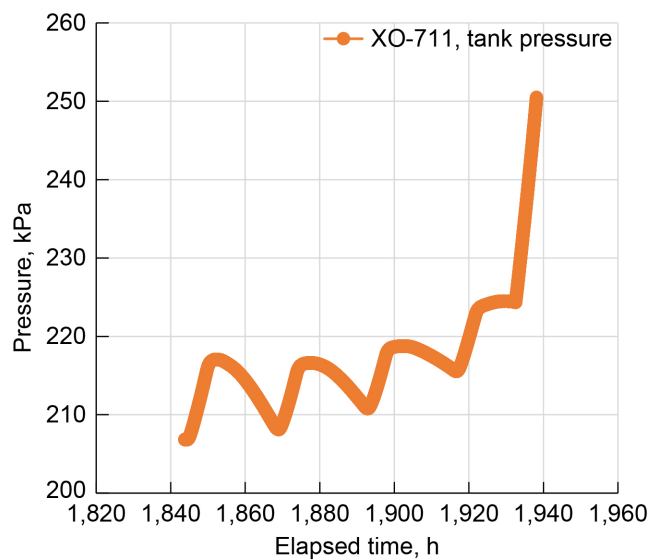


Figure 107.—Tank pressure during Test 31.

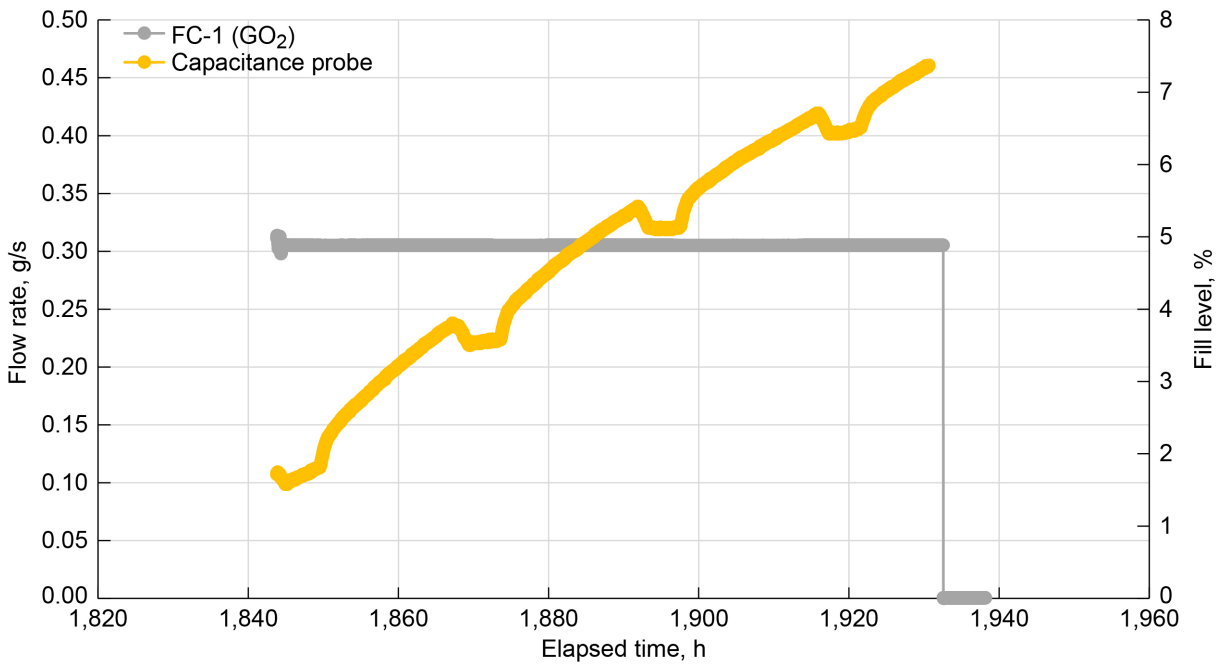


Figure 108.—Inlet gas flow rate and capacitance probe measurement during Test 31.

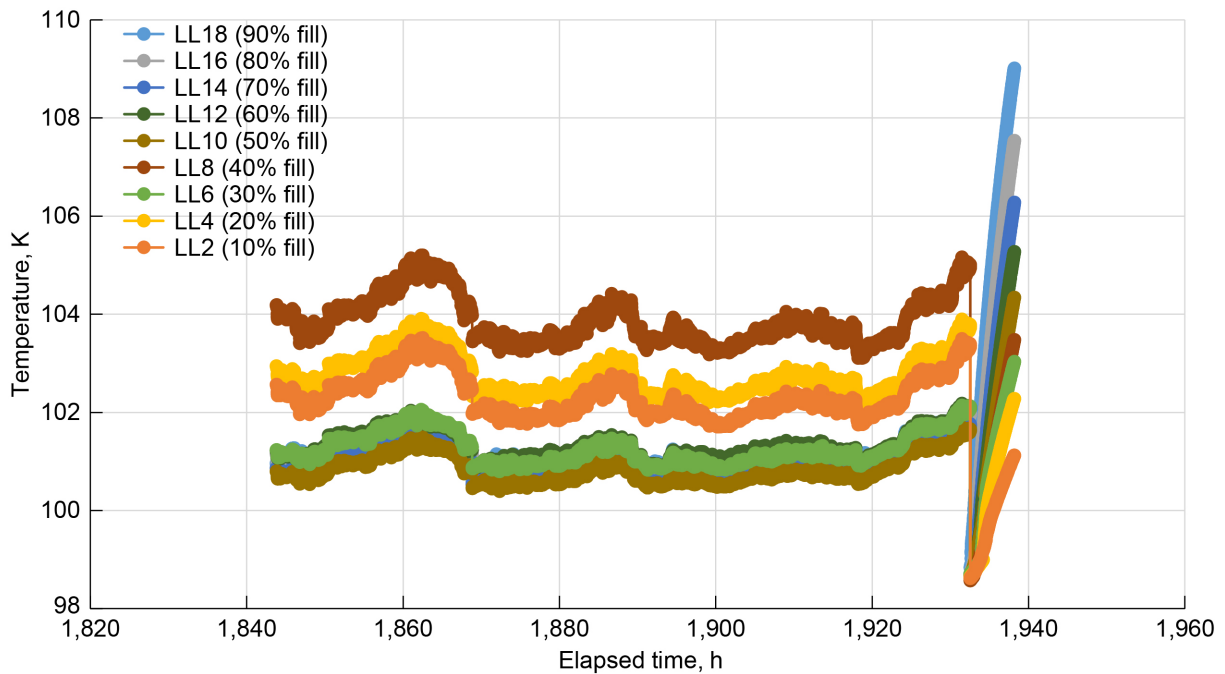


Figure 109.—Internal fluid temperatures during Test 31.

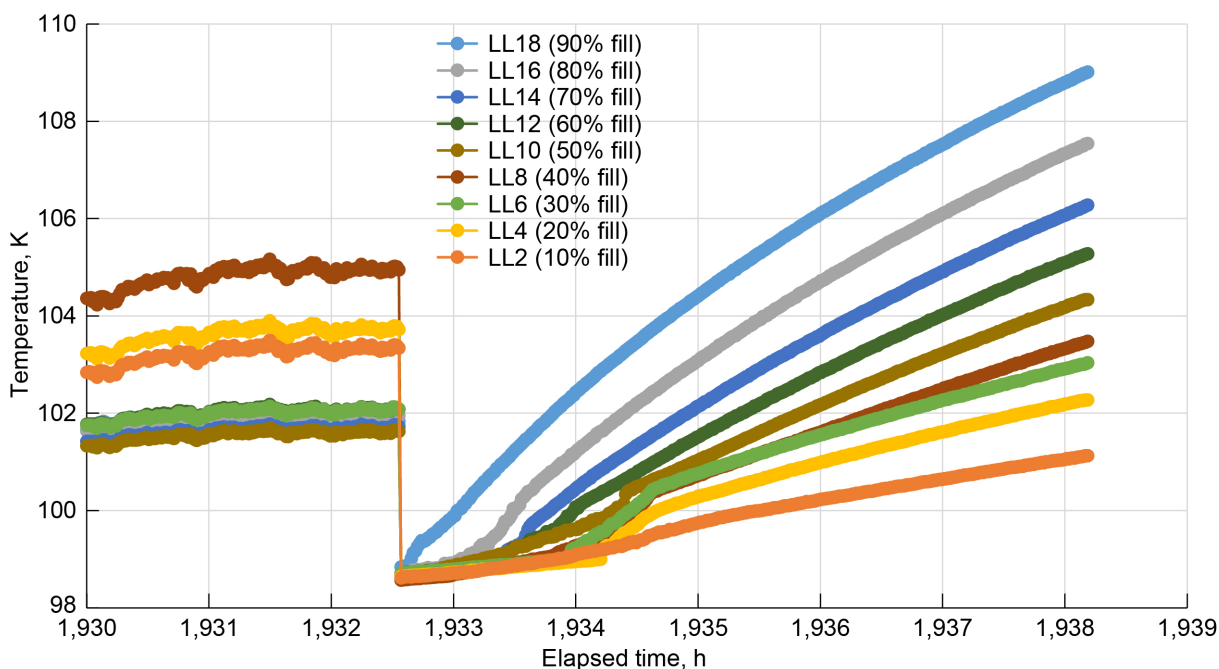


Figure 110.—Internal test fluid temperatures at the end of Test 31 around the shutdown of the cryocooler system.

TABLE 30.—VARIABLE GO₂ FLOW RATE LIQUEFACTION TEST MATRIX

Test no.	Test description	Fill level, %	Cold wall temperature, K	Initial tank pressure, kPa	GO ₂ flow, kg/h	Heaters, W	Neon loop fan speed, krpm	GO ₂ injection method
26	Set initial conditions	<10	250	207	^a 1.1	47	20	Vent line
27	Variable GO ₂ flow rate	<10	250	^a 207	0.9 to 1.6	47	20	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

Test 26 (Table 30) was restarted using the same nominal setup as Tests 28 and 30 in order to create the initial conditions for Tests 27, 29, and 31, respectively. The results for Tests 26 and 27 are shown in Figure 111 to Figure 115. Test 27 started at approximately Hour 2,036, where the incoming liquefaction flow rate was increased to 0.44 g/s (1.58 kg/h) for 7 h and then decreased to 0.24 g/s (0.86 kg/h) for 17 h. This averaged out to 0.3 g/s (1.07 kg/h) over the 24-h cycle. Three cycles were repeated as shown in Figure 111. Figure 112 shows the pressure response of the oxygen system to the three input cycles. The tank pressure peaks and minimums were very repeatable. Figure 113 shows the full suite of internal tank temperature

sensors and Figure 114 shows a selected subset (mainly in the ullage); for the most part, the fluid in the tank followed the saturation pressure, both up and down. In Figure 114, LL7 is a liquid sensor while LL17, LL18, and LL19 are at the top of the ullage. LL18 and LL19 show some initial effects of perhaps a degree of stratification during the higher flow rate portions of the testing, although LL17 does not indicate any stratification below it when the flow changes quantity. Figure 115 shows that the changes in the fluid temperature and tank wall translated over to the neon flow, which affected the entire cryocooler system with temperature swings on the order of 3 K.

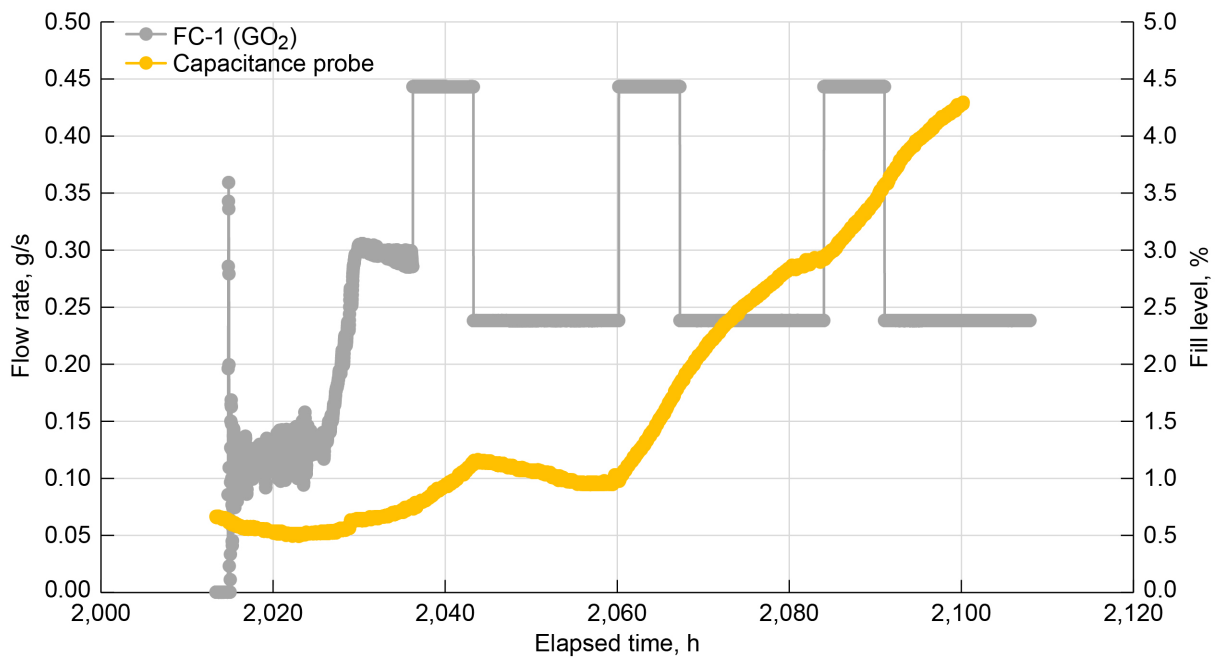


Figure 111.—Capacitance probe and GO₂ flow rate as function of time during Test 26 and Test 27.

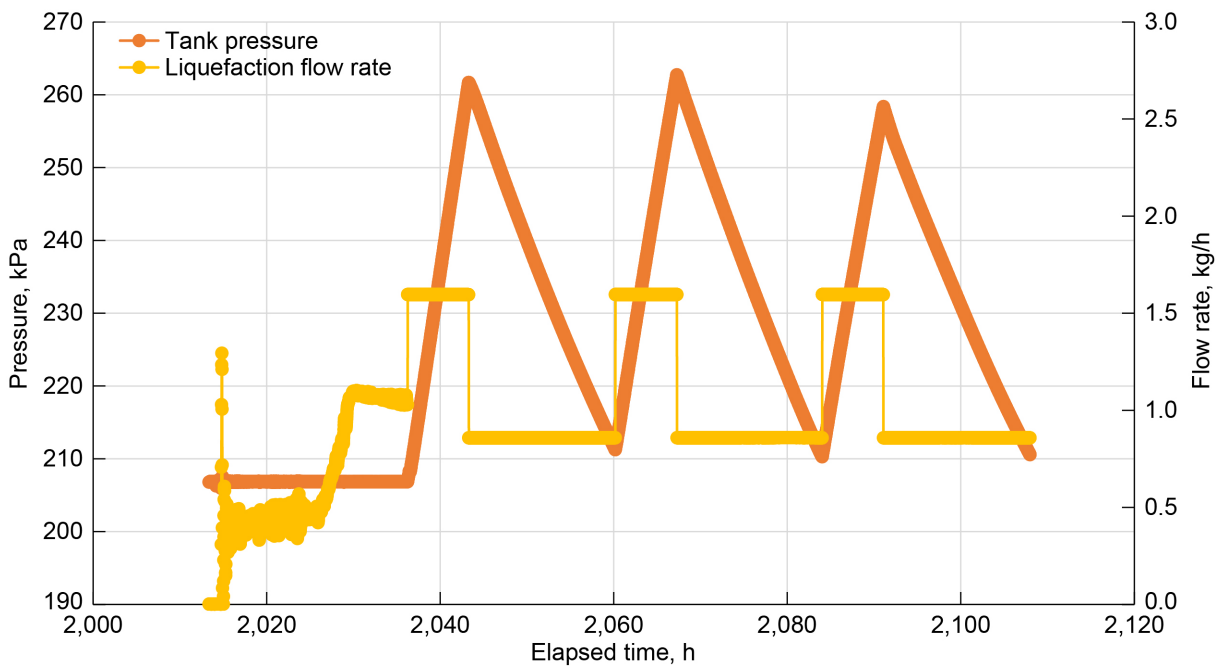


Figure 112.—Oxygen liquefaction flow rate and tank pressure as function of time during Test 26 and Test 27.

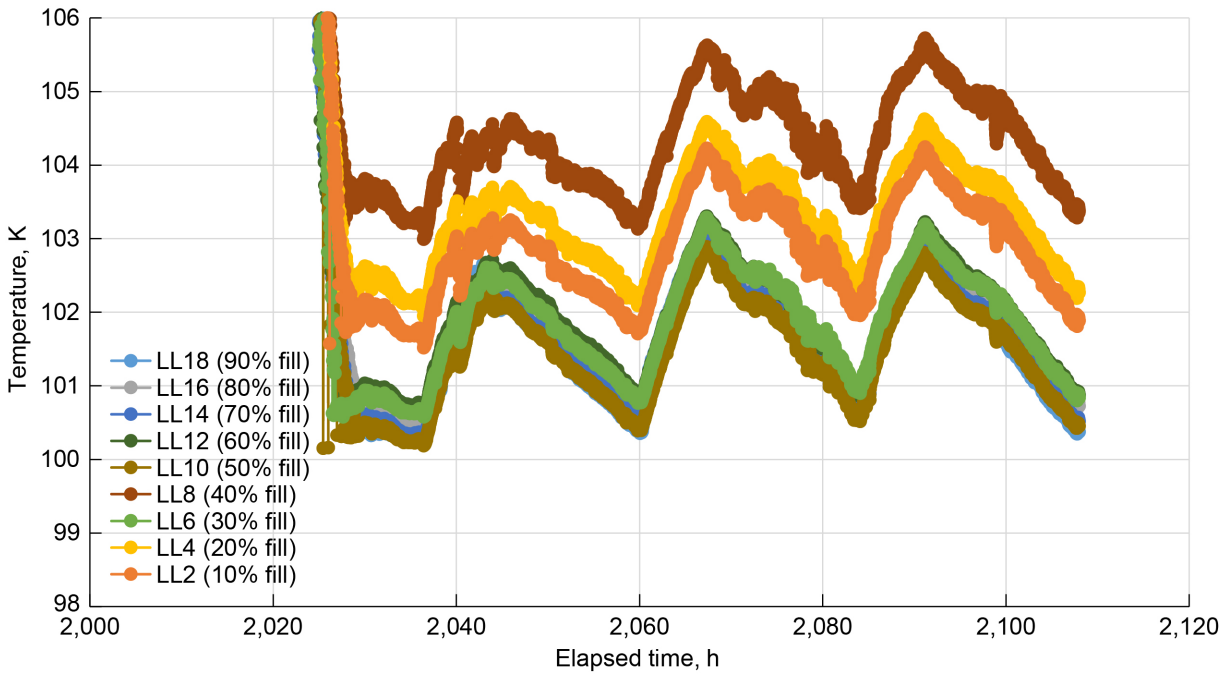


Figure 113.—Oxygen temperature sensors inside tank during Test 26 and Test 27.

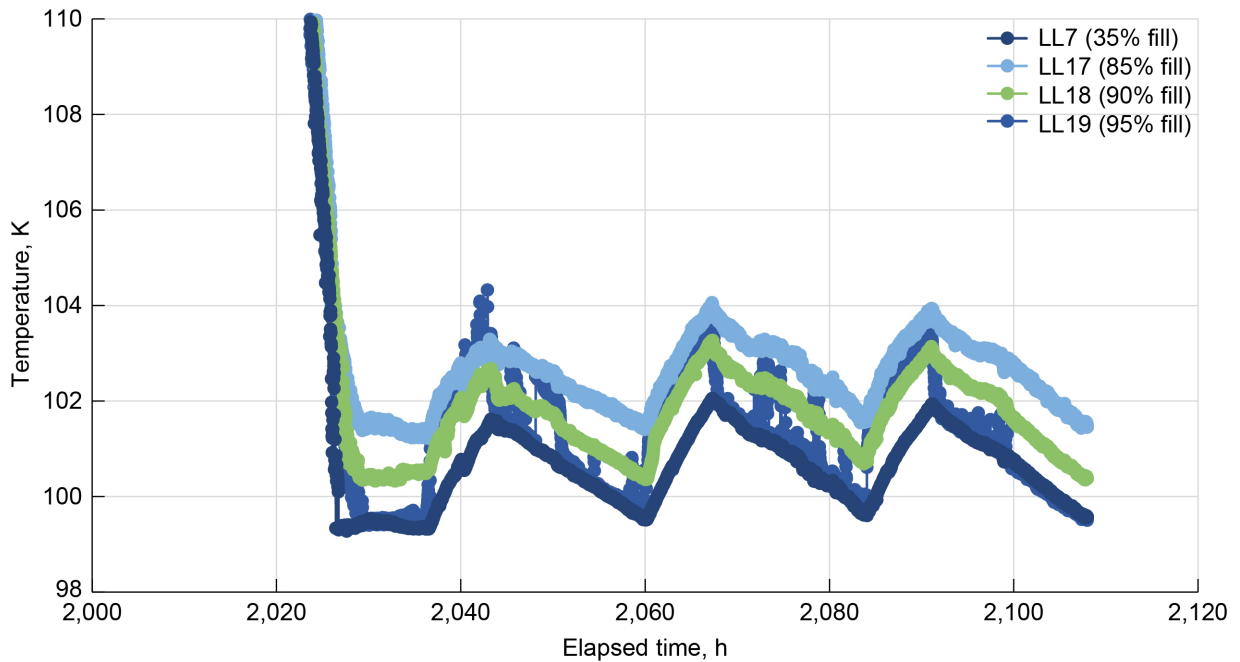


Figure 114.—Select oxygen temperature sensors during Test 26 and Test 27.

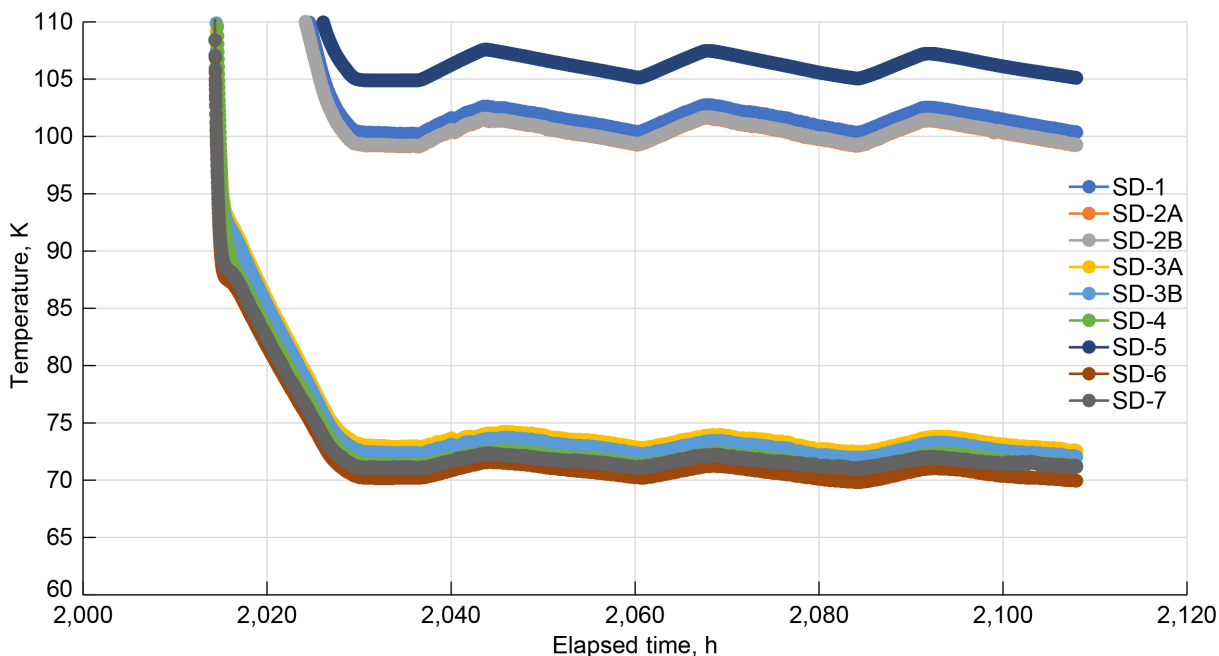


Figure 115.—Neon flow loop temperatures during Test 26 and Test 27.

Following Test 27, it was decided to repeat Test 29 because the original test did not meet the repeatability guidelines laid out in the steady-state criteria. This test was called Test 29-2 (Table 31). Both the magnitude of the heater power and the duration of the cycles were changed from Test 29; this was driven by observations that a 24-h cycle was not necessary to obtain a linear response as well as a desire to speed up testing to achieve more of the test matrix. Instead, a 4-h cycle was used (as seen in Figure 116) as this allowed two cycles to be run per day. Before the test and overnight in between the test cycles, a separate test (from the 4z series) was run, the venting event at approximately Hour 2,228 is to reset the pressure for Test 29-2 on the second day. The tank pressure response from these cycles is shown in Figure 116 and the oxygen internal tank temperatures are shown in Figure 117. The heater setpoints were changed to be 93.5 W (30 W on the neon loop heater and 63.5 W on the tank heaters) for 2 h and then 0 W on both heaters

for 2 h (see Figure 118). Although the second cycle was slightly off in response, the first, third, and fourth cycles met the repeatability criteria.

TABLE 31.—VARIABLE CRYOCOOLER
LIFT LIQUEFACTION TEST MATRIX

Test 29-2	
Test description	Variable cryocooler lift
Fill level, %	<10
Cold wall temperature, K	250
Initial tank pressure, kPa	^a 207
GO ₂ flow, kg/h	1.1
Heaters, W	0 to 93.5
Neon loop fan speed, krpm	20
GO ₂ injection method	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

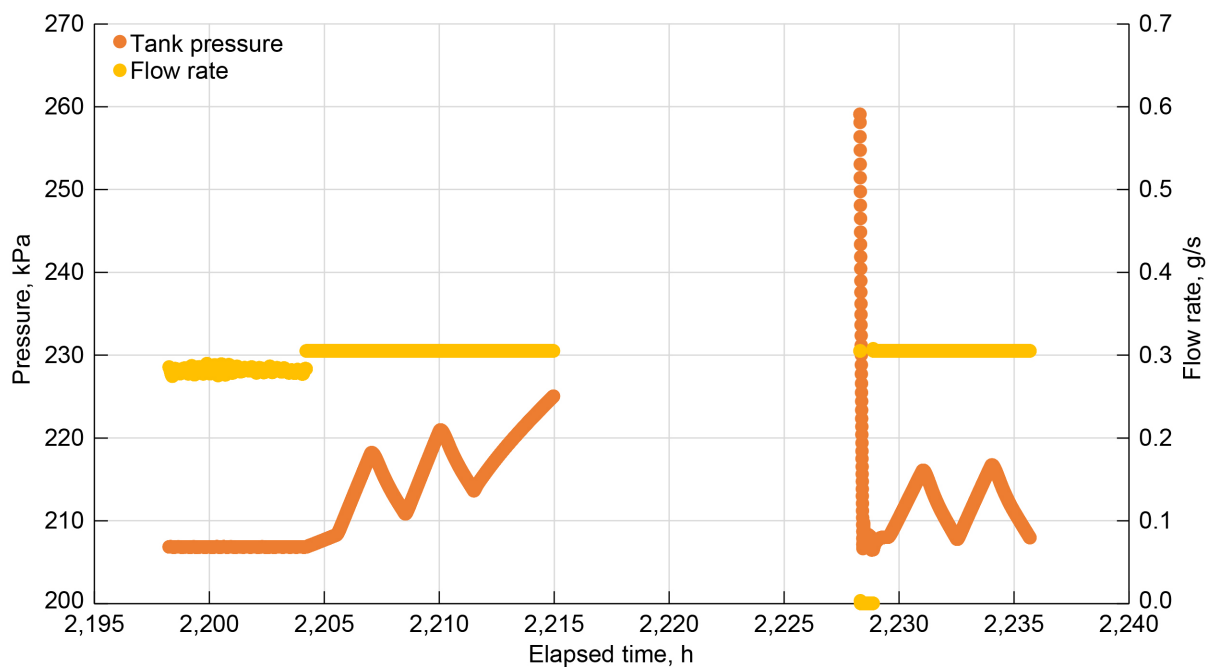


Figure 116.—Incoming oxygen mass flow rate and pressure response as function of time for Test 29-2. Note that tank pressure variations prior to Test 29-2 starting at Hour 2,206 and after Hour 2,212, as well as decreases at Hour 2,230 are due to changing of fan speed for Test 4z-1.

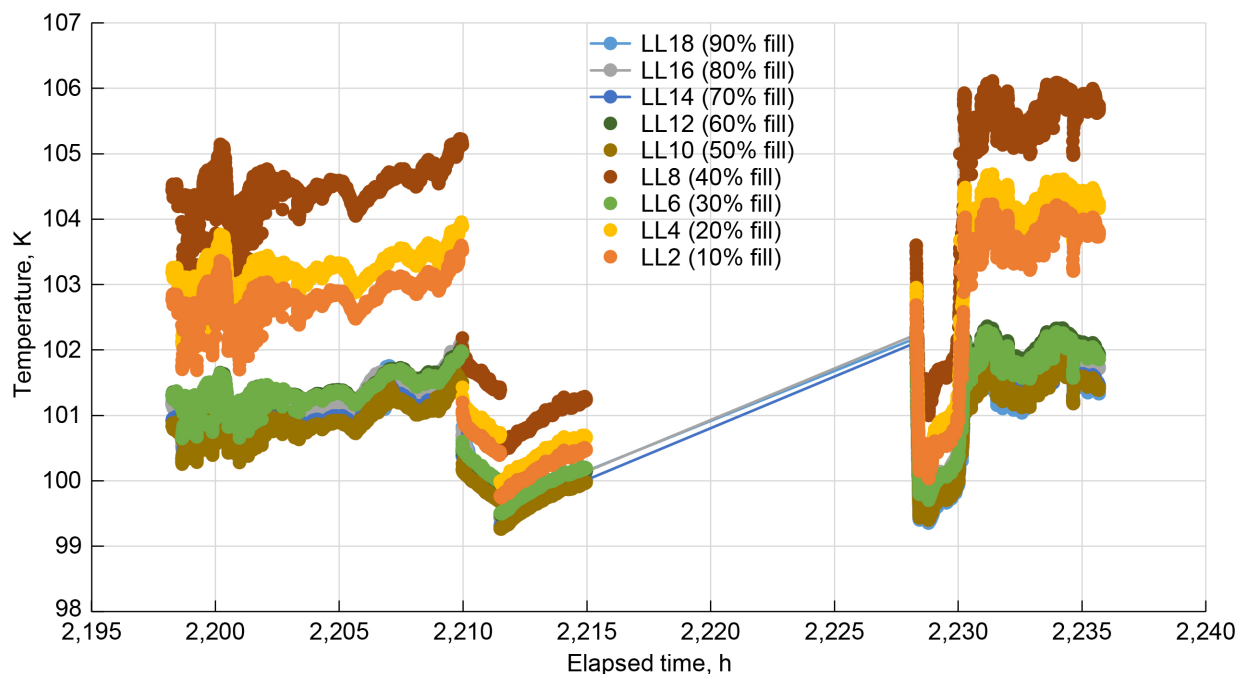


Figure 117.—Oxygen fluid temperature response during Test 29-2.

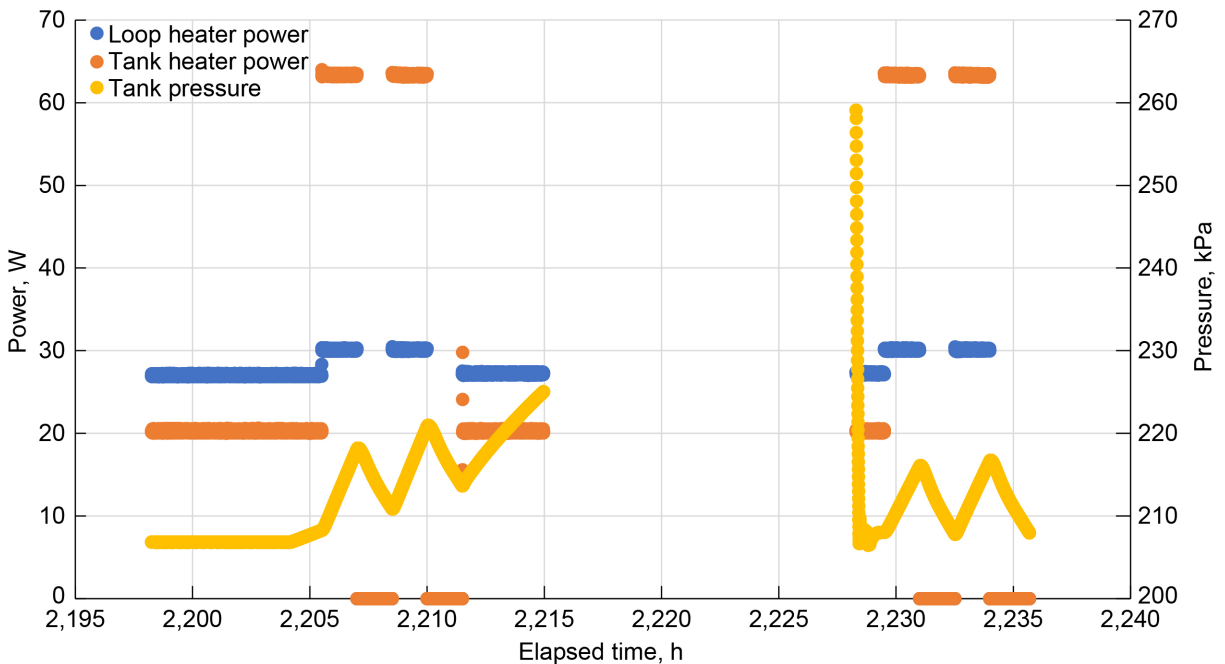


Figure 118.—Heater power settings and pressure response for Test 29-2. Note that tank pressure decreases at Hour 2,230 at the end of Test 4z-1.

TABLE 32.—RESET LIQUEFACTION
INITIAL CONDITIONS TEST MATRIX

Test 32	
Test description.....	Set initial conditions
Fill level, %.....	90
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	207
GO ₂ flow, kg/h..... ^a	1.1
Heaters, W.....	47
Neon loop fan speed, krpm.....	20
GO ₂ injection method.....	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

The last transient test (Test 32) was run at the 90 percent fill level instead of ~5 percent (Table 32). In order to get to an appropriate fill level and let the temperatures stabilize, Test 32 was run over several days. The pressure response is shown in Figure 119. After filling the tank to more than 90 percent full (see Figure 120), the oxygen inlet flow rate was turned on using the dip tube to bubble through the liquid and warm it up faster (see Temperature response in Figure 121). Additionally, the tank heaters were set to ~70 W (see Figure 122). This caused the tank to saturate at 207 kPa (30 psia) in ~40 h, some 50 h faster than in initial conditioning attempts earlier in testing. The decrease in pressure between Hour 2,425 and Hour 2,433 is due to the decrease of the constant bubbling flow rate to 0.3 g/s (1.08 kg/h) as it was not enough flow to maintain constant

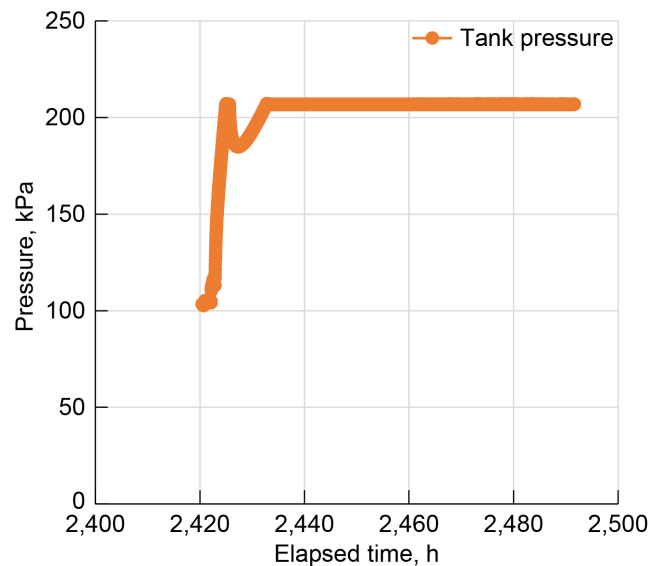


Figure 119.—Pressure response for Test 32.

pressure while the system initially stabilized. During Test 32, the flow meters were bypassed to allow for venting of the tank to maintain pressure control with the constant flow rate of GO₂ coming into the tank. The bypassing of the flow meters was to remove them from the restriction in maintaining tank pressure. This general approach of bypassing the flow meters was used multiple times during the oxygen conditioning, especially over the weekend when operations were more reliant on the automated control of the system.

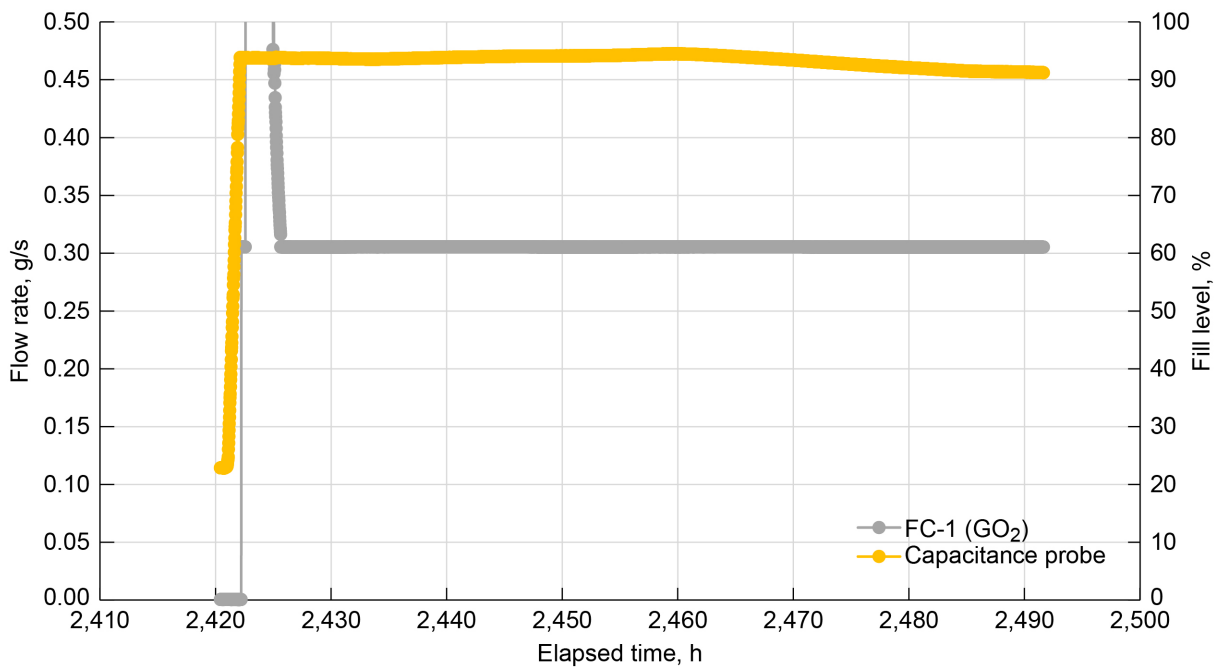


Figure 120.—Fill level and oxygen inlet flow for Test 32.

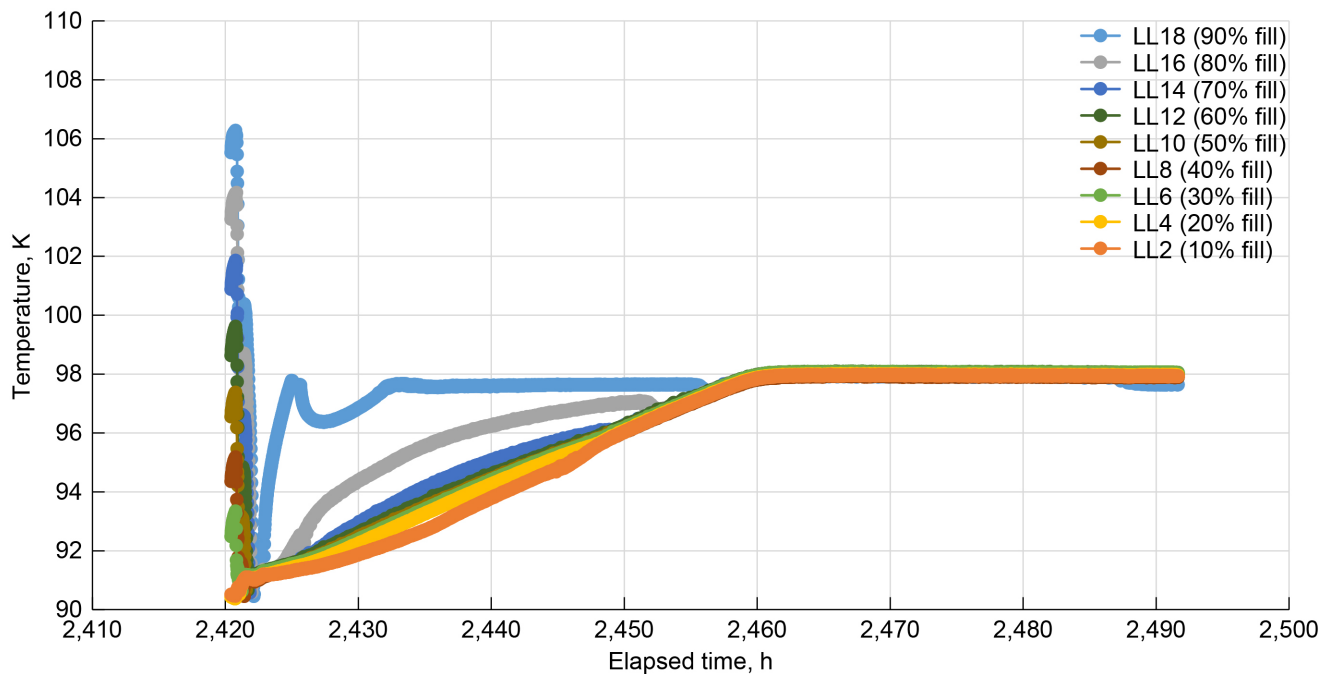


Figure 121.—Oxygen temperature response during Test 32.

Once the test tank was conditioned appropriately, Test 33 commenced around Hour 2,516 (Table 33). Flow settings similar to those used as in Test 27 were used with shorter durations, closer to Test 29-2. Overnight, in between cycles of Test 33, the Test 4z-3 series was run. That data is omitted from

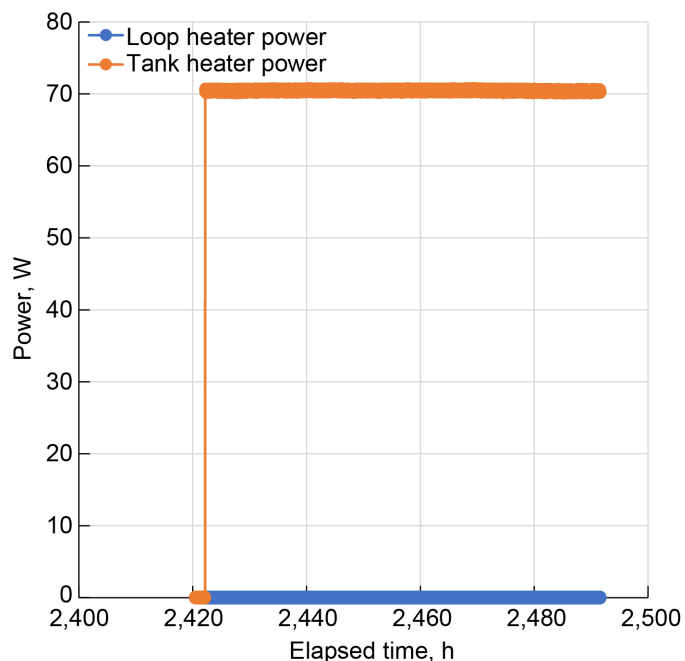


Figure 122.—Heater settings during Test 32.

the following plots. The peak flow of 0.44 g/s (1.58 kg/h) was used, for a duration of 4 h; the lower flow of 0.24 g/s (0.86 kg/h) was then applied for 2.5 h (see Figure 123). Four tests were run, the first three used ullage injection and the fourth used dip tube injection. The pressure responses for the four cycles can be seen in Figure 124. The oxygen fluid temperatures are shown in Figure 125 with a few select sensors shown in Figure 126 to demonstrate the stratification that was observed in the ullage and along the liquid/vapor interface. The stratification is clearly present in LL18 and LL19 in the first three cycles, and not present at all in the fourth cycle. Figure 127 shows the neon flow temperatures, which unlike in Figure 115 (Test 27) did not have much time to respond to the system changes in Test 33.

TABLE 33.—VARIABLE GO₂ FLOW RATE LIQUEFACTION TEST MATRIX

Test 33	
Test description	Variable GO ₂ flow rate
Fill level, %	90
Cold wall temperature, K	250
Initial tank pressure, kPa	^a 207
GO ₂ flow, kg/h	0.9 to 1.6
Heaters, W	47
Neon loop fan speed, krpm	20
GO ₂ injection method	Vent line and dip tube

^aNominal value given, but test allowed this variable to respond to all other inputs.

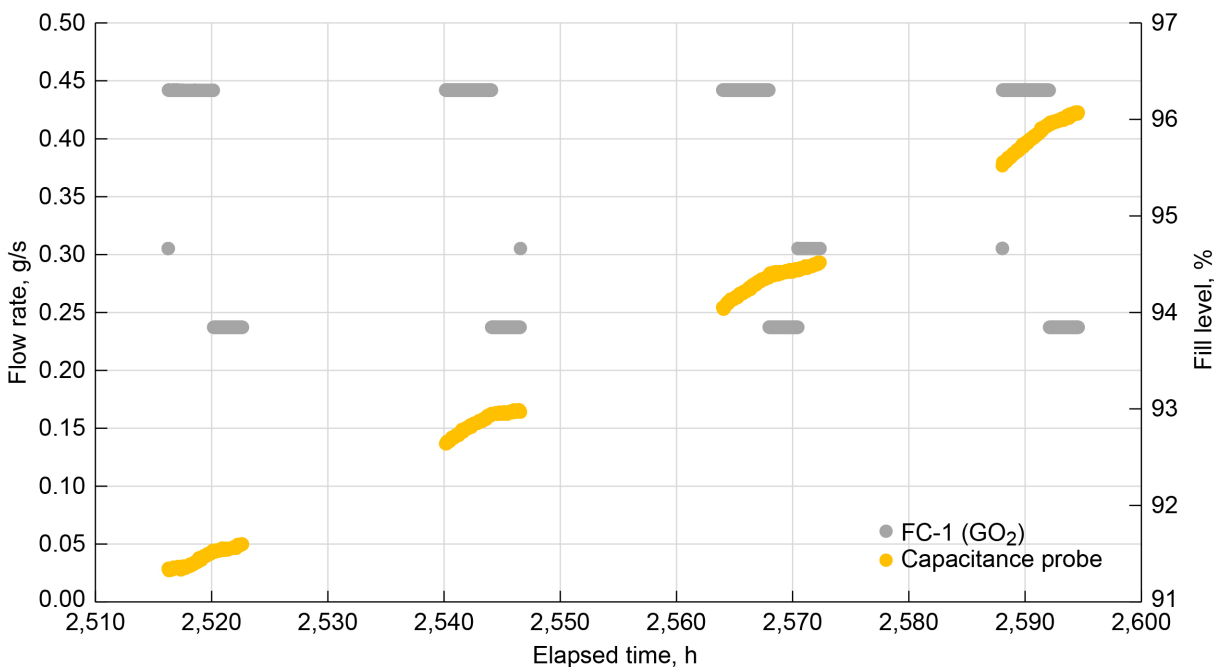


Figure 123.—Capacitance probe and GO₂ flow rate as function of time during Test 33.

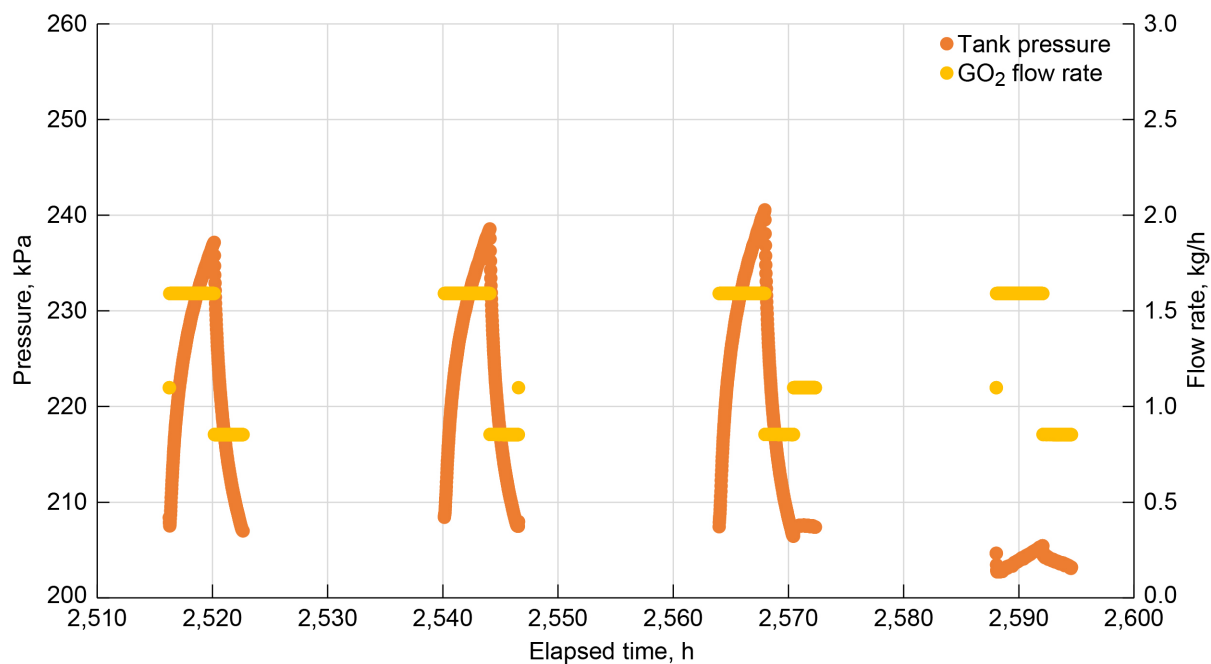


Figure 124.—Oxygen liquefaction flow rate and tank pressure as function of time during Test 33.

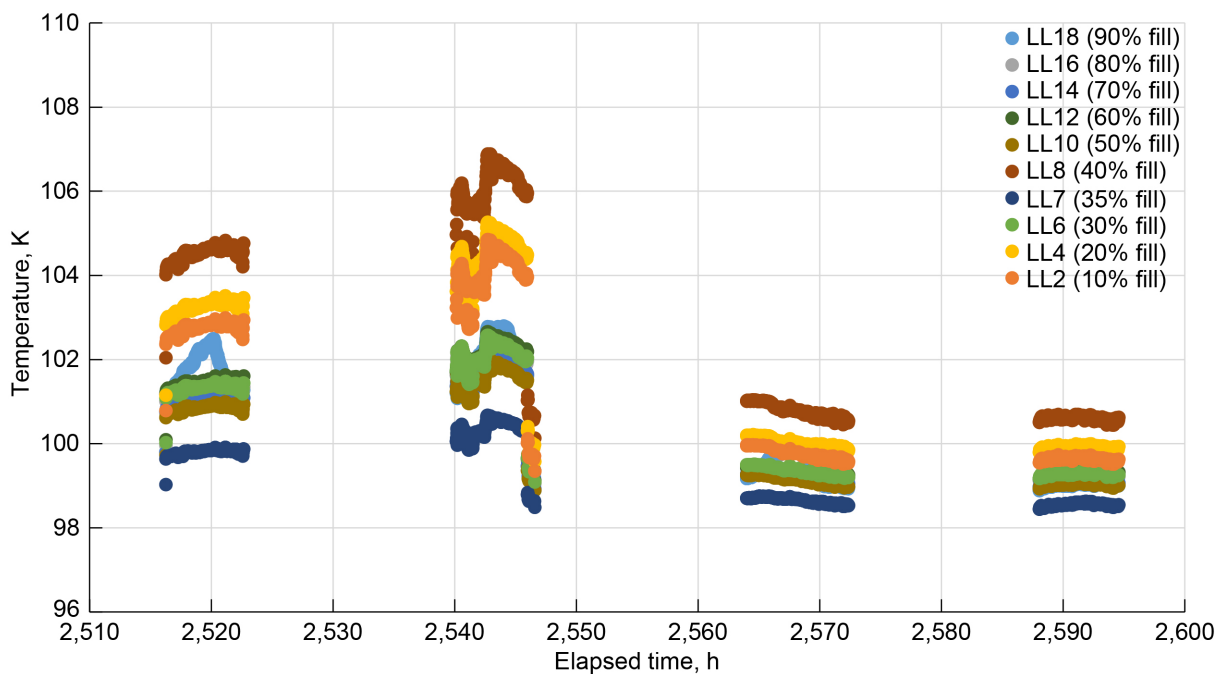


Figure 125.—Oxygen temperature sensors inside tank during Test 33.

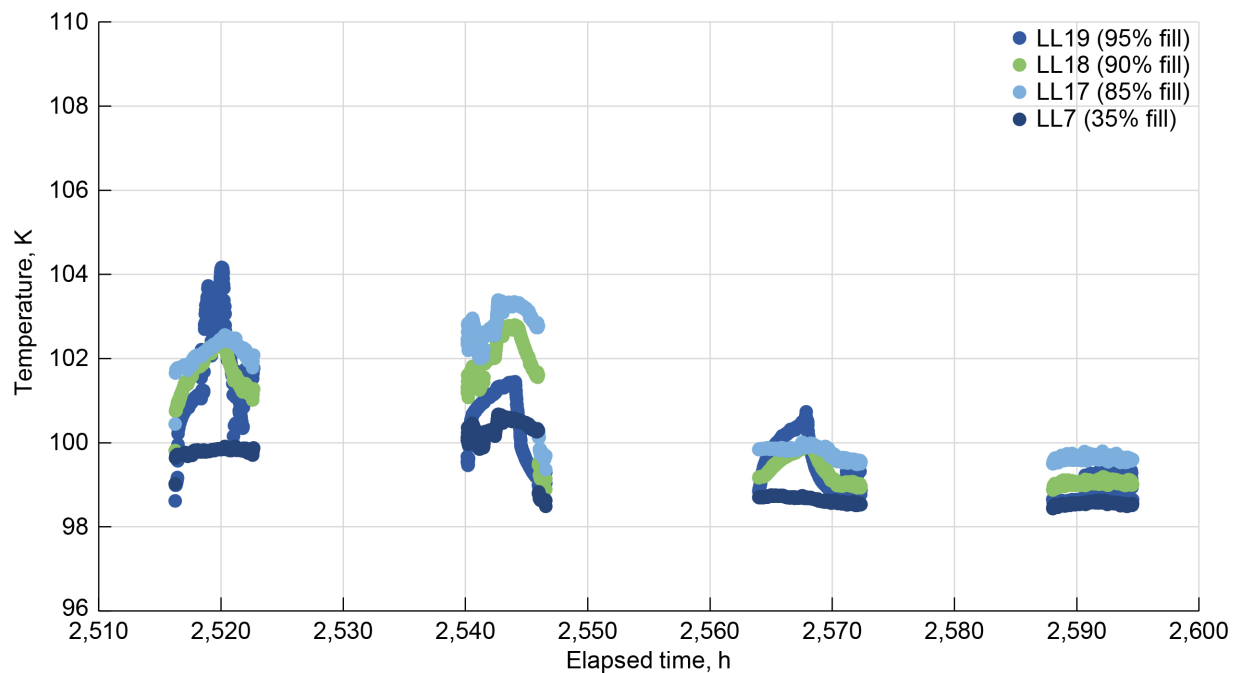


Figure 126.—Select oxygen temperature sensors during Test 33.

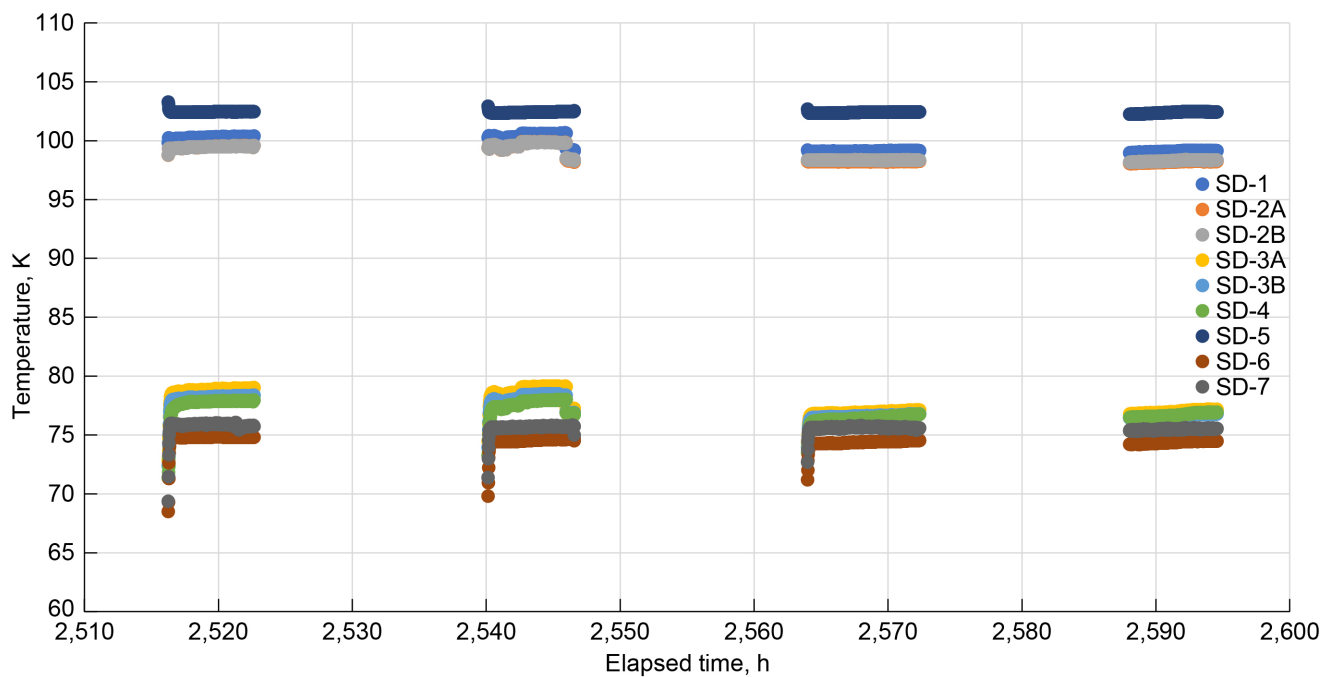


Figure 127.—Neon flow loop temperatures during Test 33.

4.4 Supplemental Liquefaction Tests

Several tests were run as supplemental tests, not in the original test matrix. These were run after learning how the system operated, either to maximize the potential of the system performance or better understand it.

The 4z test series was set up to help the modeling team better evaluate the system performance with how the models operate (Table 34). The tank pressure, rather than being controlled, was allowed to float given a specific fan speed, oxygen mass flow rate, and heater setpoints. All Test 4z tests were run using ullage gas insertion. The main variable changed during the tests was the fan speed. Three different tests were run in the 4z test series at three different fill levels: Test 4z-1 was run at 5 percent full (during Test 29-2), Test 4z-2 was run at ~15 percent fill level, and Test 4z-3 was run at ~90 percent fill level (during Test 33). Each test was run at fan speeds of 15, 16.25, 17.5, and 20 krpm. The tank heater was held constant at 20 W, the loop heater at 27 W, the oxygen inlet flow at 0.3 g/s (1.08 kg/h). The 4z tests were often run overnight in between transient tests that occurred during the day.

Figure 128 shows the different tests at different fan speeds for Test 4z-1. The neon flow rate is seen to vary significantly across the four fan speeds. The fill level is also shown to vary from ~3.5 to 7.5 percent. The tank pressure and pressurization rates are shown in Figure 129 with the average pressurization rate as a function of fan speed shown in Figure 130. The decrease in fill level at Hour 2,230 is a venting activity to reset the tank pressure for running Test 29-2.

TABLE 34.—NEON LOOP MASS FLOW VARIATIONS LIQUEFACTION TEST MATRIX

Test 4z, -2, and -3	
Test description	Neon loop flow variations, control flow
Fill level, %	<10, 15, 90
Cold wall temperature, K	250
Initial tank pressure, kPa	^a 207
GO ₂ flow, kg/h	1.1
Heaters, W	47
Neon loop fan speed, krpm	15, 16.25, 17.5, 20
GO ₂ injection method	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

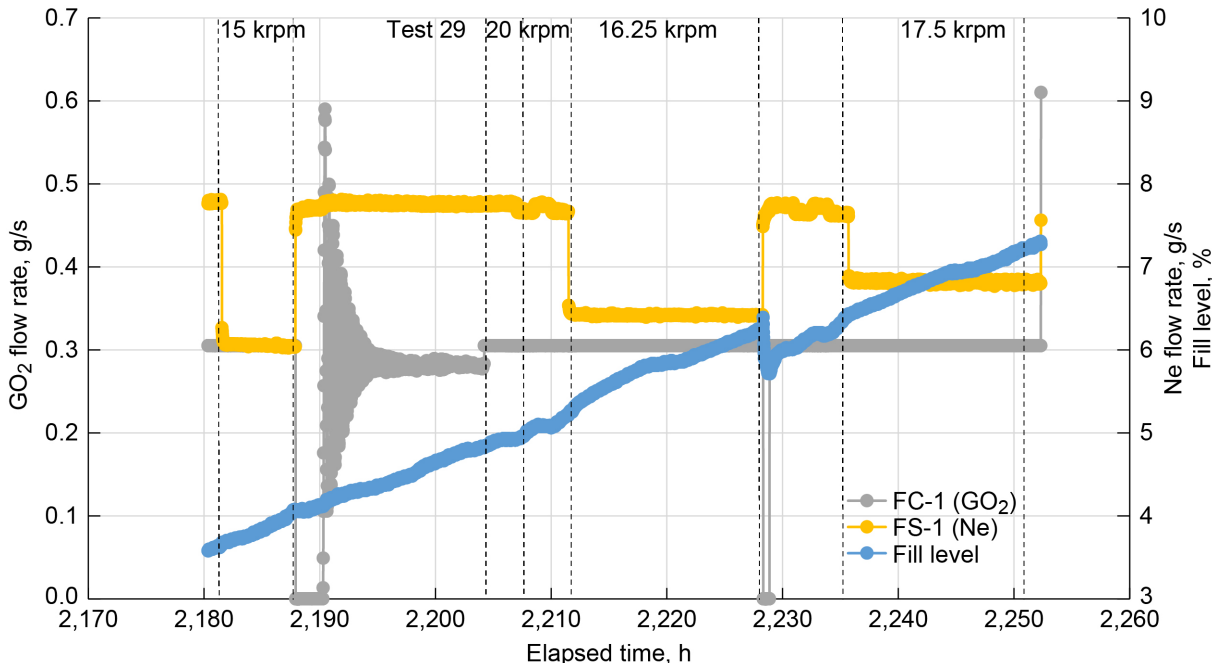


Figure 128.—Flow rates and fill level during Test 4z-1.

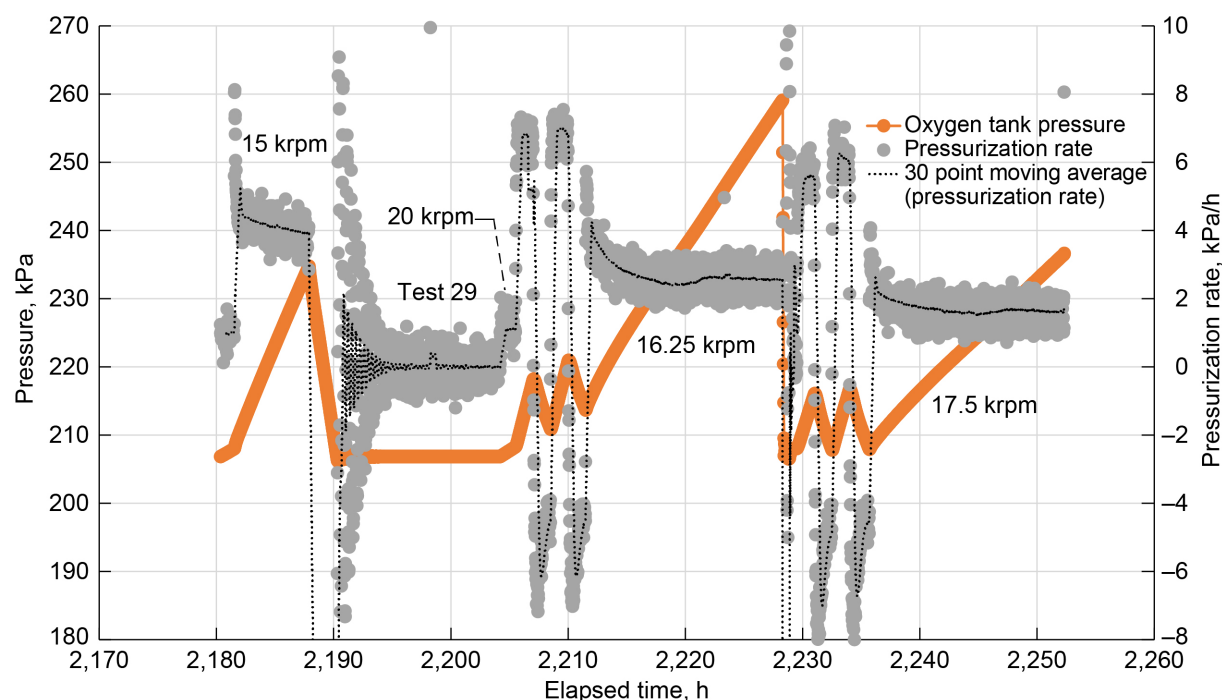


Figure 129.—Tank pressure and pressurization rates as function of time during Test 4z-1.

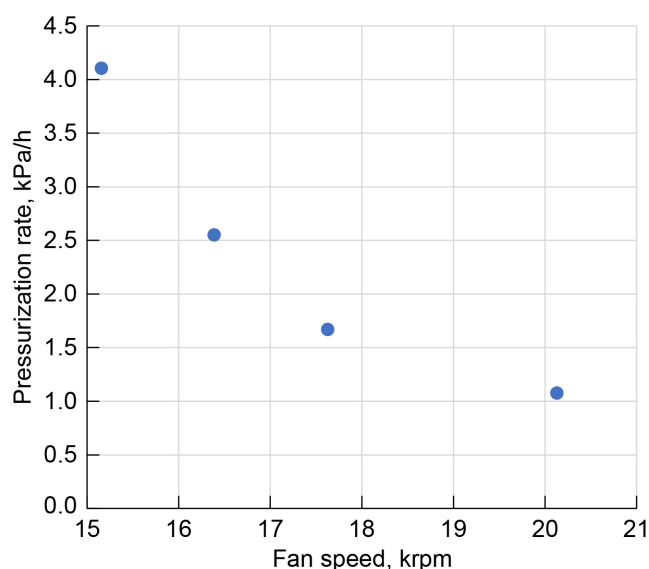


Figure 130.—Tank pressurization rates as function of fan speed Test 4z-1.

Test 4z-2 was run under the same conditions as Test 4z-1 but at a higher fill level: between 13 and 15 percent full as seen in Figure 131 (the neon flow rate shown in the figure is based on the cold head equations from Section 5.2). The neon flow rates in Test 4z-2 are much higher because the pressure in the neon loop was much higher (~420 kPa during Test 4z-1 and ~650 kPa during Test 4z-2). Due to it not being run around other tests, Test 4z-2 was the cleanest of the 4z series of tests. Figure 132 shows the fan speed and current draw during the different test conditions. Figure 133 shows the tank pressure response as a function of time. The inflection points in the curve are readily visible when the fan speed is changed. The system readily adapted to the change and provided a new slope on the pressurization rate. The change in fan speed is also readily noticeable in the fluid temperature response (see Figure 134) where the electrical interference changes with the fan speed setting. The changes in the neon loop temperatures (see Figure 135) are not necessarily from the altered interference, but also represent true aspects of changes in the integrated refrigeration system where, as the fan slowed down, the dwell time in the cryocooler heat exchanger increased, allowing greater heat exchange.

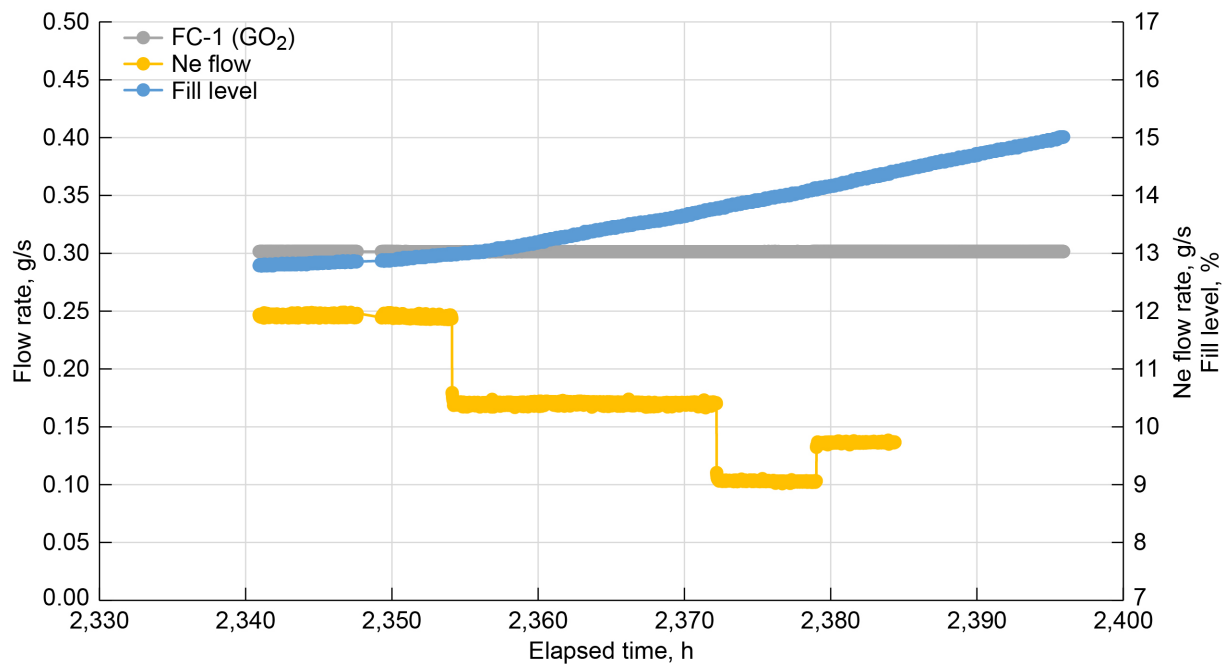


Figure 131.—Fill level and flow rates for Test 4z-2.

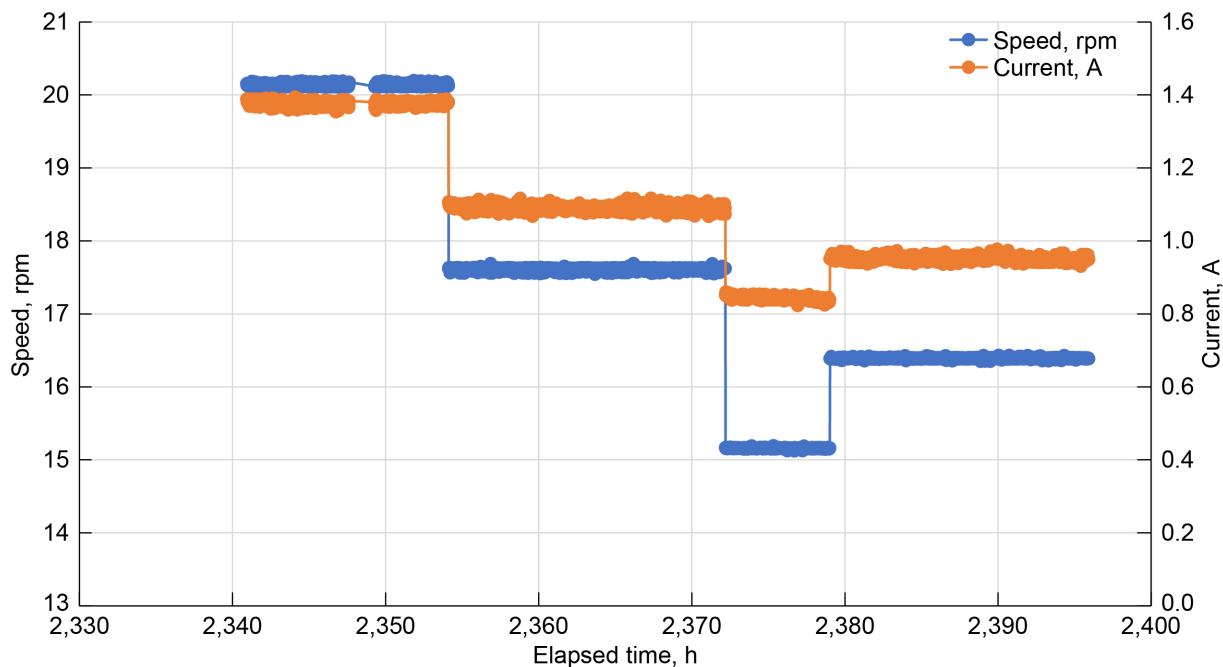


Figure 132.—Neon fan speed as function of time for Test 4z-2.

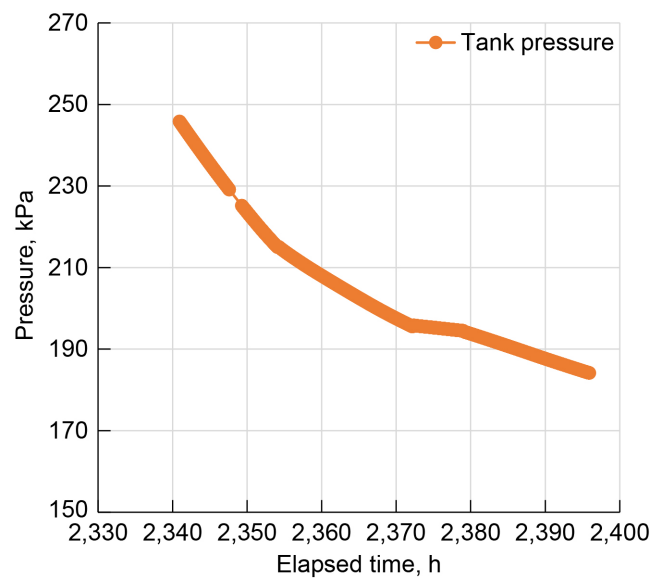


Figure 133.—Tank pressure as function of time during Test 4z-2.

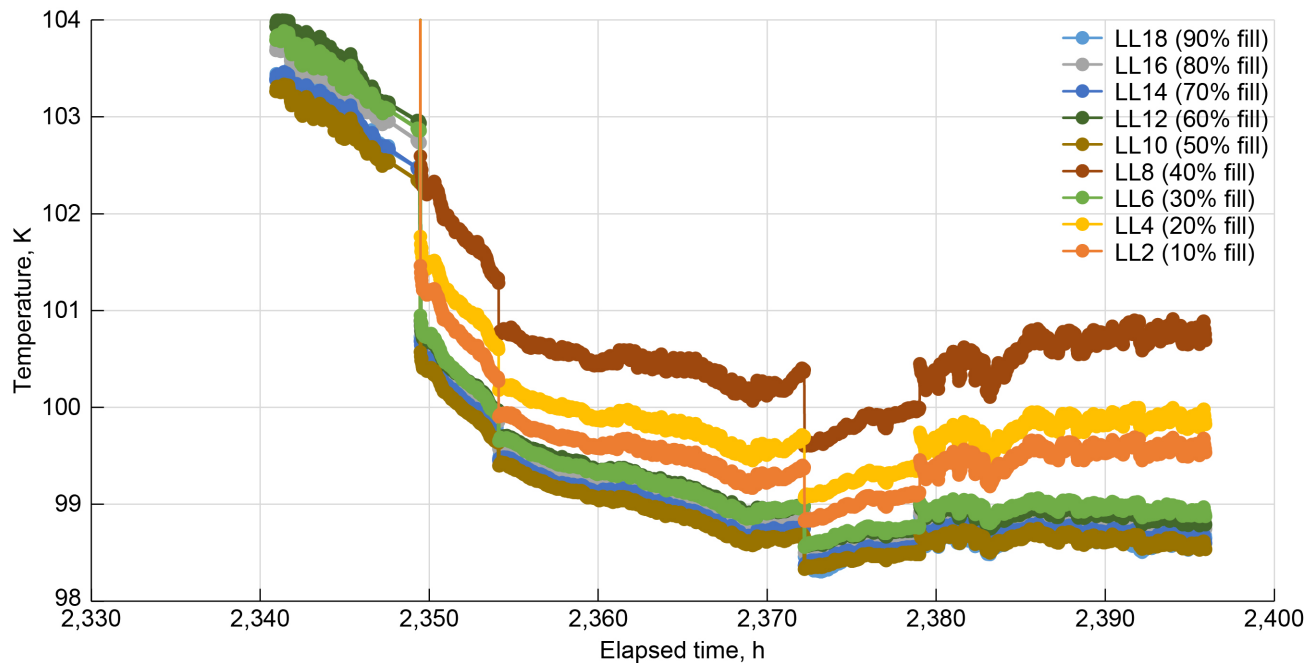


Figure 134.—Oxygen temperatures during Test 4z-2.

Test 4z-3 was run around Test 33 at the high fill level (>90 percent). Figure 136 shows the fan speeds and tank fill level as a function of time; Figure 137 shows the GO₂ mass flow rate at 0.31 g/s and the neon flow rate response throughout the test (Test 33 occurs when the GO₂ flow is at higher or lower). The pressure is shown in Figure 138, shows the tank pressure. Test 33 occurs in the windows where the tank pressure is spiking off-scale

on Figure 138 and the fan speed is at 20 krpm. The system, now at >90 percent full, took several hours to respond to the different fan speeds and set up a constant pressurization rate. Even with the initial slow response, each fan speed produced essentially the same liquefaction rate (slope of the fill level in Figure 136. This is slightly different then the observed liquefaction rates as a function of fan speed at 50 percent full (see Figure 56).

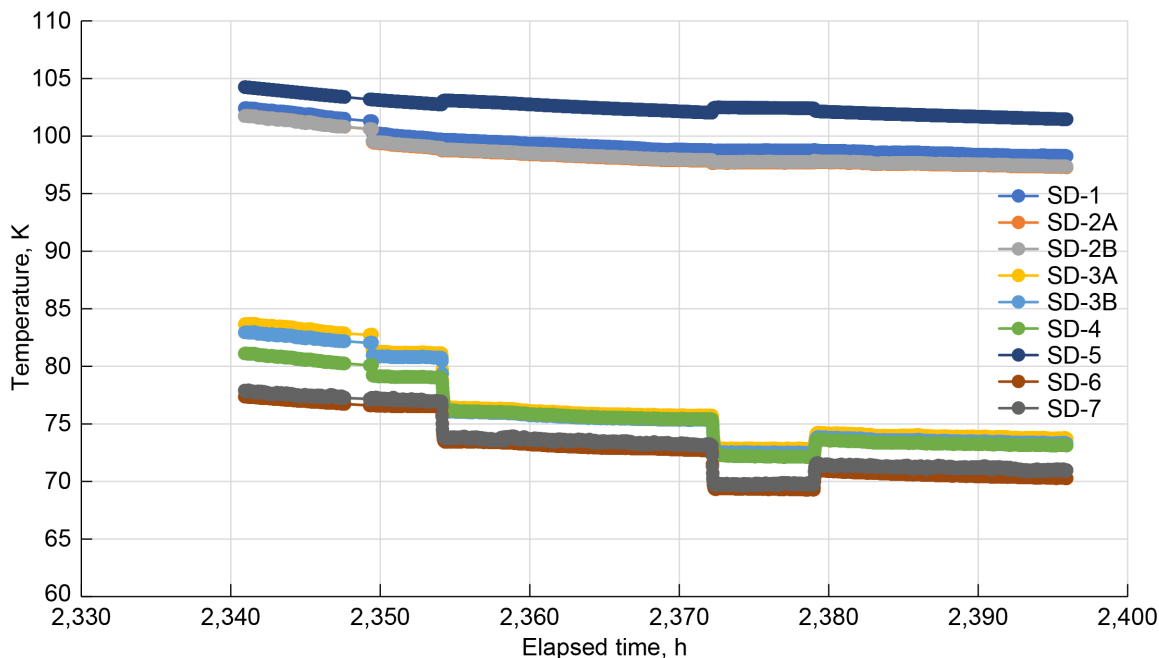


Figure 135.—Neon loop temperatures during Test 4z-2.

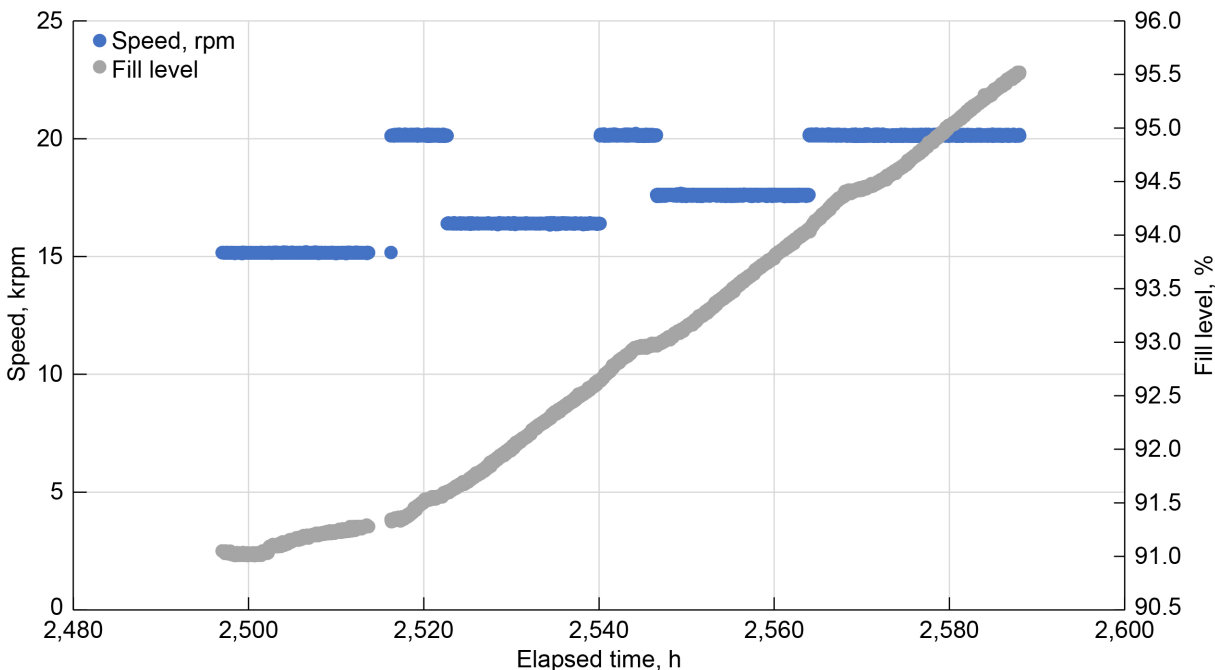


Figure 136.—Fan speed and tank fill levels during Test 4z-3.

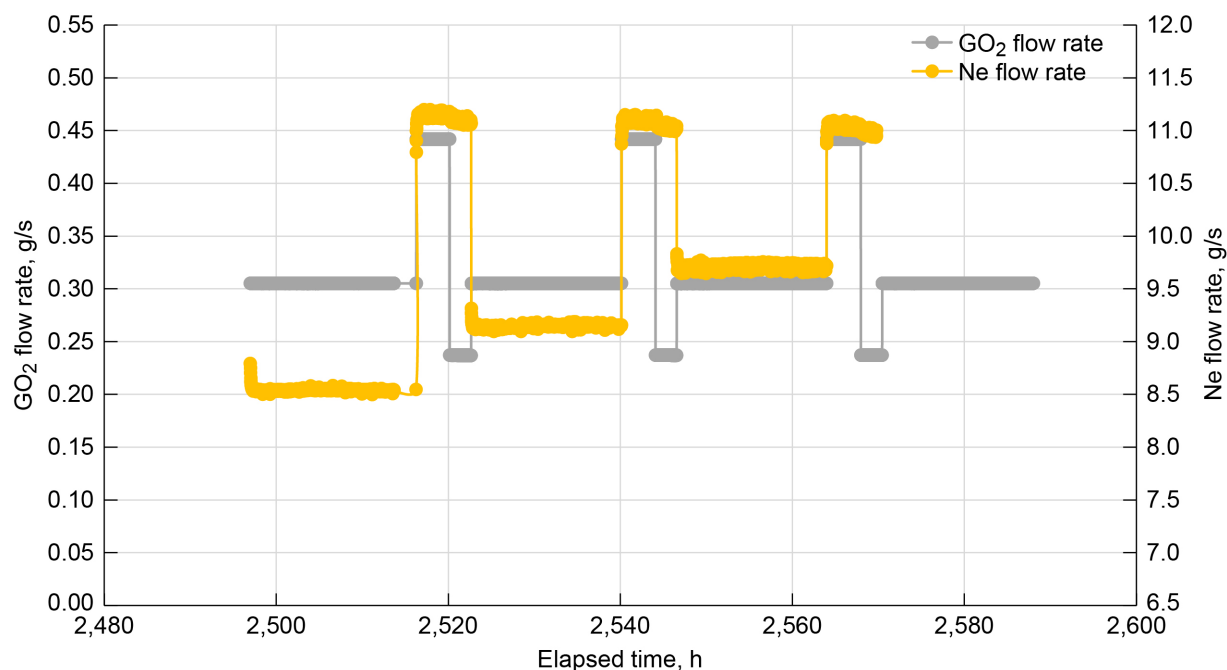


Figure 137.—Mass flow rates during Test 4z-3.

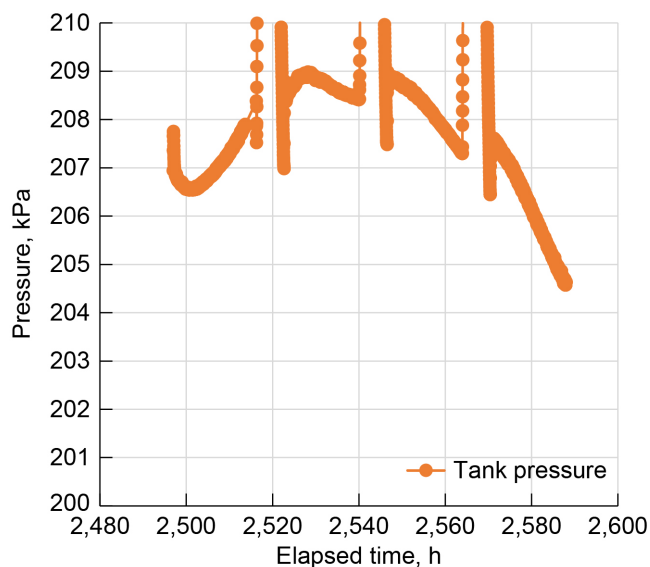


Figure 138.—Tank pressure during Test 4z-3.

Test 6c (Table 35) was run to see how close to a maximum fill level could be achieved before the liquefaction rate started decreasing. During the test, the pressure was held constant and the incoming GO_2 flow was allowed to vary. Figure 139 shows the capacitance probe and flow rate as a function of time during the test. Testing started at ~96 percent full and went to over 100 percent full (note that the capacitance probe went above the top of the tank in order to get out of the 6-way cross). There are several interesting phenomena, the first peak in flow occurs while the capacitance probe appears to be holding constant at

Hour 2,638—it is thought that this is essentially where there are two ullages that are separated by the slight extension down in of the fill port into the tank (to visualize this, view top cutaway in Figure 10). A second peak occurs at approximately Hour 2,655 as the flow noses over and falls off just before the capacitance probe starts to increase again. The separation of the ullages at this high fill fraction is something that would want to be avoided in normal operation and can cause such phenomena to occur. In Figure 140, it can be observed that as the oxygen flow rate falls off and the control band on the pressure control doubles. This makes sense as at this point the ullage volume is rapidly shrinking and the control parameters of the system would normally need to be adjusted so that it can react faster. Figure 141 shows the fluid temperatures and there does appear to be a slight increase in temperature over time between the time of “no fill increase” (Hours 2,630 to 2,657), especially from Hours 2,640 to 2,657, after which there is a small drop in temperature. It is interesting that the capacitance probe did not increase during this time period even though, it is known that GO_2 continued to come into the tank. Figure 142 shows the neon loop system temperatures, which show hardly any response to the system operations at all. It is interesting that the tank was able to liquefy at $>0.3 \text{ g/s}$ (1.08 kg/h) up to nearly 99 percent full on the capacitance probe. This is probably directly driven by the integration of the neon manifold on the tank neck and fill tube. Apparently, that is all the surface area that is required to liquefy the incoming gas. Observations of wet/dry sensor operation during testing indicated that at the beginning of this test, LL19 (~95 percent full) was marginally wet. By the end of the testing, LL19 was fully wetted.

TABLE 35.— MAXIMUM-FILL-LEVEL
LIQUEFACTION TEST MATRIX

Test 6c	
Test description.....	Max. fill level
Fill level, %.....	95 to 100
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	207
GO ₂ flow, kg/h.....	^a 1.1
Heaters, W.....	47
Neon loop fan speed, krpm.....	20
GO ₂ injection method.....	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

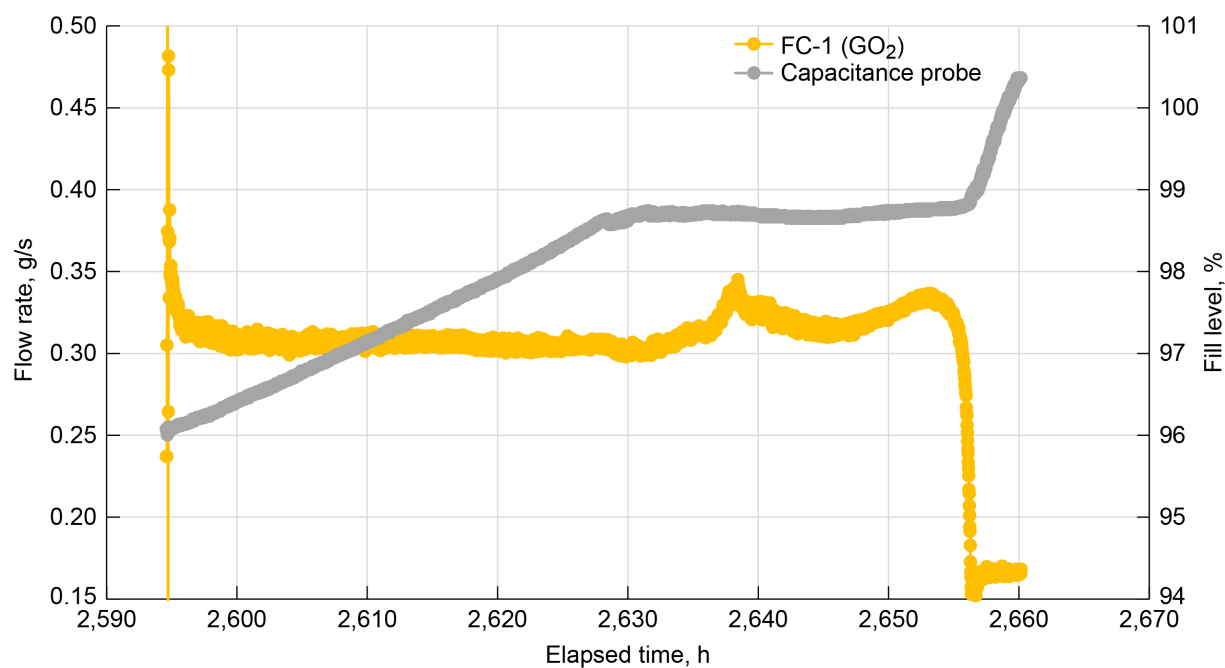


Figure 139.—Oxygen flow rate and fill level as function of time for Test 6c.

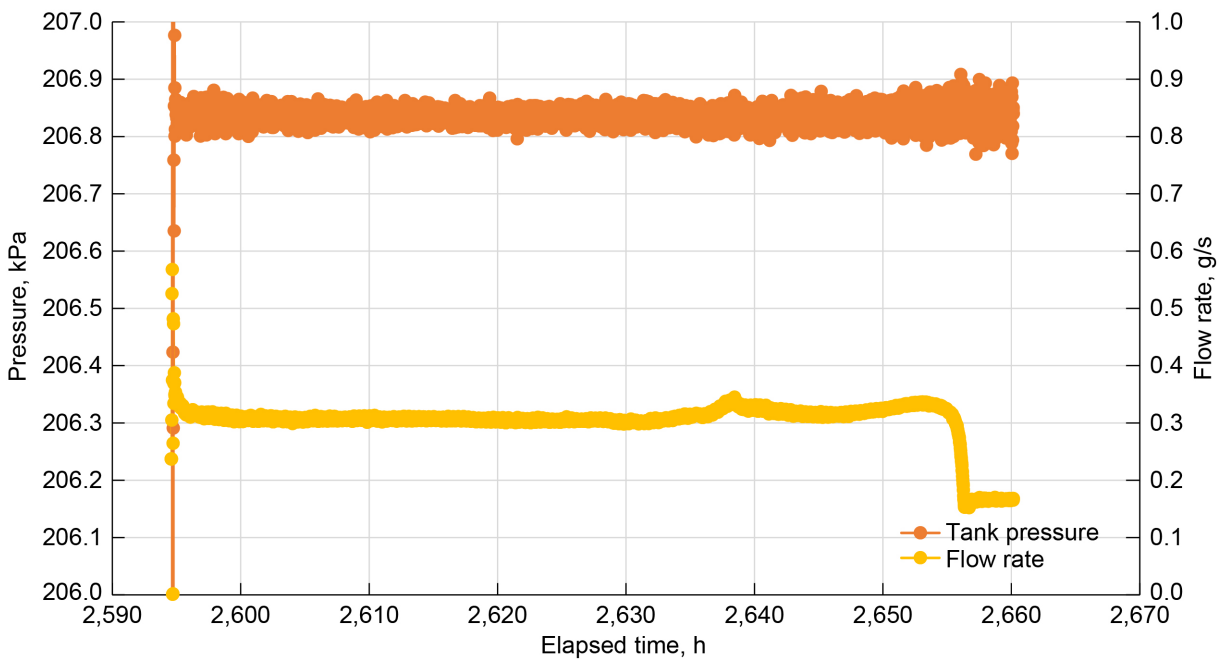


Figure 140.—Tank pressure and oxygen flow rate as function of time for Test 6c.

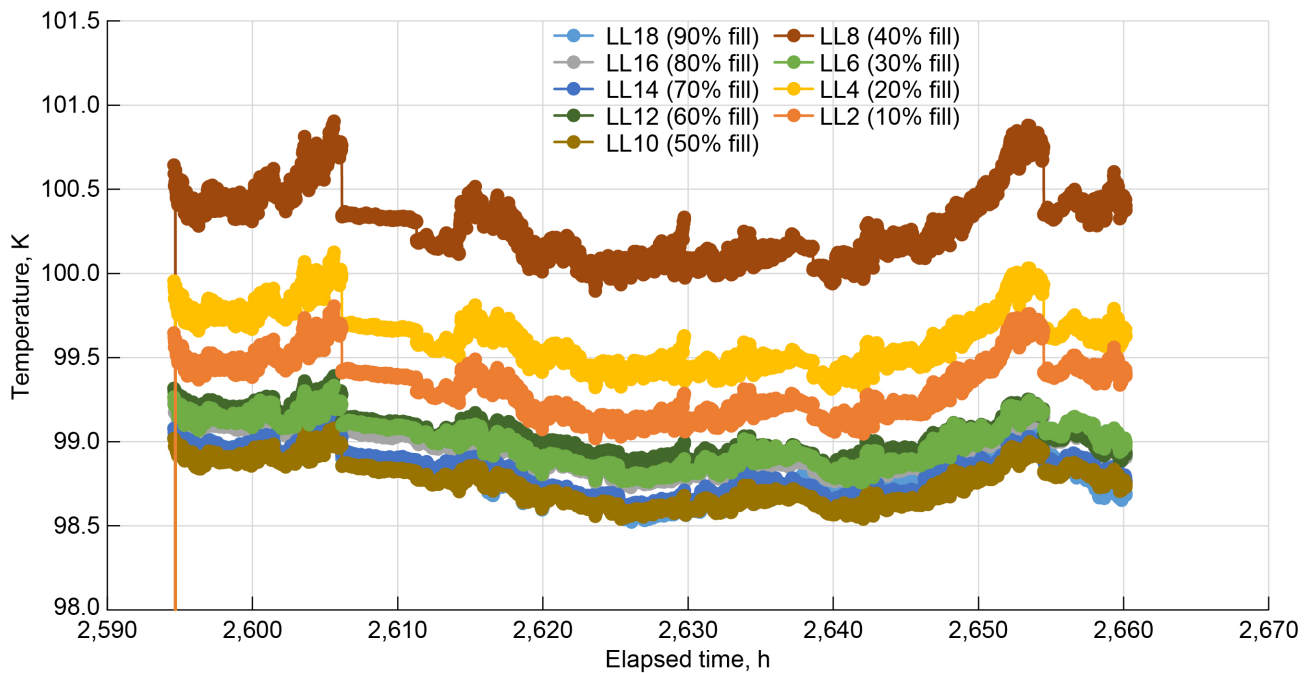


Figure 141.—Oxygen temperatures as function of time during Test 6c.

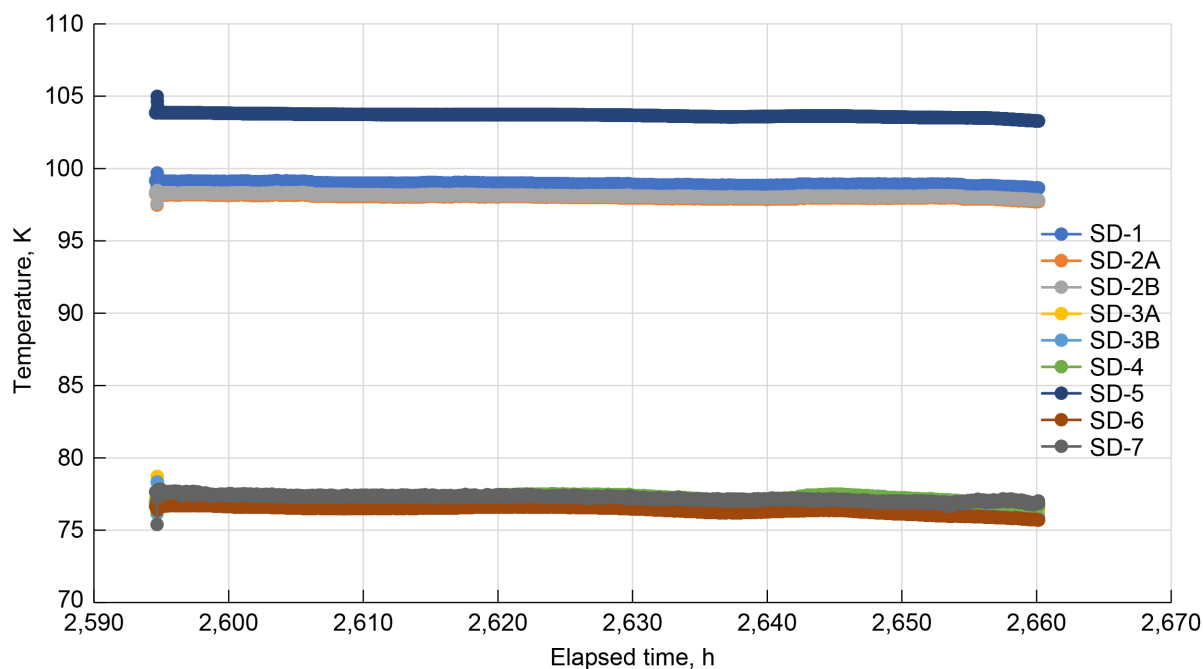


Figure 142.—Neon loop temperatures as function of time during Test 6c.

Test 40 (Table 36) was run to determine the maximum achievable liquefaction rate based on the previous run conditions, and turning off both the tank and neon loop heaters. Based on the results of Tests 8 to 10, it was observed that the liquefaction rate was greater at higher pressures than at lower pressures likely due to the smaller latent heat of vaporization at higher pressures. Thus, Test 40 was held constant at 275 kPa (40 psia) and controlled there by allowing the flow rate to vary. During Test 40, it was observed that the GO_2 flow rate had periodic fluctuations (see Figure 143). The stable flow rate was 0.434 g/s (1.6 kg/h) over a 48-h period. This was traced down to the variation in neon loop temperature and pressures shown in Figure 144 that were driven by the diurnal environmental temperatures on the accumulator. Figure 145 shows this testing occurring in the 7 to 12 percent fill-level range.

TABLE 36.—MAXIMUM LIQUEFACTION RATE TEST MATRIX

Test 40	
Test description	Max. liquefaction rate
Fill level, %	0 to 5
Cold wall temperature, K	250
Initial tank pressure, kPa	276
GO_2 flow, kg/h	^a 1.6
Heaters, W	0
Neon loop fan speed, krpm	20
GO_2 injection method	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

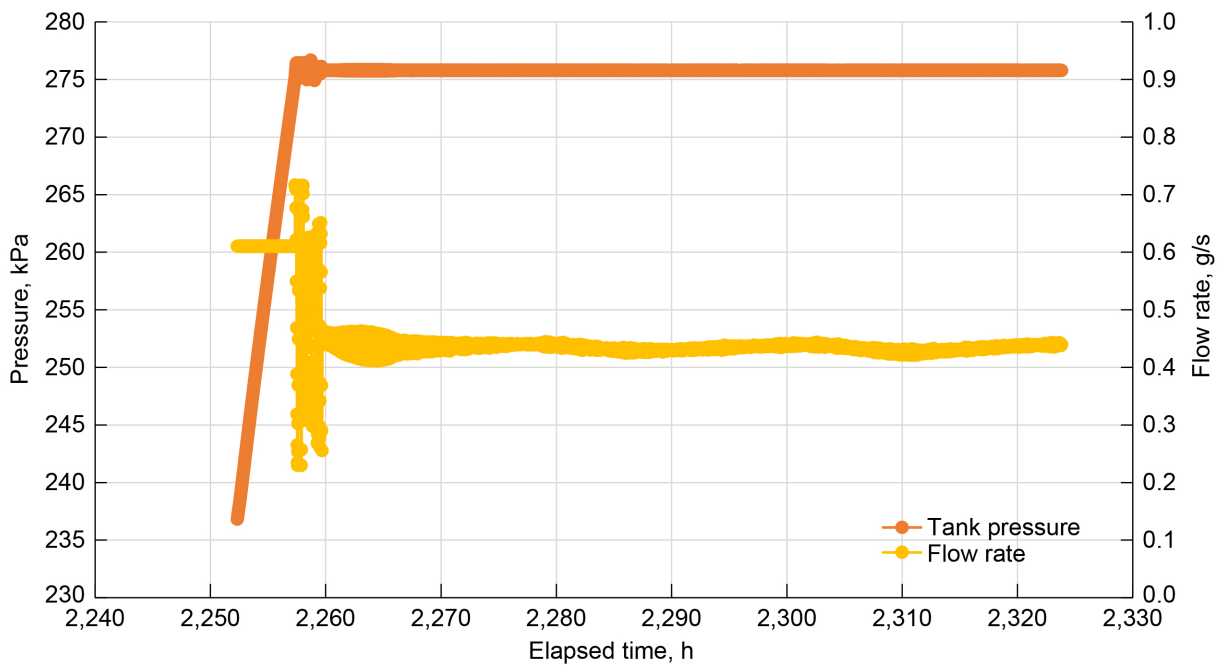


Figure 143.—Oxygen flow rate and tank pressure for Test 40.

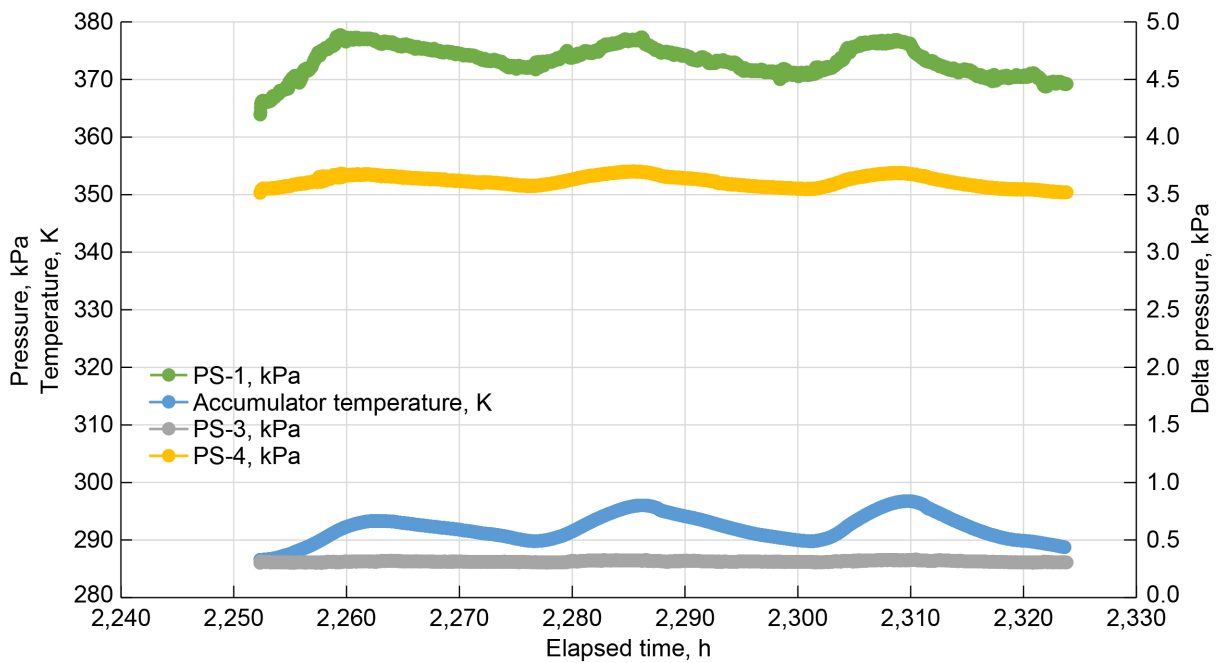


Figure 144.—Neon loop temperature and pressure during Test 40.

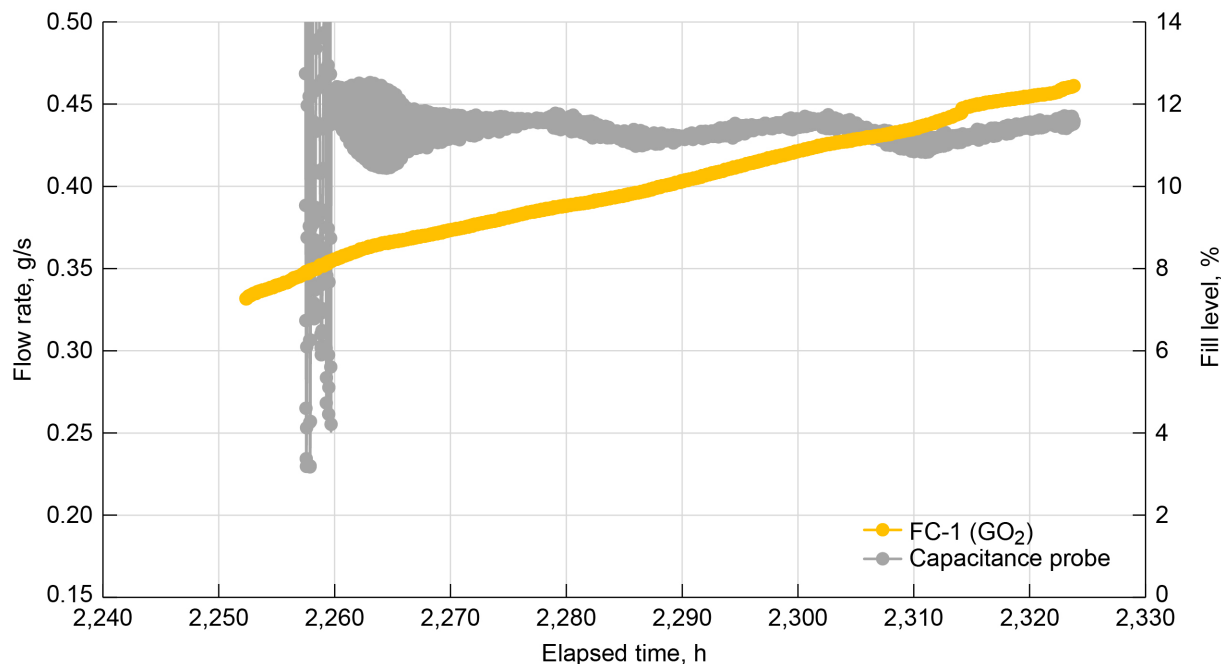


Figure 145.—Oxygen flow rate and fill level during Test 40.

TABLE 37.—PRESSURE COLLAPSE
LIQUEFACTION TEST MATRIX

Test 41	
Test description.....	Pressure collapse test
Fill level, %.....	0 to 5
Cold wall temperature, K.....	250
Initial tank pressure, kPa.....	^a 276 to 210
GO ₂ flow, kg/h.....	1.1
Heaters, W.....	47
Neon loop fan speed, krpm.....	20
GO ₂ injection method.....	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

Test 41 (Table 37) was focused on trying to repeat some of the conditions seen during Tests 11 to 13, in particular how the pressure would coast into a value that was not the same whether coasting down in pressure or up in pressure. During that time period the coasting up in pressure had been shown to be somewhat repeatable, but the coasting down was not repeated.

This was an attempt to coast down in pressure. During the initial attempt to perform the test, the tank was saturated at 275 kPa (40 psia) and the GO₂ flow was set up to 0.3 g/s (1.08 kg/h) as with other parameters set to nominal operations for 207 kPa (30 psia). This should have caused the pressure in the tank to drop. However, after a few hours, it was noticed that the pressure was not dropping (see Figure 146) and the neon flow pressure (see PS-2 in Figure 147) had dropped. An action was taken to raise the neon pressure from 420 kPa (60.9 psia) to a target of 480 kPa (69.6 psia), however, more gas was let in than planned and the pressure rose up to 725 kPa (105.2 psia). The neon loop pressure then leveled off at closer to 675 kPa (98 psia). Once the extra neon was added to the loop, the mass flow rate in the fan went up proportionally to the change in pressure (see Figure 148). With the increase in flow rate, the cryocooler heat exchanger exit temperatures (SD-7, SD-4, and SD-3A/B) all increased, but the heat removal was still more than before the fill. With the increase in cryocooler heat removal, the tank pressure immediately started decreasing.

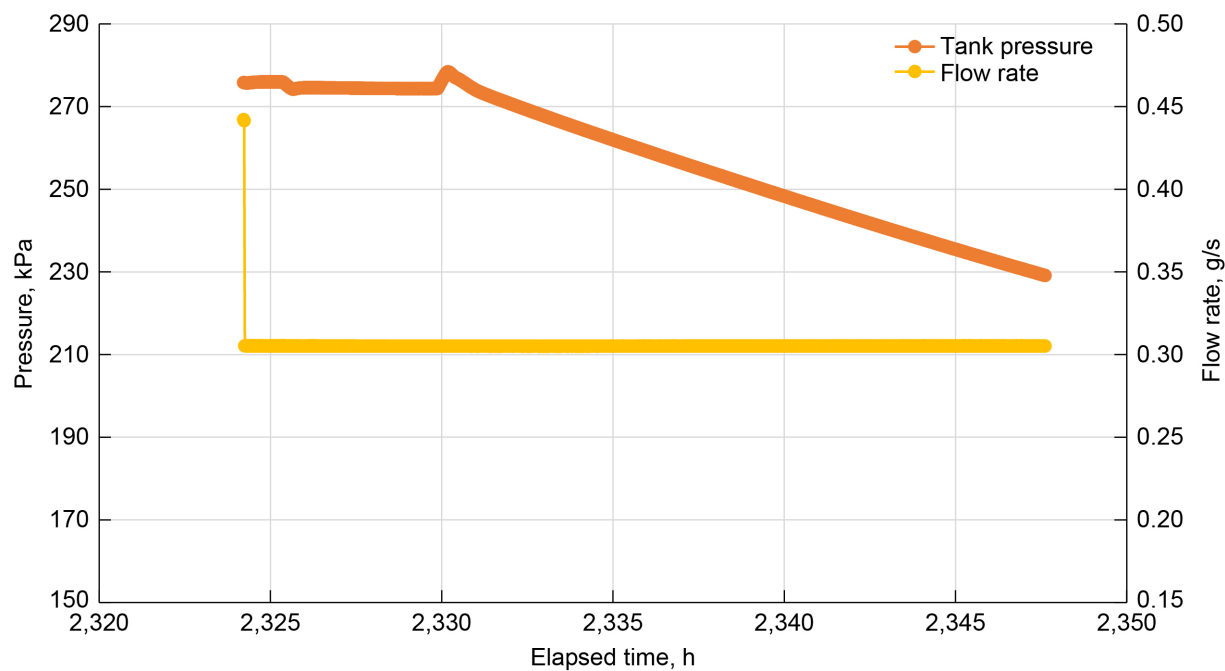


Figure 146.—Tank pressure and oxygen flow rate during Test 41.

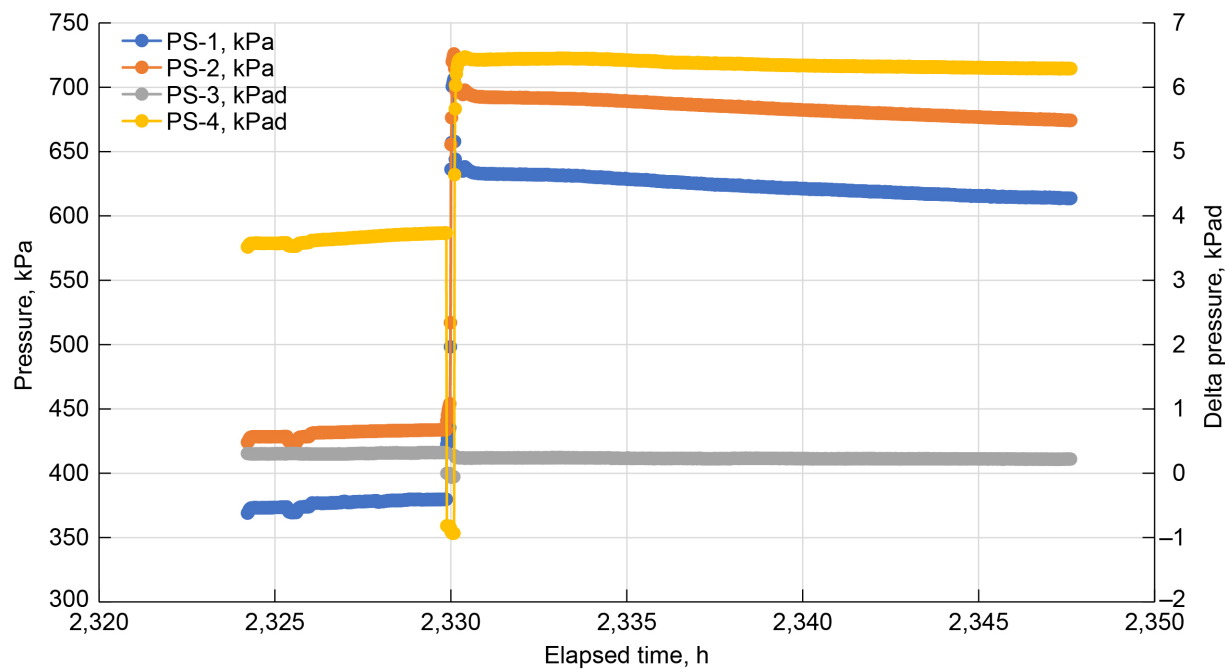


Figure 147.—Neon loop pressures during Test 41.

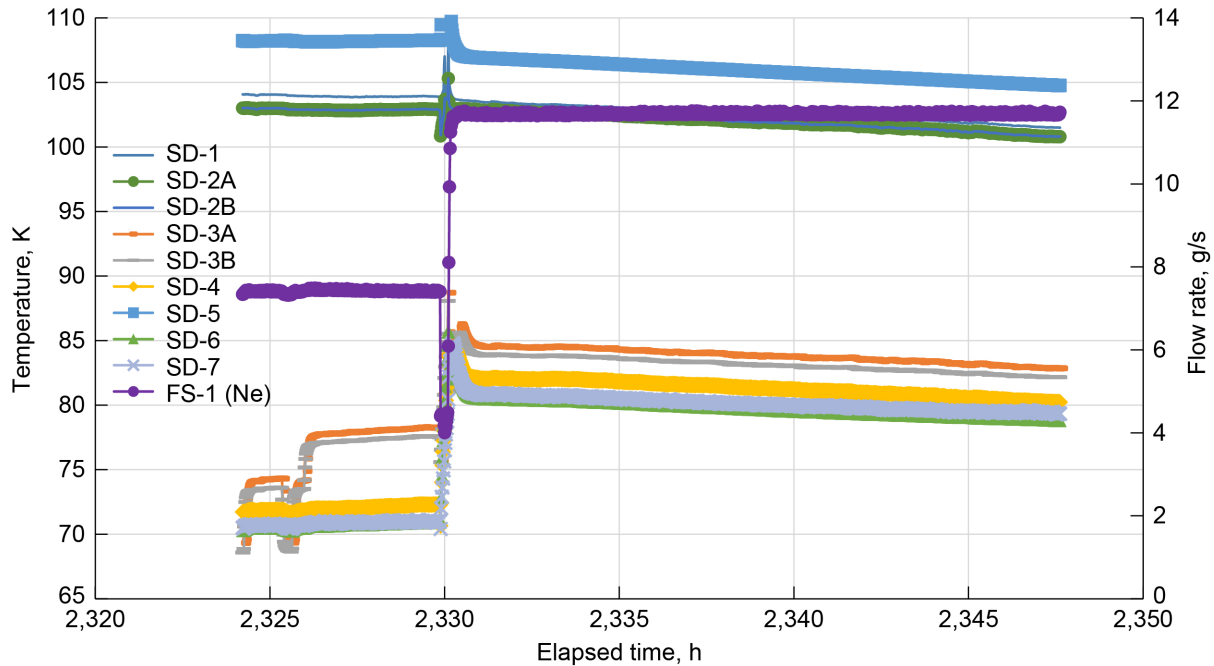


Figure 148.—Neon loop temperatures and flow rate during Test 41.

5.0 Test Data Analysis

5.1 Base Boil-off Rate and Passive Heat Load

As shown in Figure 25, the average boil-off rate for Test 1 was 0.179 g/s (0.64 kg/h), averaged over Hours 135 to 140. Two different temperatures could be referenced as the vent gas temperature: LL19 at the 95 percent full level (average of 107 K) and LL20 in the vent line just upstream of the 6-way cross (see Figure 12) (average temperature of 184 K). The heat load from the test can be calculated from Equation (8):

$$\dot{Q}_{total} = \dot{m}_{boil-off} \left[h_{vent}(T_{vent}, P_{sat}) - h_{liq}(P_{sat}) \right] \frac{\rho_{liq}}{\rho_{liq} - \rho_{vap}} \quad (8)$$

where $\dot{Q}$ is the total tank heat load, $\dot{m}_{boil-off}$ is the vented mass flow rate, h is the enthalpy of the oxygen at various states, T_{vent} is the temperature of the vapor being vented, P_{sat} is the saturation pressure of the oxygen in the tank, ρ_{liq} is the saturated liquid density, and ρ_{vap} is the vapor density. The density term accounts for the replacing of any boil-off liquid with vapor in the volume that boils off and it is ~ 1.004 . Calculations of the heat load using both LL19 and LL20 are shown in Table 38 and Table 39, respectively. LL20 was far enough upstream in the vent line, above the uninsulated 6-way cross, that it is not thought to be as representative of the actual tank heat load. The temperatures through the test period are shown in Figure 149

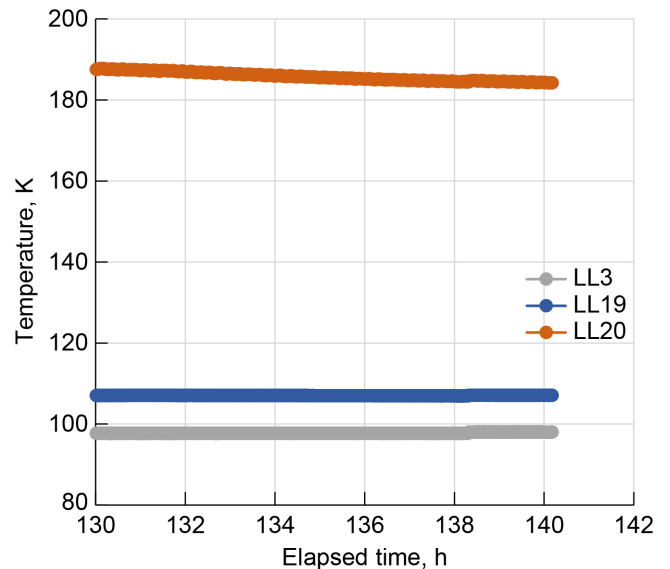


Figure 149.—Temperature sensors LL3, LL19, and LL20 during Test 1.

with LL3 as a reference for liquid temperature. These values of between 38 and 51 W demonstrate a much larger tank heat load than in most experimental test tanks that are designed to minimize heat load (Refs. 16 and 17). The tank heat load is much more representative of a lander type tank due to the solid structural attachments holding the tank in place on both the top and bottom and the fluid connections on both the top and the bottom as shown in Figure 10. A comparison of multiple lander

TABLE 38.—RELEVANT BOIL-OFF
CALCULATION VALUES USING LL10

Boil-off parasitic heat load, referenced from LL19	
Vent mass flow, g/s.....	0.18
Enthalpy exit vapor, kJ/kg.....	93.87
Enthalpy liquid, kJ/kg.....	-120.64
Density vapor, kg/m ³	7.74
Density liquid, kg/m ³	1,103.55
Q _{tank} , W.....	38.7

TABLE 39.—RELEVANT BOIL-OFF
CALCULATION VALUES USING LL20

Boil-off parasitic heat load, referenced from LL20	
Vent mass flow, g/s.....	0.18
Enthalpy exit vapor, kJ/kg.....	166.65
Enthalpy liquid, kJ/kg.....	-120.64
Density vapor, kg/m ³	4.34
Density liquid, kg/m ³	1,103.55
Q _{tank} , W.....	51.6

concepts was performed that showed lander tank heat loads to be between 20 to 80 W (Ref. 15). The differences in the heat load were determined to mainly be driven by insulation system design and environmental temperature assumptions. However, it was also observed that the structural heat loads were at a relatively low fidelity compared to other portions of the heat load and could have also been driving the differences.

The tank was supported by three aluminum rods connected to straps that suspended the tank by the vacuum chamber lid, as seen in Figure 150. Each rod had three evenly spaced thermocouples to capture the temperature profile across them. The three support legs, for ground transportation, at the bottom of the tank are hollow aluminum cylinders, each with two thermocouples on either end of the leg. Figure 150 also indicates the location of the thermocouples for both the support rods and legs. It should be noted that both the support rods and legs were wrapped with MLI. Equations (9) and (10) were used to approximate the structural heat loads associated with the support rods and legs respectively. The evaluation of the mentioned structural heat loads during Test 1 are documented in Table 40. Some variation is to be expected between each support, but one support rod (rod 3) and one support leg (leg 2) experienced a greater deviation in heat load than their counterparts. These variations in heat load could be a result of inconsistent thermal interactions experienced by each support as they were positioned 120° apart from one another. Specifically on the lid there are multiple thermal hot spots that may have interacted with the support rods. The variation in the heat load seen on the supports may also be related to

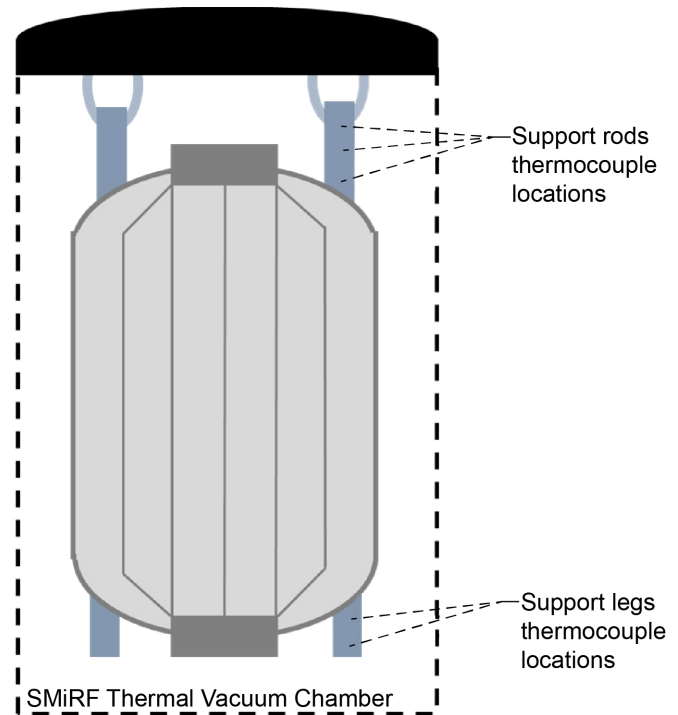


Figure 150.—Tank with support structures.

TABLE 40.—ESTIMATED STRUCTURAL
HEAT LOADS DURING BOIL-OFF TEST

Structure	Heat load, W
Rod 1	7.10
Rod 2	5.91
Rod 3	2.26
Leg 1	0.61
Leg 2	4.74
Leg 3	0.46

inconsistent installation of MLI around the support structures. Using the as-calculated values for the structural heat loads, 21 W (or slightly more than half the heat load) can be attributed to the structure.

$$\dot{Q}_{Rod} = \frac{\pi D_{Rod}^2}{4x} \int_{T_{Cold}}^{T_{Hot}} k_{AL5083} dT \quad (9)$$

$$\dot{Q}_{Leg} = \frac{\pi D_{Leg}^2}{4x} \int_{T_{Cold}}^{T_{Hot}} k_{AL5083} dT \quad (10)$$

5.2 Flow Rate Measurements/Determination

Initial reviews of test data and CFD modelling of test conditions from the first oxygen liquefaction tests with the

cryocooler active indicated the neon mass flow meter may have been underestimating the measured flow rate. The leading theory for this issue was there being a lack of distance between the elbow upstream of the flow meter and the flow meter entrance causing the flow to not have stabilized prior to the measurement. This was accounted for when designing the cryocooler loop, but before testing it was decided to switch the direction of the neon flow. It is thought that the elbow, being quite close to the neon loop flow meter entrance, was exposed to turbulent eddies that lead to inaccurate measurements by the flow meter. To further investigate this issue, posttest data collected from points around the neon cooling loop were used to calculate the neon mass flow rate using mass and energy balances. Figure 151 is a simplified block flow diagram of the neon cooling loop that illustrates the sequence in which the temperature and pressure sensors were located. Note the sensor locations in Figure 151 are for reference only and are not an exact representation of their placement. A total of four methods were compared to the mass flow meter measurements (Figure 151, Box 1) to approximate the neon mass flow rate in the cryocooler loop. The flow meter measurements were compared to the cryocooler's cryofan performance curve, the

cryocooler's cold head cooling capacity curve, a mass and energy balance around the neon heater, and a mass and energy balance around the test tank.

The cryofan (Figure 151, Box 2) facilitating forced convection in the neon loop came with a performance curve from the manufacturer, Absolut System (Ref. 23). The curve mapped delta pressure (ΔP) over density (ρ) and fan speed (n) squared as a function of volumetric flow (Q_v) over fan speed. Manipulating this performance data, the pressure gain across the cryofan during testing measured with PS-4 and the measured fan speed were used to calculate the expected volumetric flow rate of the neon. Density properties of neon in the fan were approximated based on averages from temperature sensor SD-5 at the entrance of the cryofan and the pressure calculation (PS-2 minus PS-3 minus PS-4) to convert the volumetric flow rate into a neon mass flow rate. Figure 152 contains the cryofan performance curve provided by Absolut System (Ref. 23). The pressure of the neon entering the cryofan was calculated with in-flow pressure transducers PS-2, PS-3, and PS-4 as it was observed during testing that PS-1, located in front of the cryocooler, was reading unreliably after changing the direction of the neon flow before testing.

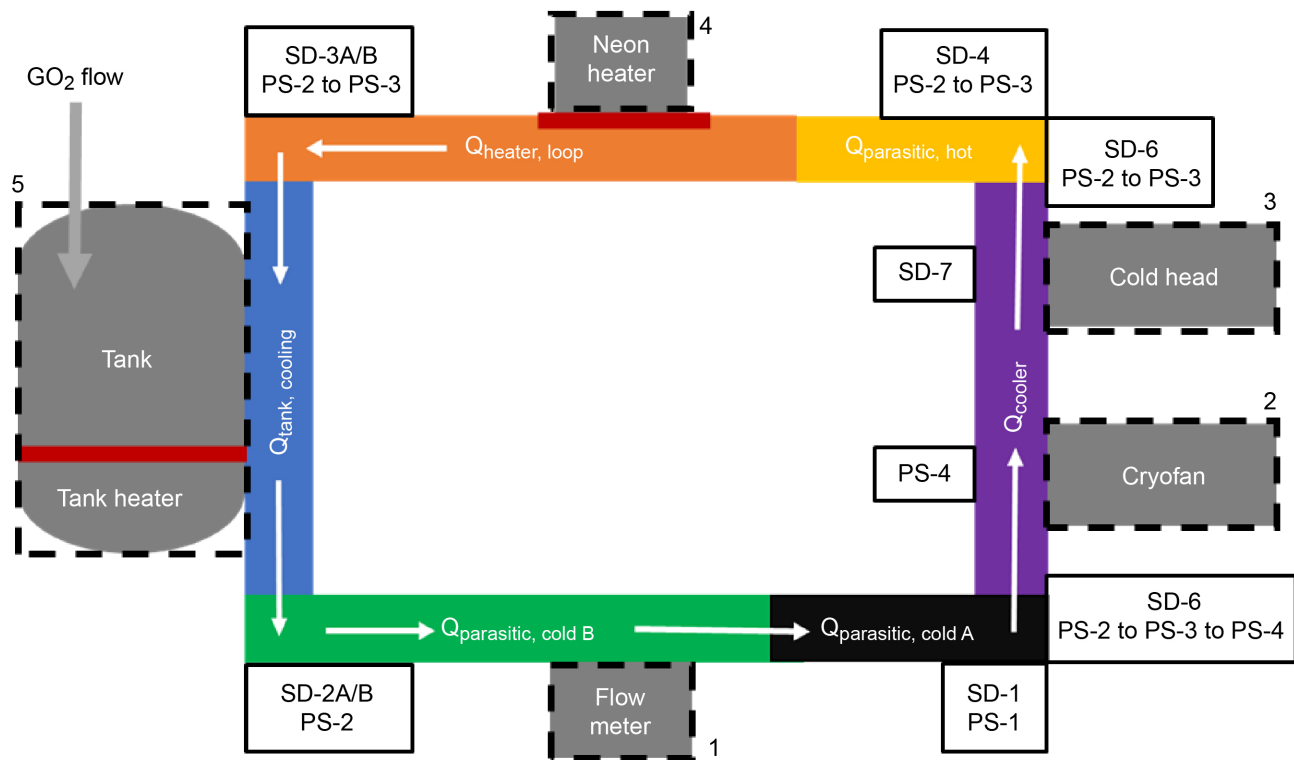


Figure 151.—Neon cooling loop flow.

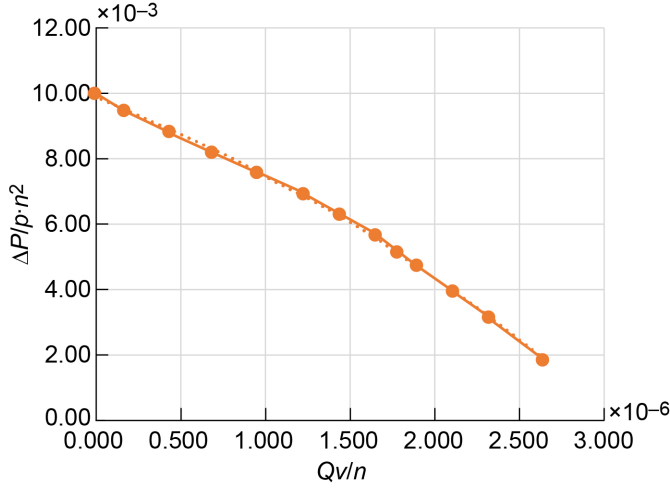


Figure 152.—Absolut System's cryofan performance curve (Ref. 23), pressure coefficient as function of flow coefficient.

The cold head temperature measured with SD-7 was used to estimate the cooling capacity of the cryocooler (Figure 151, Box 3) with a cooling capacity curve for the AL300 cold head provided by Cryomech (Ref. 24). The performance data provided by Cryomech mapped the heat load removed by the cold head as a function of the cold head temperature in Figure 153.

Knowing the heat load being removed from the cold head, a mass and energy balance around the cold head was performed to calculate what the neon mass flow should have been. Equation (11) defines the enthalpy change across the cold head. The enthalpy change across the cold head ($\Delta h_{Cold Head}$) evaluates enthalpies based on the pressures and temperatures of the neon entering ($h_{CHentry}$) and exiting (h_{CHexit}) the cold head. This calculation assumes the pressure drop across the cold head is minimal (PS-2 to PS-3) with SD-5 representing the neon temperature when entering the cold head and SD-6 representing the neon temperature when leaving the cold head. The neon mass flow ($\dot{m}_{Neon}$) was evaluated with Equation (12) that divides the cold head cooling capacity ($Q_{Cold Head}$) based on the cold head temperature by the enthalpy change across the cold head. The assumption is made that there is no parasitic heat load onto the cryocooler cold head, or that it is minimal compared to the neon flow load. Both SD-5 and SD-6 are tube wall mounted external RTDs; thus, the assumption is made that the temperature difference between the neon flow and the tube wall is similar in both locations.

$$\Delta h_{Cold Head} = h_{CHexit} - h_{CHentry} \quad (11)$$

$$\dot{m}_{Neon} = \frac{Q_{Cold Head}}{\Delta h_{Cold Head}} \quad (12)$$

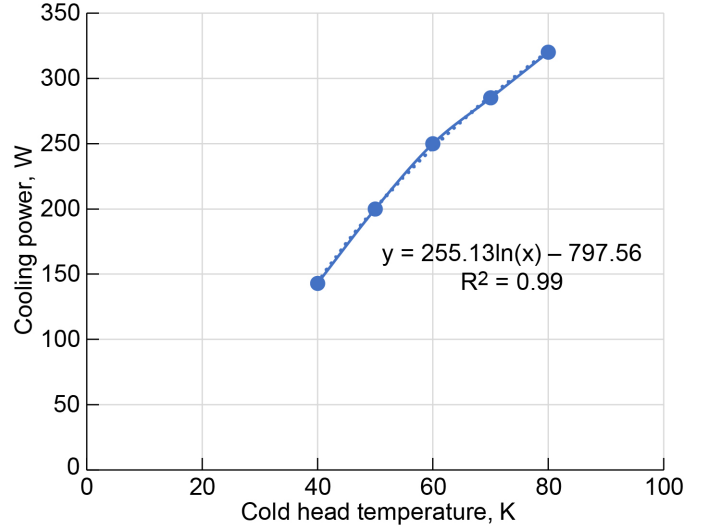


Figure 153.—Cryomech cold head cooling capacity curve (Ref. 24).

The neon heater that imposed a controllable heat load on the neon loop (Figure 151, Box 4) provided another opportunity to calculate the neon mass flow rate because the surrounding temperatures, pressures, and neon heater power were measured for each test. Enthalpies of neon were evaluated based on the temperatures and pressure entering ($h_{NHentry}$) and exiting (h_{NHexit}) the neon loop exposed to the neon heater. The enthalpy change across the neon heater ($\Delta h_{Neon Heater}$) section is captured in Equation (13). For these calculations, it was assumed that the pressure drop across the neon heater section was minimal (PS-2 to PS-3). The neon temperature before the neon heater section was measured by SD-4 and the neon temperature exiting the neon heater section was captured by SD-3. The neon mass flow rate ($\dot{m}_{Neon}$) was calculated by taking the heat load imposed by the neon heater ($Q_{Neon Heater}$) and dividing it by the enthalpy change across the neon heater section as seen in Equation (14). This method neglects any other parasitic heat loads to the neon line between SD-4 and SD-3, as well as assuming that the tube wall temperature and neon temperature have small differentials at the SD-4 location (SD-3 is a probe in the flow).

$$\Delta h_{Neon Heater} = h_{NHexit} - h_{NHentry} \quad (13)$$

$$\dot{m}_{Neon} = \frac{Q_{Neon Heater}}{\Delta h_{Neon Heater}} \quad (14)$$

The neon mass flow rate calculated using this method varied quite drastically when compared to the cryofan and cold head calculations. This can also be seen in the following tank thermal balance and calls for further discussion of potential unidentified parasitic heat loads in Section 5.3.

Mass and energy balances were also performed around the test tank (Figure 151, Box 5) and its interaction with the neon loop through the tube-on-tank BAC network. The enthalpy difference between the entry ($h_{Tankentry}$) and exit ($h_{Tankexit}$) of the neon loop across the tank surface is called out in Equation (15). The entry neon enthalpy was evaluated with temperature SD-3 and pressure (PS-2 to PS-3) sensors; the exit neon enthalpy was evaluated with temperature SD-2 and pressure PS-2 sensors. The mass and energy balance around the tank also accounted for any heat load imposed by heaters on the tank ($Q_{Tank Heater}$), heat loads associated with incoming GO_2 (Q_{GO_2}) for liquefaction, and the tank parasitic heat load ($Q_{Tank Parasitics}$) of ~ 38.1 W evaluated from the boil-off test described in Section 5.1. The incoming heat load associated with any GO_2 flow ($\dot{m}_{GO_2}$) was determined by utilizing the enthalpy difference between the GO_2 at the flow controller to the saturated LO_2 in the tank detailed in Equation (16). The neon mass flow rate ($\dot{m}_{Neon}$) was calculated with Equation (17) for comparison by summing the heat loads relevant to the tank and dividing that sum by the enthalpy difference of the neon across the tank's surface. This analysis assumes that the boil-off tank heat load on a venting tank is applicable for a locked-up tank and that the parasitic heat loads are fairly constant between the different tests.

$$\Delta h_{Tank} = h_{Tankexit} - h_{Tankentry} \quad (15)$$

$$\dot{Q}_{GO_2} = \dot{m}_{GO_2} (h_{LO_2} - h_{Trailer}) \quad (16)$$

$$\dot{m}_{Neon} = \frac{Q_{Tank Heater} + Q_{GO_2} + Q_{Tank Parasitics}}{\Delta h_{Tank}} \quad (17)$$

The five described methods for evaluating the neon mass flow rate were calculated for all the tests. The graphs in Figure 154 to Figure 162 compare the neon mass flow rate values for each liquefaction test that had the cryocooler active. FS-1 represents the cryocooler flow meter reading; Cryofan, Cold Head, Neon Heater, and Tank Balance refer to the previously mentioned mass flow rate calculation methods. The average of the calculation methods for each test is also included for comparison; however, the average is not necessarily the appropriate mass flow rate to use for analyzing the test data. Note that the transient liquefaction tests are excluded in this due to the quantity of variations during a single transient test. Figure 154 compares the neon mass flow

rate calculations from the ZBO tests performed in Test 2 and 2a. Although the tests were run nearly identically, there were slight variations on the overall pressure in the neon loop.

Figure 155 compares the neon mass flow rate calculations of the nominal liquefaction test, Test 3, with variations of the neon heater power, Test 3a, and similar liquefaction tests, Test 5 and 5a, that introduce GO_2 to the tank through a dip tube instead of the ullage. The tank heater power was held constant at 20.3 W for the previously mentioned tests. The neon heater mass flow calculation varies the most as that calculation directly considers the input power of the neon heater imposed onto the forced convection loop. The cryofan and cold head calculations are rather consistent across these tests because the neon heater power has a larger impact on the lift across the tank surface. The entry temperature (SD-3) into the BAC tubes varies with neon heater power, but the BAC exit temperature (SD-2) remains around the oxygen saturation temperature relative to the tank pressure. The variations in lift across the tank would cause a tank pressure response, but the GO_2 mass flow rate controlled into the tank was allowed to float to maintain a constant tank pressure. This implies the saturation conditions within the tank were not varying drastically between these tests. Therefore, the cold head was maintained at 70 ± 1 K across all these tests while the cryofan was held at the same operating speed.

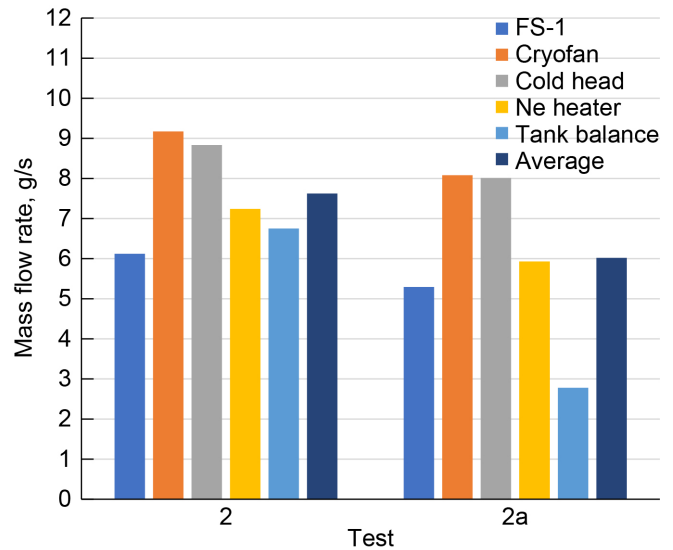


Figure 154.—Test 2 and 2a neon mass flow rate calculations.

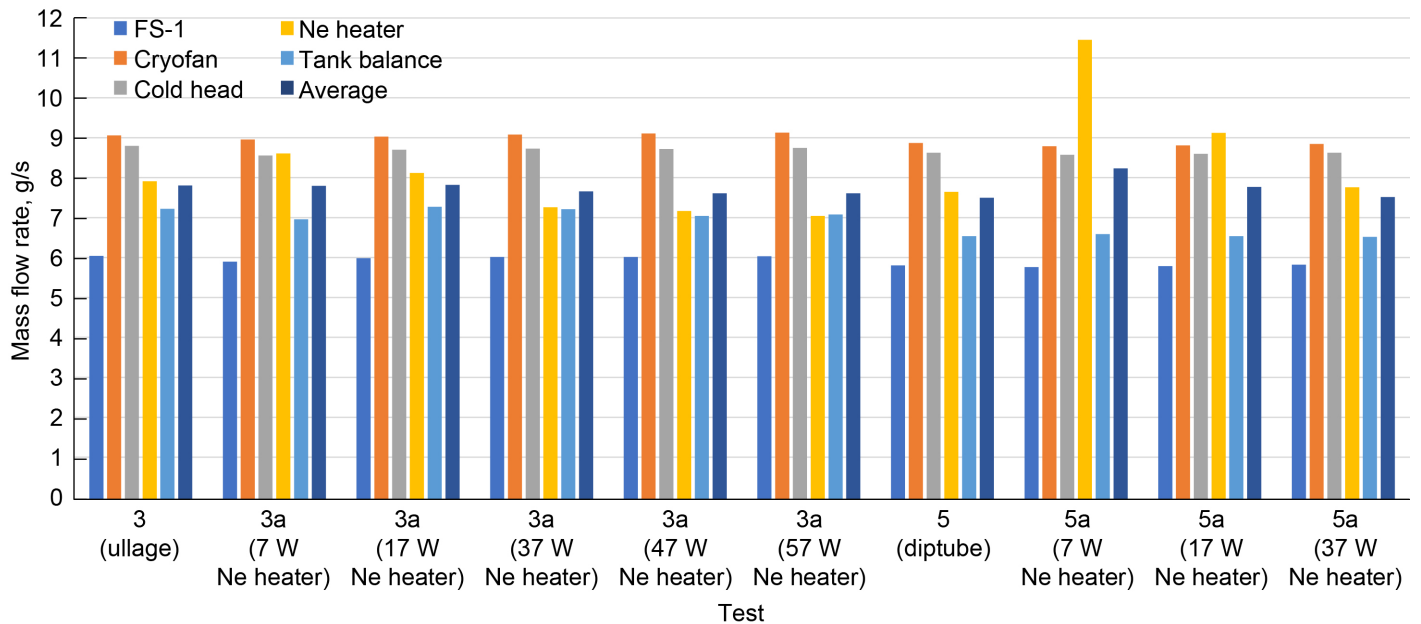


Figure 155.—Tests 3, 3a, 5, and 5a neon mass flow rate calculations.

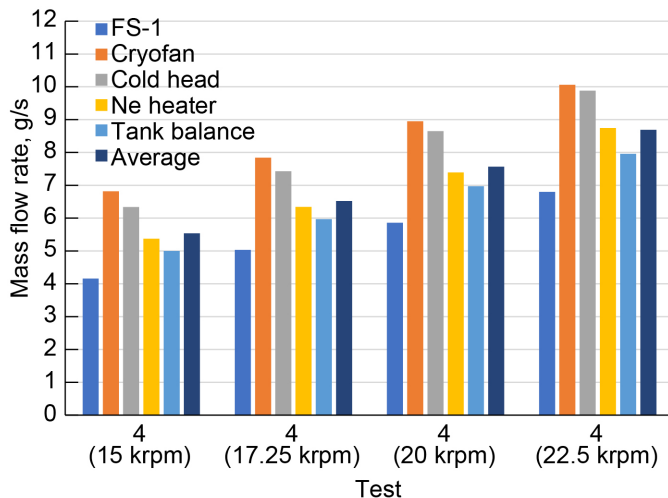


Figure 156.—Test 4 neon mass flow rate calculations.

Test 4 was the first test with variations of the cryofan speed. As expected, higher fan speeds should result in greater mass flow rates within the neon forced convection loop. In Figure 156, the mass flow calculations are highlighted for the various fan speeds that were tested. Figure 157 contains the results from the neon mass flow rate calculations for Tests 6, 7, and 8. These liquefaction tests were run with the same operational conditions other than the tank liquid fill level. Tests 6, 7, and 8 were run at 90 percent, 50 percent, and <10 percent full, respectively. These tests all had similar results with respect to the various neon mass

flow calculations. This also confirms that fill level has a minor impact on the operation of the liquefaction system.

Oxygen liquefaction Tests 8, 9, and 10 were all run under similar test conditions. As shown in Figure 158, the flow rates for Tests 8 and 9 did not vary; however, the flow rates were 15 percent higher for Test 10 after the neon loop was charged as discussed in Section 5.8. The neon loop occasionally had to be recharged with neon throughout testing. The only intentional variation between these tests was the tank pressure, which directly impacts the saturation conditions within the tank during liquefaction operations. Because the GO_2 mass flow rate was allowed to float to maintain a constant pressure for each of these tests, the neon mass flow rate calculations did not vary too much.

Figure 159 covers the neon mass flow rate calculations for Tests 11, 12, and 13. The neon loop was operated the same for all these tests. The GO_2 mass flow into the tank was fixed at various rates to observe the liquefaction system's response. With a fixed GO_2 flow input, the tank pressure was allowed to respond accordingly. The nominal GO_2 flow rate maintained constant tank pressure, the low GO_2 mass flow decreased tank pressure, and the high GO_2 mass flow increased tank pressure. The effect of the GO_2 flow on the neon mass flow calculation is most evident in the tank balance calculation because it considers the heat load associated with the incoming GO_2 flow.

The 4z tests were another series intended to understand how the variation in cryofan speed impacts the oxygen liquefaction rate of the system. For each 4z test, the calculated neon mass flow rates increased rather uniformly with increased cryofan speed.

Figure 160 contains the neon mass flow rate calculations for the various fan speeds operated while the tank liquid fill level was near 50 percent full during Test 4z, Test 4z-2 shown in Figure 161 had a fill level at 13 percent, and Test 4z-3 ran at the 90 percent fill level documented in Figure 162. The neon mass flow rate increased with cryofan speed as expected for Tests 4z, 4z-2, and 4z-3. However, Test 4z's neon mass flow rates are on average 45 percent lower than those seen in Tests 4z-2 and Test 4z-3 at various cryofan speeds. This is because Test 4z had a neon pressure of 420.6 kPa (61 psia) while Tests 4z-2 and 4z-3 had neon pressures of 645.3 kPa (93.6 psia) and 611.6 kPa (88.7 psia), respectively. The variation in the neon loop pressure is attributed to the recharging of the neon loop throughout testing that is described further in Section 5.8 for Test 10.

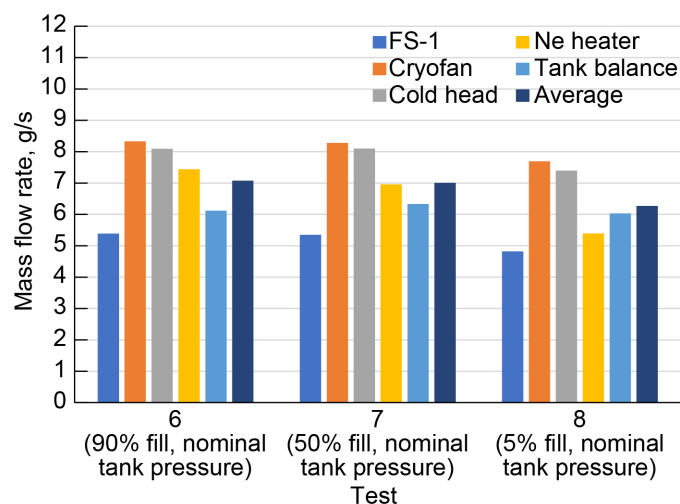


Figure 157.—Tests 6, 7, and 8 neon mass flow rate calculations.

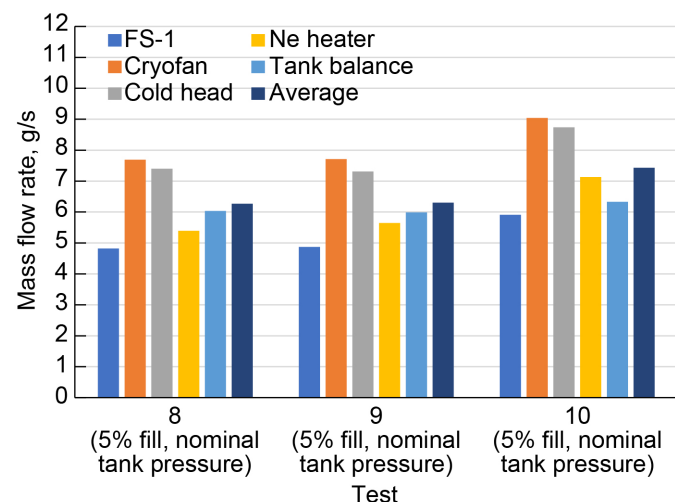


Figure 158.—Test 8, 9, and 10 neon mass flow rate calculations.

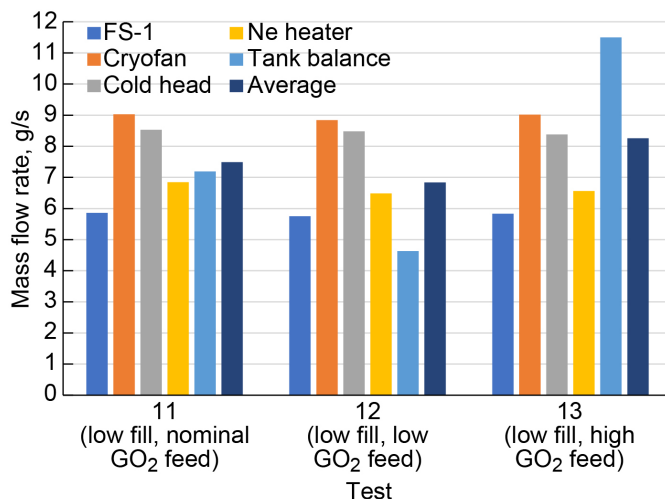


Figure 159.—Tests 11, 12, and 13 neon mass flow rate calculations.

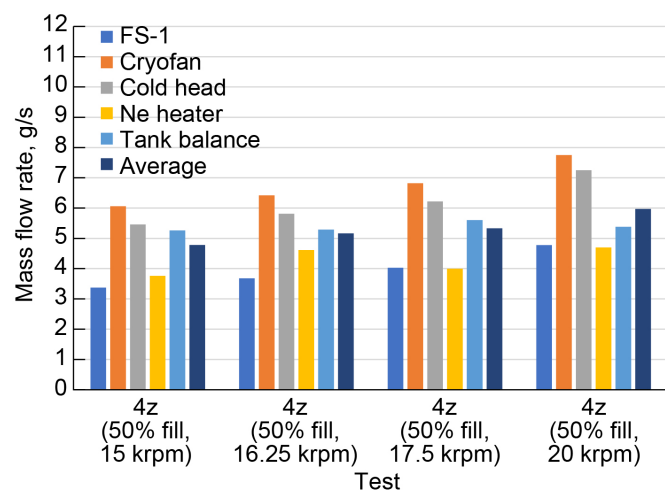


Figure 160.—Test 4z neon mass flow rate calculations.

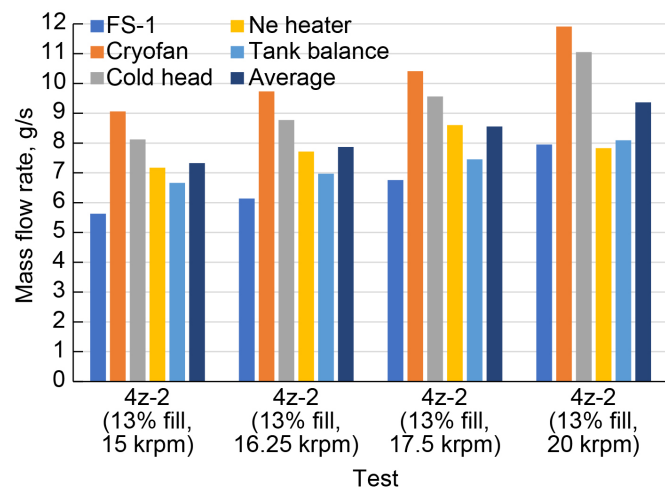


Figure 161.—Test 4z-2 neon mass flow rate calculations.

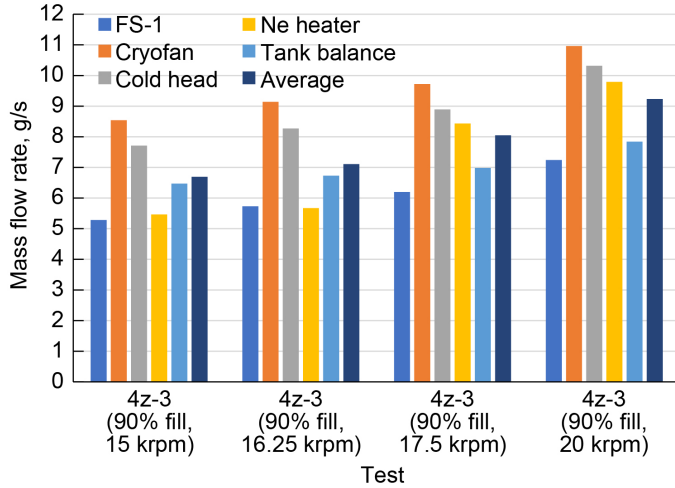


Figure 162.—Test 4z-3 neon mass flow rate calculations.

5.3 Thermal Balance Around the Neon Loop

Thermal and fluid modeling of the CryoFILL tests using Thermal Desktop® modeling software (formerly C&R Technologies, now Ansys) indicated that the neon mass flow rates produced from the cold head calculation described in Section 5.2 best represents each test in simulation when compared to the test data (Ref. 25) and are used in all plots in Section 4.0. The cryofan calculation provided the second-best estimation of the neon mass flow rate. It was always within 11 percent higher than the cold head calculation. In general, the mass flow rate meter in the neon loop produced the lowest neon mass flow rate value for most tests. It varied anywhere from 39 to 62 percent less than the typical value calculated by the cold head method. The neon heater and tank balance calculations saw a large variation in predicted neon mass flow rates when compared to the more consistent cold head and cryofan calculation methods. This large variation is attributed to not being able to accurately account for all the parasitic heat loads imposed on the neon cooling loop and the tank because there is some variation with each test. The tank balance calculation method had more uncertainty than the neon heater calculation because it must account for the variables of tank storage pressure, fill level, structural heat loads, incoming GO₂ mass flow, and occasional venting. The cold head and cryofan calculation methods are grounded in data from performance testing provided by their respective vendors (Refs. 26 and 27). Coupling this with the best representation of each test through modeling software indicates the cold head calculation method is the closest representation of the neon mass flow rate throughout CryoFILL testing. Statistical analysis was performed on the various neon mass flow rate calculation methods to highlight any deviations across the nontransient liquefaction tests. An average of the five methods for determining the neon mass flow rate, $\overline{\dot{m}_{neon}}$, was calculated in Equation (18) and included in plots in Section 5.2.

Each neon mass flow rate, $\dot{m}$, in Equation (18) refers to one of the neon mass flow calculation methods. The neon loop flow meter is represented by the subscript “FM,” the cryofan calculation has the subscript “CF,” the cold head calculation has the subscript “CH,” the neon loop heater calculation has the subscript “NH,” and the tank balance calculation has the subscript “TB.” The average of the neon mass flow rate calculations for a given test summed the five methods for calculating the neon mass flow rate and was divided by n . The variable n refers to the number of neon mass flow rate calculation methods for a given test. The variable n was equal to five for each test.

$$\overline{\dot{m}_{neon}} = \frac{(\dot{m}_{FM} + \dot{m}_{CF} + \dot{m}_{CH} + \dot{m}_{NH} + \dot{m}_{TB})}{n} \quad (18)$$

A sample standard deviation of the neon mass flow rate calculation methods was also performed for each nontransient liquefaction test. The sample standard deviation calculation, $StdDev$, is detailed in Equation (19). The i refers to one of the five neon mass flow rate calculation methods within the analysis. The five neon mass flow rate calculations are substituted in the numerator for summation in the evaluation. A sample standard deviation was selected as each neon mass flow rate calculation method uses test data that was delineated and averaged from the raw output. The sample standard deviation refers to how spread the neon mass flow rate calculation methods are from the mean for a given test. Recall that the mean of the neon mass flow rate calculations is not the best representation of the actual neon mass flow rate. The cold head calculations are recommended to represent the neon mass flow rate and are highlighted in green for each test in Table 41 and Table 42.

$$StdDev = \sqrt{\frac{\sum (\dot{m}_i - \overline{\dot{m}_{neon}})^2}{(n-1)}} \quad (19)$$

Following that the cold head calculation method best represents the neon mass flow rate for each test, the greater the deviance from the cold head neon mass flow calculation indicates a given calculation method of the neon mass flow rate is less representative of the neon mass flow rate during a test. The deviation from the cold head calculation for every neon mass flow rate calculation method was evaluated using Equation (20) for each test and compiled in Table 42. The final row in Table 42 holds the average of the deviations from the cold head neon mass flow rate calculation for all the nontransient liquefaction tests. It broadly iterates that the flow meter, neon heater, and tank balance calculations vary significantly from the cryofan and cold head neon mass flow rate calculations.

$$Deviation \text{ from } \dot{m}_{CH} = \dot{m}_{CH} - \dot{m}_i \quad (20)$$

TABLE 41.—AVERAGE AND STANDARD DEVIATION OF NEON MASS FLOW RATE
CALCULATION METHODS FOR TESTS WITHOUT TRANSIENTS

Test	Neon mass flow approximation, g/s					Average, g/s	Standard deviation
	FS-1	Cryofan	Cold head	Neon heater	Tank balance		
2	6.12	9.17	8.83	7.24	6.75	7.62	1.32
2a	5.29	8.08	8.01	5.93	2.78	6.02	2.19
3 (ullage)	6.07	9.07	8.81	7.93	7.24	7.82	1.22
3a (7-W neon heater)	5.92	8.97	8.57	8.62	6.98	7.81	1.31
3a (17-W neon heater)	6.01	9.04	8.71	8.13	7.29	7.84	1.22
3a (37-W neon heater)	6.04	9.09	8.74	7.28	7.23	7.68	1.24
3a (47-W neon heater)	6.04	9.12	8.73	7.19	7.06	7.63	1.27
3a (57-W neon heater)	6.06	9.14	8.76	7.06	7.10	7.62	1.29
4 (15 krpm)	4.16	6.82	6.34	5.37	5.00	5.54	1.06
4 (17.25 krpm)	5.03	7.84	7.43	6.34	5.97	6.52	1.13
4 (22.5 krpm)	6.80	10.06	9.88	8.74	7.96	8.69	1.36
4 (20 krpm)	5.86	8.95	8.65	7.39	6.97	7.56	1.26
5 (dip tube)	5.83	8.88	8.64	7.66	6.56	7.51	1.31
5a (7-W neon heater)	5.79	8.80	8.59	11.45	6.61	8.25	2.20
5a (17-W neon heater)	5.81	8.82	8.61	9.13	6.56	7.79	1.50
5a (37-W neon heater)	5.85	8.86	8.64	7.77	6.54	7.53	1.31
6 (90% fill, nominal tank pressure)	5.39	8.33	8.09	7.44	6.12	7.07	1.27
7 (50% fill, nominal tank pressure)	5.35	8.28	8.10	6.96	6.33	7.00	1.23
8 (5% fill, nominal tank pressure)	4.82	7.69	7.40	5.39	6.03	6.27	1.25
9 (5% fill, high tank pressure)	4.87	7.71	7.31	5.64	5.99	6.30	1.18
10 (5% fill, low tank pressure)	5.91	9.04	8.74	7.13	6.33	7.43	1.41
11 (low fill, nominal GO ₂ feed)	5.86	9.03	8.53	6.85	7.19	7.49	1.29
12 (low fill, low GO ₂ feed)	5.75	8.84	8.48	6.48	4.63	6.84	1.80
13 (low fill, high GO ₂ feed)	5.83	9.02	8.38	6.56	11.50	8.26	2.23
4z (50% fill, 15 krpm)	3.37	6.06	5.46	3.76	5.26	4.78	1.16
4z (50% fill, 16.25 krpm))	3.68	6.42	5.81	4.61	5.29	5.16	1.06
4z (50% fill, 17.5 krpm)	4.03	6.82	6.22	4.00	5.60	5.33	1.28
4z (50%, 20 krpm)	4.78	7.75	7.25	4.70	5.38	5.97	1.43
4z-2 (13% fill, 15 krpm)	5.63	9.06	8.12	7.17	6.66	7.33	1.32
4z-2 (13% fill, 16.25 krpm))	6.14	9.73	8.77	7.71	6.97	7.86	1.42
4z-2 (13% fill, 17.5 krpm)	6.76	10.41	9.56	8.60	7.45	8.56	1.49
4z-2 (13%, 20 krpm)	7.95	11.91	11.05	7.83	8.09	9.37	1.96
4z-3 (90% fill, 15 krpm)	5.28	8.54	7.71	5.46	6.47	6.69	1.41
4z-3 (90% fill, 16.25 krpm)	5.73	9.14	8.27	5.67	6.73	7.11	1.55
4z-3 (90% fill, 17.5 krpm)	6.20	9.72	8.89	8.43	6.98	8.04	1.43
4z-3 (90%, 20 krpm)	7.24	10.96	10.32	9.79	7.84	9.23	1.61

TABLE 42.—DEVIATION FROM COLD HEAD CALCULATION AND AVERAGE OF DEVIATIONS FOR EACH MASS FLOW RATE CALCULATION METHOD FOR TESTS WITHOUT TRANSIENTS

Test	Test deviation from the cold head neon mass flow approximation, g/s				
	FS-1	Cryofan	Cold head	Neon heater	Tank balance
2	−2.71	0.34	0.00	−1.59	−2.08
2a	−2.72	0.07	0.00	−2.08	−5.23
3 (Ullage)	−2.74	0.26	0.00	−0.88	−1.57
3a (7-W neon heater)	−2.65	0.40	0.00	0.05	−1.59
3a (17-W neon heater)	−2.70	0.33	0.00	−0.58	−1.42
3a (37-W neon heater)	−2.70	0.35	0.00	−1.46	−1.51
3a (47-W neon heater)	−2.69	0.39	0.00	−1.54	−1.67
3a (57-W neon heater)	−2.70	0.38	0.00	−1.70	−1.66
4 (15 krpm)	−2.18	0.48	0.00	−0.97	−1.34
4 (17.25 krpm)	−2.40	0.41	0.00	−1.09	−1.46
4 (22.5 krpm)	−2.79	0.30	0.00	−1.26	−1.68
4 (20 krpm)	−3.08	0.18	0.00	−1.14	−1.92
5 (Dip tube)	−2.81	0.24	0.00	−0.98	−2.08
5a (7-W neon heater)	−2.80	0.21	0.00	2.86	−1.98
5a (17-W neon heater)	−2.80	0.21	0.00	0.52	−2.05
5a (37-W neon heater)	−2.79	0.22	0.00	−0.87	−2.10
6 (90% fill, nominal tank pressure)	−2.70	0.24	0.00	−0.65	−1.97
7 (50% fill, nominal tank pressure)	−2.75	0.18	0.00	−1.14	−1.77
8 (5% fill, nominal tank pressure)	−2.58	0.29	0.00	−2.01	−1.37
9 (5% fill, high tank pressure)	−2.44	0.40	0.00	−1.67	−1.32
10 (5% fill, low tank pressure)	−2.83	0.30	0.00	−1.61	−2.41
11 (low fill, nominal GO ₂ feed)	−2.67	0.50	0.00	−1.68	−1.34
12 (low fill, low GO ₂ feed)	−2.73	0.36	0.00	−2.00	−3.85
13 (low fill, high GO ₂ feed)	−2.55	0.64	0.00	−1.82	3.12
4z (50% fill, 15 krpm)	−2.09	0.60	0.00	−1.70	−0.20
4z (50% fill, 16.25 krpm))	−2.13	0.61	0.00	−1.20	−0.52
4z (50% fill, 17.5 krpm)	−2.19	0.60	0.00	−2.22	−0.62
4z (50%, 20 krpm)	−2.47	0.50	0.00	−2.55	−1.87
4z-2 (13% fill, 15 krpm)	−2.49	0.94	0.00	−0.95	−1.46
4z-2 (13% fill, 16.25 krpm))	−2.63	0.96	0.00	−1.06	−1.80
4z-2 (13% fill, 17.5 krpm)	−2.80	0.85	0.00	−0.96	−2.11
4z-2 (13% fill, 20 krpm)	−3.10	0.86	0.00	−3.22	−2.96
4z-3 (90% fill, 15 krpm)	−2.43	0.83	0.00	−2.25	−1.24
4z-3 (90% fill, 16.25 krpm))	−2.54	0.87	0.00	−2.60	−1.54
4z-3 (90% fill, 17.5 krpm)	−2.69	0.83	0.00	−0.46	−1.91
4z-3 (90%, 20 krpm)	−3.08	0.64	0.00	−0.53	−2.48
Average of deviations	−2.64	0.47	0.00	−1.25	−1.69

TABLE 43.—SAMPLE OF TESTS WITH VARIATION BETWEEN RTDS SD-5, SD-6
AND SD-7 CRYOCOOLER OUTLET TEMPERATURE

	CC entry	CC cold head	CC exit	Difference	RTD uncertainty
Test	SD-5, K	SD-7, K	SD-6, K	SD-7 to SD-6, K	U _{SD-6} , K
3	103.13	71.19	71.84	−0.65	1.61
3a	103	71.03	71.63	−0.6	1.61
5	102.97	70.31	71.40	−1.09	1.61
5a	102.98	70.32	71.40	−1.08	1.61
6	103.19	70.7	69.66	1.04	1.63
7	103.36	70.76	69.46	1.3	1.63
8	103.68	68.34	67.67	0.67	1.64
10	98	SD-7 gets colder halfway through		-----	-----
27	104.94	69.31	68.31	1	1.64
29-2	103.75	68.26	66.94	1.32	1.65
33	102.41	75.64	74.49	1.15	1.59
40	107.04	68.45	68.26	0.19	1.64
41	103.59	77.41	76.88	0.53	1.57

It was observed that the temperature outputs from RTDs SD-6 and SD-7 were within 1.5 K of each other throughout testing. Physically, SD-7 was located on the surface of the active cold head and SD-6 was mounted on the surface of the tube exiting the cold head of the cryocooler. Table 43 contains a sample of tests that show the temperature measurement variation between SD-6 and SD-7 is within the uncertainty of those RTDs (larger value of 0.5 °C or 0.8 percent of the measured temperature in °C) (Ref. 26). The cold head temperature must always be colder than the neon temperature exiting the cold head, but the test data indicates differently. Although this may just fall within the uncertainty of the RTDs in the cryocooler, it does not discount the potential for variations in the parasitic heat load imposed on the cryocooler cold box.

5.4 Liquefaction Flow Rates

Tests of liquefaction with a constant flow rate of GO₂ into the tank were performed in Tests 11, 12, and 13 and are discussed in Section 4.2. In these tests, the oxygen flow rate was in the range 0.14 to 0.61 g/s (0.5 to 2.2 kg/h) as shown in Table 44. As discussed in Section 4.3, the tank pressure achieved a steady state for a nominal GO₂ flow rate of 0.3 g/s (1.1 kg/h); for lower flow rates the tank was depressurized, and for higher flow rates the tank pressure increased with time. The tank pressure, GO₂ flow rates, and fill level for the entire duration of Tests 11, 12, and 13 are shown in Figure 163 and Figure 164. Note that the pressurization rate is in kPa/min in Figure 163 so that it can be

TABLE 44.—AVERAGED DATA IN SELECTED TIME
PERIODS FOR TESTS 11, 12, AND 13

T _{start} , h	T _{stop} , h	Flow rate, g/s	P _{min} , kPa	P _{max} , kPa	P _{avg} , kPa	P _{rate} , kPa/h	Flow rate, kg/h
1,393	1,395.4	0.61	139.1	172.9	156.1	14.1	2.2
1,395.5	1,404.4	0.31	172.5	174.4	173.4	0.2	1.1
1,404.4	1,412.4	0.31	174.4	174.7	174.6	0.0	1.1
1,412.5	1,417.6	0.61	175.6	243.2	209.9	13.2	2.2
1,417.7	1,442	0.31	221.6	244.3	231.7	0.9	1.1
1,442	1,466	0.31	212.7	221.6	217.1	0.4	1.1
1,466	1,484.1	0.30	210.9	212.7	212.0	0.1	1.1
1,417.7	1,484.1	0.31	210.9	244.3	221.0	0.5	1.1
1,484.5	1,487	0.14	194.7	208.6	201.6	−5.6	0.5
1,487	1,490.6	0.14	175.9	194.6	185.0	−5.2	0.5
1,490.7	1,508	0.30	175.0	181.2	178.5	0.4	1.1
1,532.5	1,538.1	0.61	193.3	273.9	233.8	14.4	2.2
1,538.2	1,539.2	0.14	265.3	275.2	270.2	−9.8	0.5
1,539.3	1,540	0.16	259.1	264.2	261.6	−7.3	0.6
1,540	1,545	0.17	225.4	259.0	241.8	−6.7	0.6
1,545	1,550	0.17	195.8	225.3	210.3	−5.9	0.6
1,550	1,556.5	0.17	163.1	195.7	178.9	−5.0	0.6
1,557	1,563.1	0.48	166.0	212.0	189.4	7.5	1.7
1,563.5	1,580.4	0.24	170.0	213.2	189.6	−2.6	0.9

plotted in the scale of the secondary vertical axis. These tests were performed one after the other in the sequence Test 11, followed by Test 13, and then Test 12. To help understand some of the test points where the pressurization rate was not constant,

especially during depressurization, the tests were broken up into smaller blocks of time. Table 44 covers all the time periods in the plot with the exception of Hours 1,508 to 1,532, during which the tank was drained (as can be seen in Figure 164).

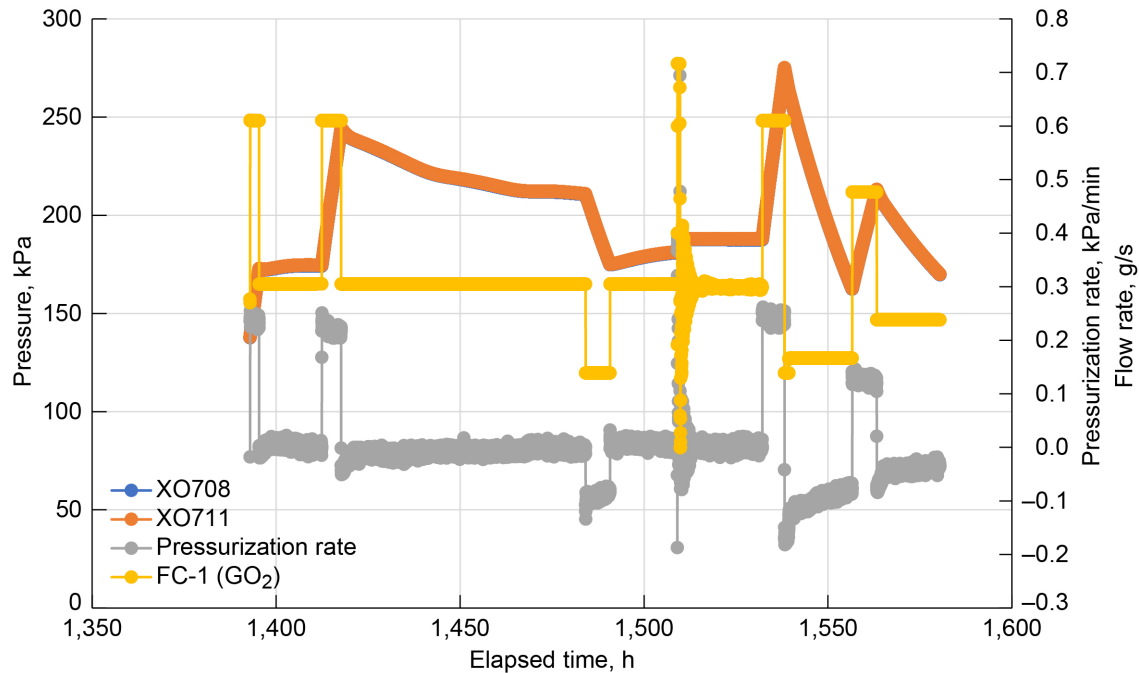


Figure 163.—Pressure and GO₂ flow rates for Tests 11, 12, and 13.

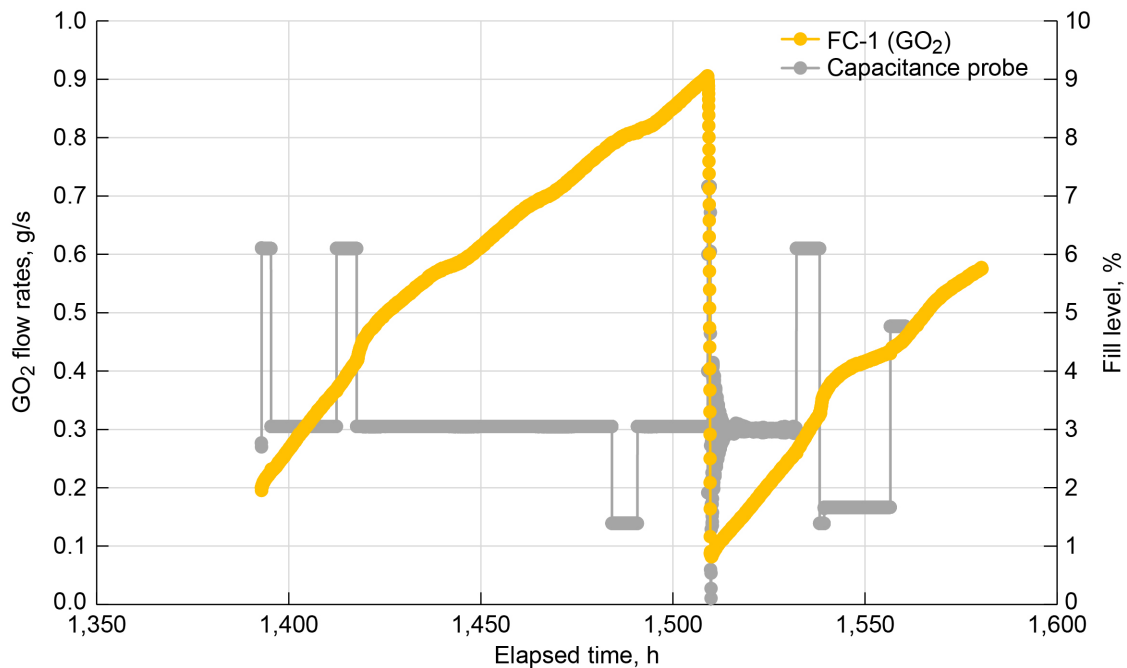


Figure 164.—Flow rates and fill level for Tests 11, 12, and 13.

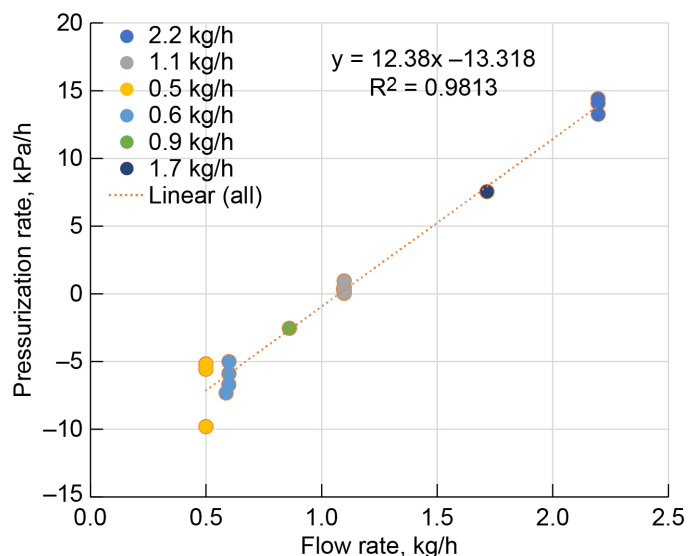


Figure 165.—Rate of tank pressurization versus flow rate of GO₂.

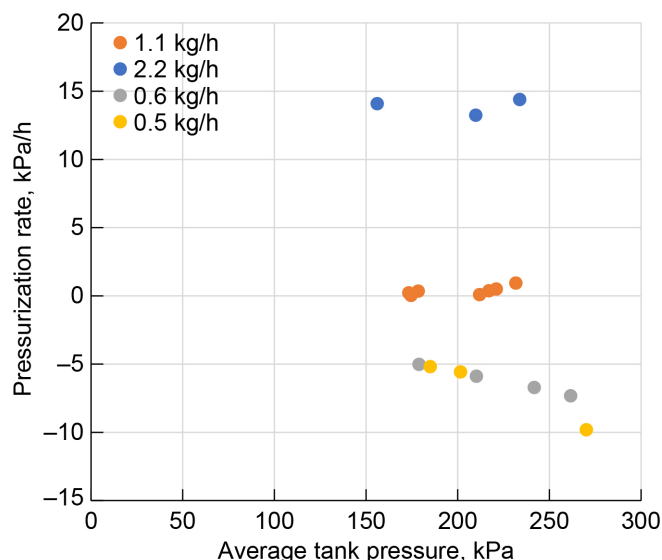


Figure 166.—Tank pressurization rate versus tank pressure.

TABLE 45.—1.1 kg/h FLOW TESTS IN BETWEEN TESTS 11, 12, AND 13

Start time, h	Initial pressure, kPa	Asymptote pressure, kPa	Trend towards asymptote
1,417.7	244.3	210.9	Downward
1,490.7	175.0	181.2	Upward
1,395.5	172.5	174.4	Upward

Table 45 shows averaged data for selected time periods during Tests 11, 12, and 13 that are used in plots shown in Figure 165 and Figure 166. Figure 165 shows a plot of the rate of pressurization of the tank with the flow rate of GO₂. Although

there is some scatter for low flow rates, the pressurization rate generally behaves linearly with the GO₂ flow rate. Note that (see Section 4.2) the tank fill level was low (<10 percent) in all these tests. Also, the tank heater power was 20 W and the neon loop heater power was 27 W in these tests. Figure 166 shows a plot of the tank pressurization rate versus the average tank pressure. For tests with a GO₂ flow rate of 1.1 kg/h, the tank pressure was constant during the course of each test shown in Figure 166, and varied with elapsed time for the other tests. In these cases, the x-axis in Figure 166 shows the average tank pressure during each test. One trend evident in the figure is that the magnitude of the rate of depressurization (for GO₂ flow rates <1.1 kg/h) appears to increase with increasing tank pressure, but the rate of pressurization (for a flow rate of 2.2 kg/h) is quite independent of the average tank pressure. However, only limited data is available when the pressurization rate is positive. A curious observation from Figure 166 is that for tests with a GO₂ flow rate of 1.1 kg/h for which the rate of pressurization is zero, the sensitivity of the thermal balance may be such that other secondary environmental conditions could drive the balance one way or the other, especially at low fill levels, where the oxygen thermal mass is low. In other words, at this flow rate, many tank pressures are possible for steady-state operation. Table 45 shows the different tests that were attempted in this manner and how they asymptoted. For tests coming off of a low flow test, the asymptote pressure was ~180 kPa (26.1 psia), for tests coming off of a high flow test, the asymptote pressure was ~210 kPa (30.5 psia). This 30 kPa (4.4 psia) gap is curious in that the upward asymptotes were on both sides of the downward asymptote.

The behavior of the rate of pressurization with the GO₂ flow rate is analyzed as follows. Starting with the ideal gas law $PV=n\hat{R}T$ for the ullage gas treated as a lumped mass, upon using logarithmic differentiation gives $\frac{dP}{P} + \frac{dV}{V} = \frac{dn}{n} + \frac{dT}{T}$, which may be written as Equation (21).

$$\frac{dP}{dt} = \frac{RT}{V} \left(\dot{m}_{\text{GO}_2} - V_0 \rho_{\text{LO}_2} \frac{d\phi}{dt} \right) + \frac{P}{T} \frac{dT}{dt} + \frac{P}{(1-\phi)} \frac{d\phi}{dt} \quad (21)$$

Using scaling, the last two terms on the right side can be estimated to be an order of magnitude smaller than the other terms in Equation (21). Thus, $\frac{dP}{dt} \approx \frac{RT}{V} \left(\dot{m}_{\text{GO}_2} - V_0 \rho_{\text{LO}_2} \frac{d\phi}{dt} \right)$, and the dependence of $\frac{dP}{dt}$ on $\dot{m}_{\text{GO}_2}$ is linear if $\frac{d\phi}{dt}$ is a constant. The value of $\frac{RT}{V} \approx \frac{8.314/32 \cdot 100}{2.1 \cdot 0.96} = 12.89$ kPa/kg is similar to the slope in Figure 165. Note that a constant $\frac{d\phi}{dt}$ implies that the liquefaction rate of oxygen is constant.

5.5 Effect of Dip Tube

During early oxygen liquefaction tests, two methods that introduced GO_2 to the test tank were employed. Test 3a introduced GO_2 through the vent line at the top of the tank into the ullage; Test 5a fed GO_2 into the bottom of the tank directly into LO_2 via a dip tube. In the latter case, the GO_2 bubbled up through the liquid before reaching the ullage space for condensation. Operationally, Tests 3a and 5a were run the same way. Both tests were performed with the tank from 55 to 66 percent full of liquid, the cryofan speed was fixed at 20 krpm, a virtually constant tank pressure was maintained at 207 kPa (30 psia), and the nominal tank heater power was at 20 W. In addition to the different methods for injecting oxygen into the test tank, the heat load imposed by the neon loop was varied for both tests to see how the liquefaction rate, the equivalent of the incoming GO_2 mass flow rate, responded to variations of lift across the tank's surface. The system response to the neon heater variation for both tests was allowed to reach a steady state before moving to the next heater power. Test 3a and Test 5a were both run with the neon heater power fixed to 7, 17, and 37 W. However, Test 3a ran additional tests with the neon heater power at 27 W (nominal operations in Test 3), 47 W, and 57 W. Figure 167 plots the results of Test 3a and Test 5a for a direct comparison of the GO_2 insertion methods.

Direct comparison of GO_2 insertion through the ullage and via the dip tube indicated that liquefaction rates associated with the ullage insertion were within 15 percent greater than the liquefaction rates associated with the dip tube under similar test conditions. The slopes of the two lines are 12 percent different, with the dip tube having a higher slope or sensitivity to heater power. A similar decrease was seen by Valenzuela using LN_2 in the Brassboard test system (Ref. 9). A possible cause for the ullage injection having a higher liquefaction rate is driven by the gas flow velocity in the ullage. Although bubbling through the liquid allows the majority of the sensible heat to be transferred to the liquid, it does not allow for much of any velocity to cause forced convection over the cryocooler-cooled tank wall. As the heater power increases, the temperature difference between the neon and the oxygen decreases, further weakening any natural convection flows within the ullage, causing further disparity between the two cases. The differences in stratification in the ullage can be observed in Figure 168.

The general decrease in the liquefaction rate while maintaining constant tank pressure with respect to the increase of the neon heater power was a result of a higher temperature

neon that provided broad area cooling at the same flow rate as the lower heat loads imposed on the neon loop. This effectively decreased the temperature difference of the neon across the tank, which directly reduced the amount of heat removed (lift) by the neon flow. The decrease in heat removal signaled the GO_2 flow controller to decrease flow to maintain constant tank pressure at 207 kPa (30 psia).

Based on the energy balance, the inverse of the slopes plotted in Figure 167 should closely resemble the enthalpy change tied to the GO_2 mass flow being introduced to the tank, whether it is introduced through the ullage or via the dip tube. Table 46 takes the inverse of the slopes from Figure 167 and compares them to the enthalpy difference derived from the incoming GO_2 temperature and pressure and the enthalpy of saturated LO_2 at the tank pressure of 207 kPa (30 psia). The GO_2 flow controller temperature, TC-62, during this test floated around 300 K and 310.25 kPa (45 psia) depending on the usage and time of day. The ullage injection calculation was also performed with the vent temperature, LL20, in place of TC-62 as both thermocouples were close to the vent line where GO_2 was introduced into the ullage. LL20 matches the heat load associated with the ullage GO_2 feed from the inverse slope calculation better than TC-62. The enthalpy change agrees quite well for both operating scenarios; however, usage of the dip tube may require additional investigation to better capture the slope depicted in Figure 167.

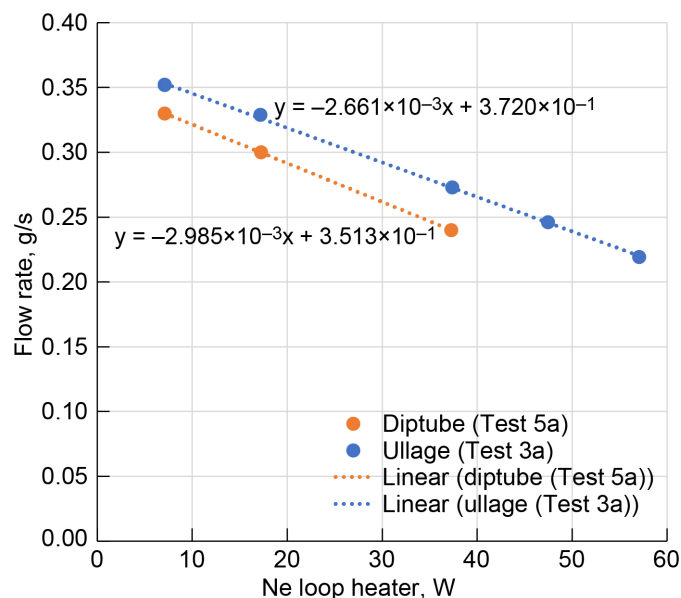


Figure 167.— GO_2 injection method's impact on liquefaction at different neon loop heater powers.

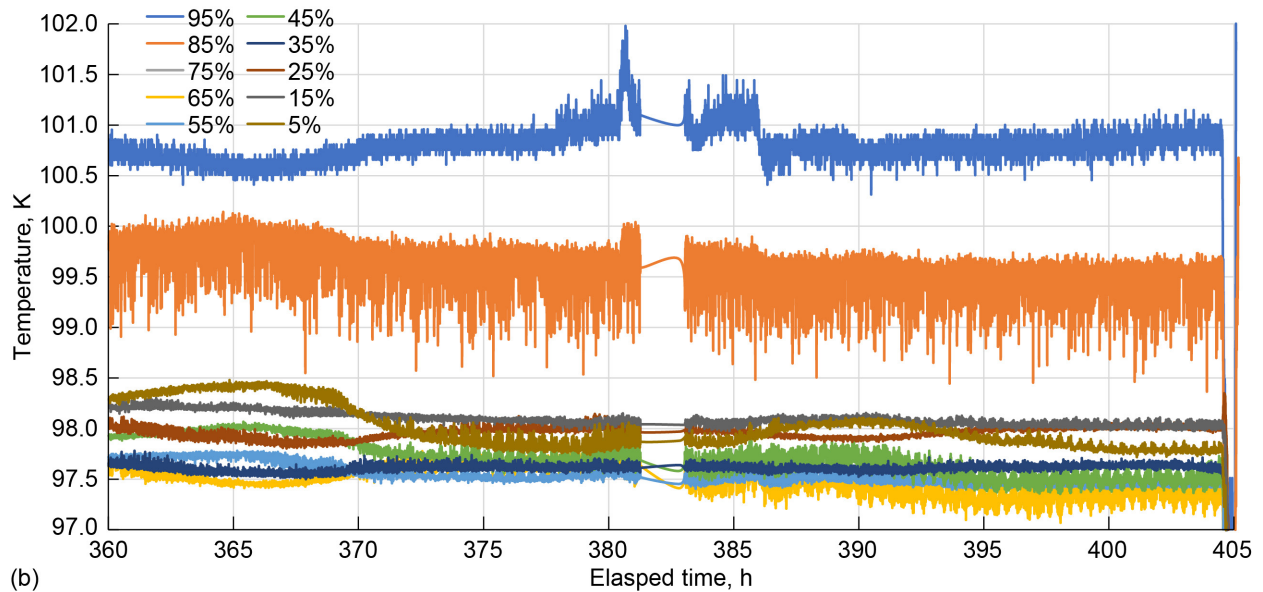
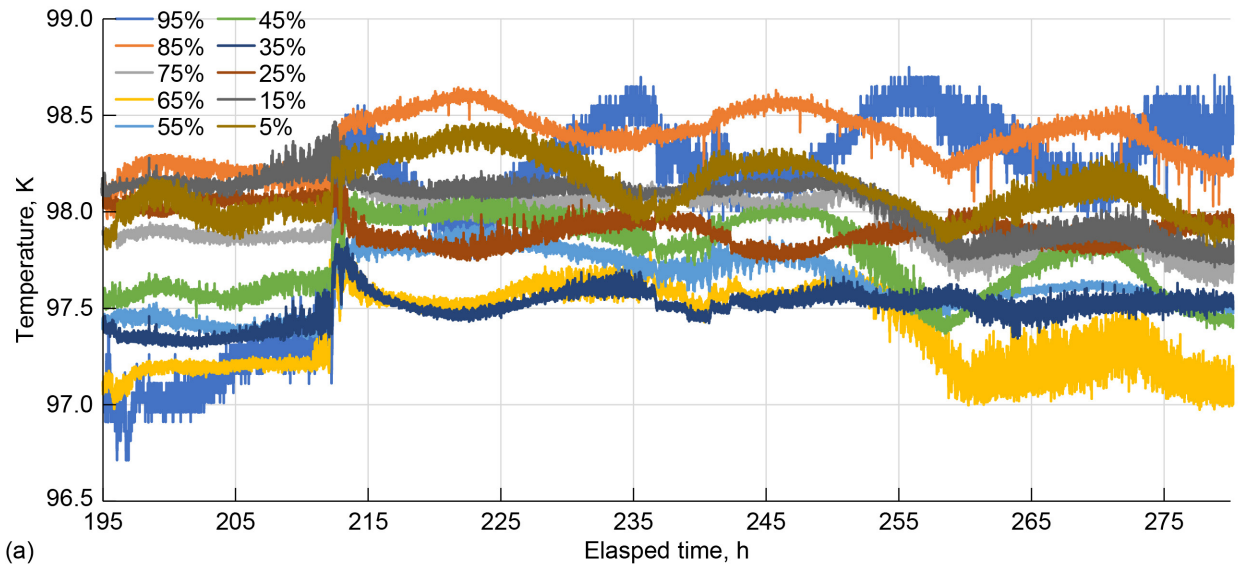


Figure 168.—(a) Test 3/3a and (b) Test 5/5a FOSS temperature response shows no measurable change in bulk liquid stratification. However, bulk ullage stratification is 2 to 3 K higher in Test 5a.

TABLE 46.—EXPERIMENTAL VERSUS ANALYTICAL EVALUATION OF GO₂ FLOW INDUCED ENTHALPY CHANGE (17-W NEON HEATER AND 27-W TANK HEATER)

	Neon heater power, W	Tank heater power, W	h GO ₂ flow controller, J/g	h saturated LO ₂ , J/g	dH GO ₂ stream, J/g	1/slope, J/g	Experimental to analytical % difference, %
Ullage (TC-62)	7.09	20.31	273.01	−120.31	393.32	375.94	4.42
Ullage (LL20)	7.09	20.31	262.70	−120.31	383.01	375.94	1.84
Dip tube	7.09	20.31	270.52	−120.31	390.83	334.45	14.43
Ullage (TC-62)	17.19	20.31	272.53	−120.31	392.84	375.94	4.30
Ullage (LL20)	17.19	20.31	261.35	−120.31	381.66	375.94	1.50
Dip tube	17.19	20.31	270.49	−120.31	390.79	334.45	14.42
Ullage (TC-62)	37.31	20.31	271.76	−120.31	392.06	375.94	4.11
Ullage (LL20)	37.31	20.31	259.94	−120.31	380.25	375.94	1.13
Dip tube	37.31	20.31	269.89	−120.31	390.19	334.45	14.29

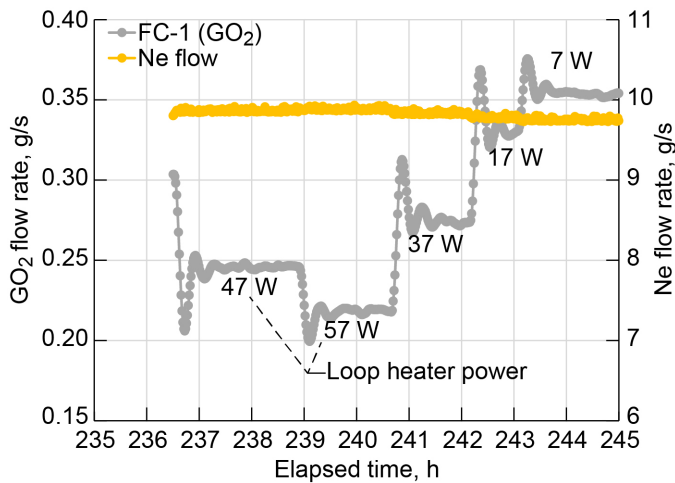


Figure 169.—Flow rates for Test 3a.

However, testing at higher fill levels showed that the system is much more controllable at the 90 percent plus fill levels. This is also similar to what was seen by Valenzuela (Ref. 8). Investigation into the performance of the dip tube versus ullage injection should be further investigated as a function of fill level.

5.6 Effect of Heater Power and Fan Speed on Neon Loop

The effect of varying the heater power in the neon loop was evaluated in Test 3a. Similarly, the effect of varying the speed of the cryofan was evaluated in Test 4. Both tests were described in Section 4.1. Figure 169 shows a plot of the GO₂ and neon flow rates. Also shown on the plot are the various powers of the neon loop heater for different portions of the test. During this test, the tank pressure was controlled to 207 kPa (30 psia), and the tank heater power was nominally fixed at

20 W for the entire test. Following a change in the neon loop heater power setting, it is seen that the GO₂ flow rate necessary to maintain the tank pressure achieves a steady state in ~1.5 h. The cryofan speed was fixed at 20 krpm and the neon flow rate was unaffected by changing the power applied to the loop heater.

It can be seen from Figure 169 that the liquefaction rate at steady state (which is equal to the GO₂ flow rate) is inversely proportional to the heater power applied to the neon loop. Basically, the heat applied increases the temperature of the neon that enters the cooling tubes; see SD-3A temperature in Figure 170, where temperatures at various locations in the neon loop are shown. However, the neon temperature exiting the cooling tubes remains constant (SD-2A in Figure 170), being approximately equal to and limited by the saturation temperature of the LO₂. Note that SD-4 does not respond as it should to the change in temperatures seen elsewhere in the loop; the cause of this was not determined. The GNe temperature difference from inlet to exit of the cooling tubes thus varies with the applied loop heater power. Therefore, the heater power controls the effective cooling power of the neon loop (or the effective lift of the cryocooler). This is shown in Figure 171, where it is evident that the neon temperature difference from exit to inlet in the cooling tubes has the same trend as the liquefaction rate, and these two quantities appear to be proportional to each other.

For steady-state operation of the neon loop, the following energy balance prevails: the rate of heat removal from the GNe in the cryocooler heat exchanger equals the rate at which heat is gained by the neon flow from the rest of the loop. The latter includes parasitic heat gain from the flow lines, the applied power to the loop heater, parasitic heat to the tank, power applied to the tank heater, and the liquefaction heat load. The energy balance can be expressed as Equation (22).

$$\dot{Q}_{\text{cryocooler}} = \dot{Q}_{\text{flowline}} + \dot{Q}_{\text{loop heater}} + \dot{Q}_{\text{parasitic,tank}} + \dot{Q}_{\text{tank heater}} + \dot{Q}_{\text{liquefaction}} \quad (22)$$

During the course of Test 3a, the tank pressure, LO₂ and ullage temperatures, and various temperatures in the neon loop (except for the cooling tube inlet temperature SD-3A) are essentially constant. Except for $\dot{Q}_{\text{loop heater}}$ and $\dot{Q}_{\text{liquefaction}}$ that equals $\dot{m}_{\text{GO}_2} \Delta h$, where Δh is the specific enthalpy difference between the incoming GO₂ and the condensed LO₂, all other quantities in Equation (22) are constants. A plot of $\dot{m}_{\text{GO}_2}$ versus $\dot{Q}_{\text{loop heater}}$ is shown in Figure 172, and the behavior is well represented by a linear fit. Furthermore, the slope of the fit is 2.66×10^{-3} and is very close (~ 4 percent) to the theoretical value of $1/\Delta h = 1/(392 \text{ J/g}) = 2.55 \times 10^{-3} \text{ g/J}$.

Another energy balance at steady state may be written for the GNe flow within the cooling tubes on the tank: the rate of increase of enthalpy of the neon flow from inlet to exit equals the rate at which energy is transferred to the flow from the tank surface. The latter equals the liquefaction heat load, the power applied to the tank heater, and the parasitic heat to the tank. The energy balance can be expressed as Equation (23).

$$\dot{Q}_{\text{cooling tube,neon}} = \dot{Q}_{\text{liquefaction}} + \dot{Q}_{\text{tank heater}} + \dot{Q}_{\text{parasitic,tank}} \quad (23)$$

with $\dot{Q}_{\text{cooling tube,neon}} = \dot{m}_{\text{neon}} C_p \Delta T$, where ΔT is the temperature difference of the neon flow in the cooling tubes from exit to inlet, and C_p is the specific heat of neon. During Test 3a, the tank heater power is constant (20 W). The tank parasitic heat load can be assumed to be constant as well, because the tank and environment temperatures are constant. Equation (23) can be rewritten as Equation (24).

$$\Delta T = \frac{\Delta h}{\dot{m}_{\text{neon}} C_p} \dot{m}_{\text{GO}_2} + \frac{1}{\dot{m}_{\text{neon}} C_p} (\dot{Q}_{\text{tank heater}} + \dot{Q}_{\text{parasitic,tank}}) \quad (24)$$

A plot of ΔT versus $\dot{m}_{\text{GO}_2}$ is shown in Figure 173, and the data is well represented by a linear fit as expected. The slope of the line is 53.7 K, which must be equal to $\frac{\Delta h}{\dot{m}_{\text{neon}} C_p}$ from Equation (24). With $\Delta h = 392.1 \text{ J/g}$ (h_{GO_2} (299 K, 30 psia) = 271.5 J/g, $h_{\text{LO}_2,\text{sat}}$ (30 psia) = -120.6 J/g), $C_p = 1.03 \text{ J/(g K)}$ for neon, the neon flow rate consistent with the data fit in Figure 173 is 7.1 g/s. This can be compared with the value 6.0 g/s measured by the flow meter for Test 3a. The measured flow rate is somewhat lower

(by ~ 15 percent) than the anticipated flow rate from the data fit. During the course of analyzing the data from the various CryoFILL tests, it was suspected that the neon flow rate measured by the flow meter is indeed lower than the actual flow rate. Several other means to correct the measured neon flow rate are discussed in Sections 5.2 and 5.3. From the intercept of the linear fit in Figure 173 (7.26 K), the tank parasitic heat load for Test 3a computes to $\dot{Q}_{\text{parasitic,tank}} = 33 \text{ W}$.

The effect of varying the speed of the cryofan was evaluated in Test 4. Figure 174 shows the GO₂ and neon flow rate during this test, and the cryofan speeds during various portions of the test are marked. The tank pressure was controlled to 207 kpa (30 psia) and the tank and loop heater power was fixed at 20 W and 27 W, respectively during Test 4. It is seen from Figure 174 that increasing the fan speed increases both the neon flow rate and consequently the GO₂ flow (the liquefaction rate) at steady state. As mentioned before (Section 4.2), the cryofan turned off overnight from a set value of 22.5 krpm when Test 4 was conducted, and the test resumed the next day at a fan speed of 20 krpm where its operation was stable.

Figure 175 shows the temperature at various locations in the neon loop. Notably, it can be seen that the inlet temperature to the cooling tubes (SD-3A) increases as the cryofan speed increases. This is likely because when the fan speed goes up, the neon flow rate increases and the residence time of the neon within the cold head heat exchanger decreases. Thus, the neon flow exiting the cold head is warmer. Offsets in SD-7 and SD-6 with changes in fan speed are a result of thermal balance responses to the change in neon mass flow rate. The cooling tube exit temperature of the neon flow (SD-2A) is relatively constant similar to that in Test 3a, for the same reasons discussed before. Figure 176 shows the temperature rise (ΔT) of the neon flow from inlet to exit in the cooling tubes, as well as its cooling capacity ($\dot{m}^* \Delta T$). It is seen that ΔT decreases when the fan speed is increased. The cooling capacity, however, is a product of an increasing quantity ($\dot{m}$) and a decreasing quantity (ΔT) and is found to increase with the fan speed up to 20 krpm, but plateaus thereafter. Figure 177 shows a plot of the GO₂ flow rate and the neon flow rate versus the speed of the cryofan. The neon flow rate increased linearly with the cryofan speed, but the liquefaction rate (that is limited by the neon cooling capacity) is seen to achieve a plateau as well.

Figure 178 shows a plot of $\dot{m}^* \Delta T$ of the neon flow in the cooling tubes versus the liquefaction rate of oxygen. Both the direct reading from the flow meter and the correction based on the fan performance curve are used for $\dot{m}_{\text{neon}}$ in this plot. Because the neon flow rate in Test 4 is not constant but varies with the cryofan speed, Equation (24) is modified and written as Equation (25).

$$\dot{m}_{neon}\Delta T = \frac{\Delta h}{C_p}\dot{m}_{GO_2} + \frac{1}{C_p}(\dot{Q}_{tank\ heater} + \dot{Q}_{parasitic,tank}) \quad (25)$$

The behavior in Figure 178 is well represented by the linear fit. The slope of the linear fit is 360 gK/s for the corrected neon flow rate and 420 gK/s for the direct reading from the flow meter. The anticipated slope from Equation (25) is

$\frac{\Delta h}{C_p} = 381.3 \text{ gK/s}$, and lies in between the slopes from the linear fit, suggesting that the true neon flow rate is also in between the direct measurement and the corrected value. Note, however, that $\dot{m}\Delta T$ is a product of two measured quantities, and the error in it would be compounded and larger than the error of the individual measurements.

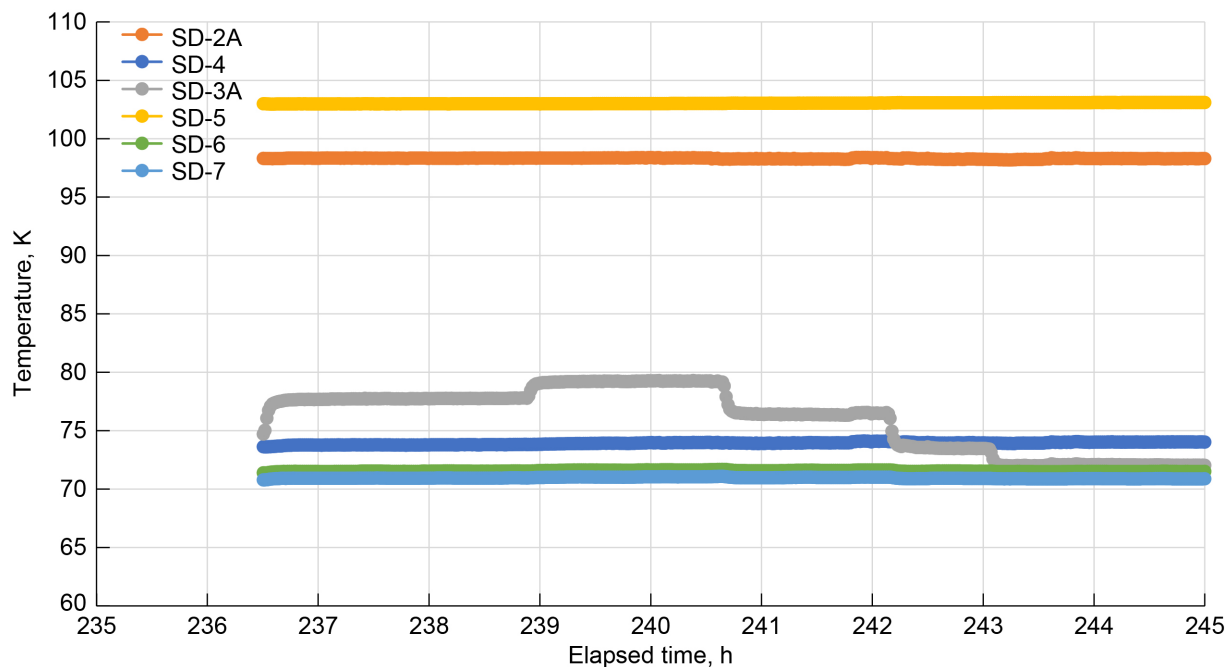


Figure 170.—Neon loop temperatures for Test 3a.

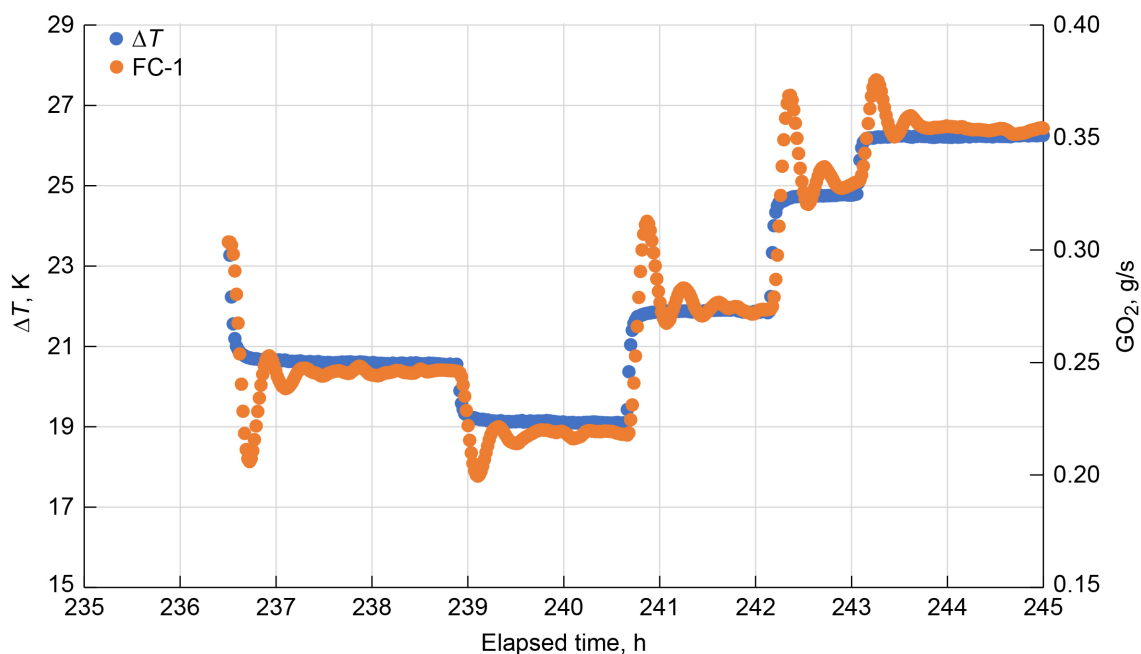


Figure 171.—Comparison of liquefaction flow rate (FC-1) with temperature change of neon flow.

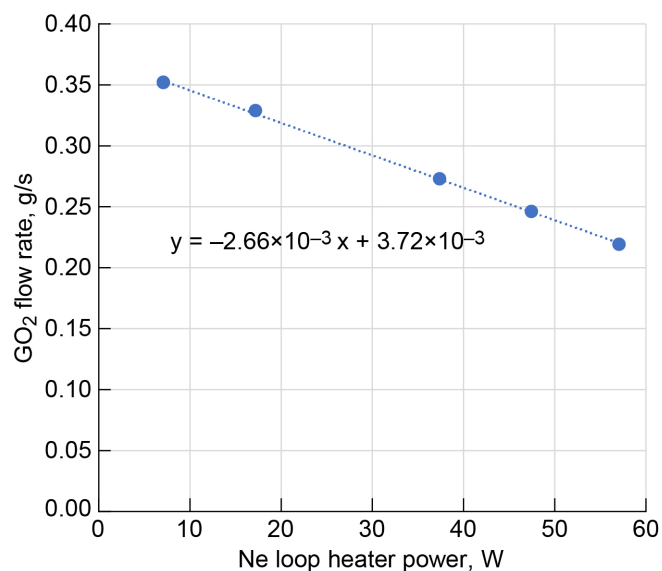


Figure 172.—Liquefaction rate versus neon loop heater power.

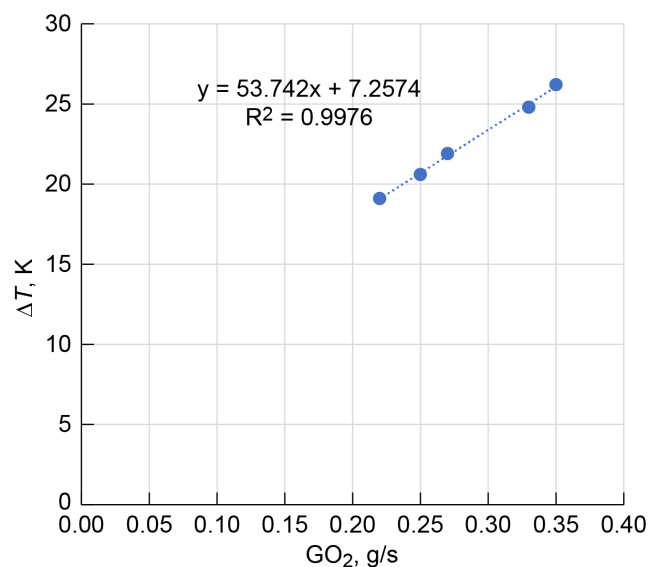


Figure 173.—Cooling capacity ($\dot{m} \Delta T$) of neon flow versus liquefaction flow rate (FC-1).

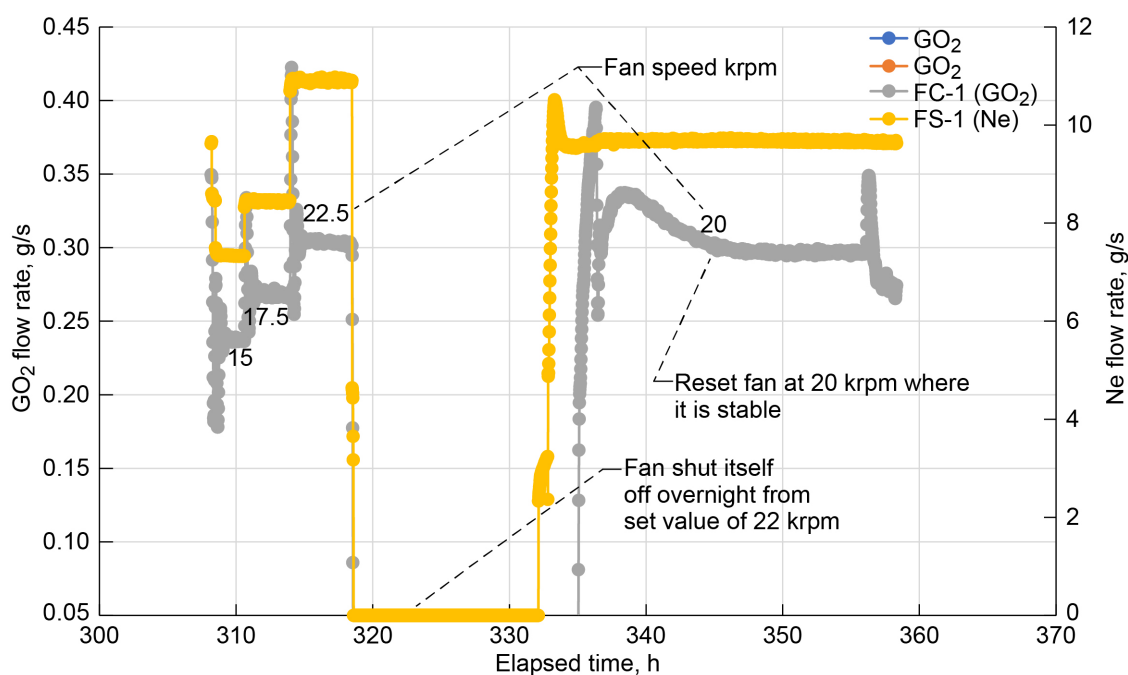


Figure 174.— GO_2 and neon flow rates for Test 4.

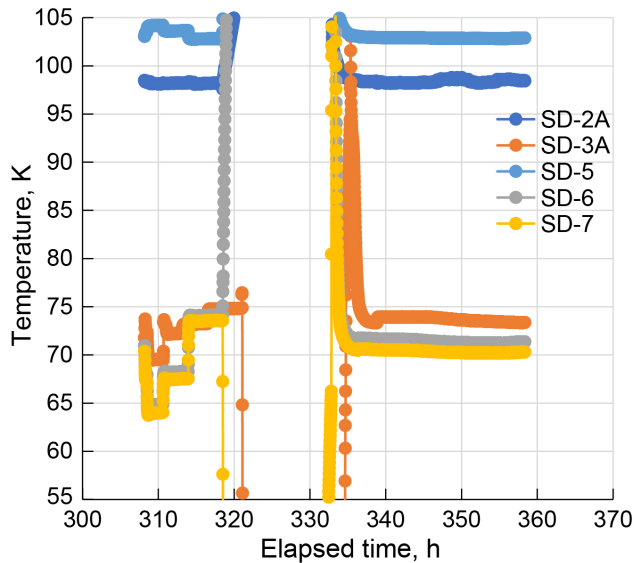


Figure 175.—Neon loop temperatures for Test 4.

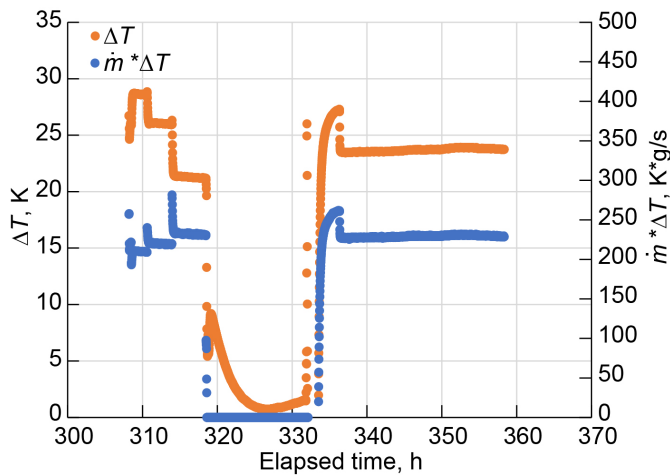


Figure 176.—Temperature change and cooling capacity of neon flow (ΔT and $\dot{m}^*\Delta T$) for Test 4.

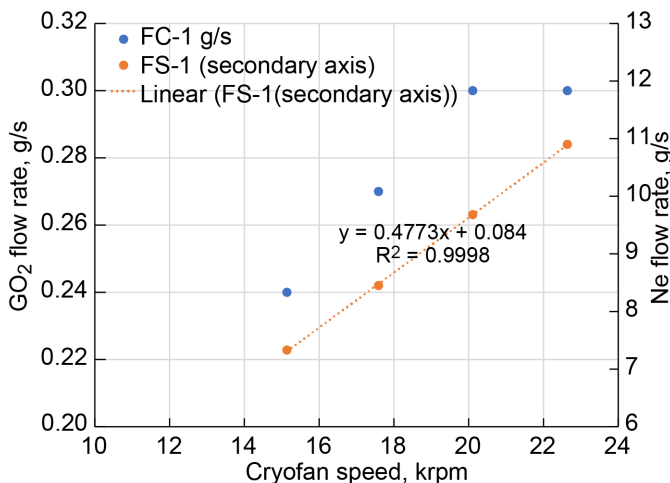


Figure 177.—GO₂ and neon flow rates versus cryofan speed.

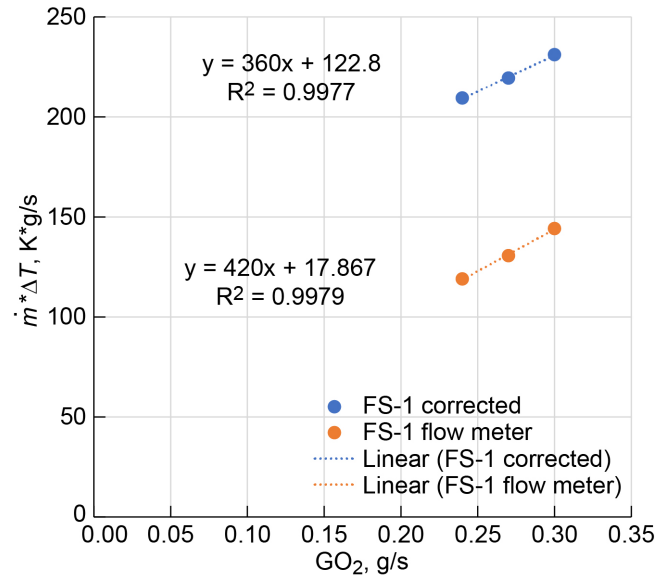


Figure 178.—Cooling capacity ($\dot{m}^*\Delta T$) of neon flow versus liquefaction rate.

5.7 Pressurization Rates

Two types of pressurization tests were run. The first type related to tests in which no gas was added and the tank was allowed to self-pressurize or self-depressurize based on the cryocooler and loop heater settings (Test 2). Autogenous pressurization tests were also performed, in which the GO₂ was added without the cryocooler on. These autogenous pressurization tests were intended to provide simplified test cases for the analytical models of CryoFILL testing, to separate condensation that occurred on the liquid-vapor interface from condensation occurring on the tank wall with the cryocooler running. This enabled the analysis models to separate the complex condensation results and make sure that the appropriate physics were used.

As mentioned in Section 4.1, the GO₂ flow controller failed so no GO₂ could be injected into the tank for a 2-week period. During this time, a repetition of the zero boil-off test originally captured in Test 2, identified as Test 2a, was performed with the tank pressure at 206.8 kPa (30 psia). Three additional zero boil-off tests—Test 2b (tank pressure = 182.4 kPa (26.5 psia)), Test 2d (tank pressure = 237.5 kPa (34.4 psia)), and Test 2f (tank pressure = 175.5 kPa (25.5 psia))—were also performed in this series of testing. The heat input to the tank and neon loop heaters were varied to raise or lower the tank pressure.

The resulting pressurization rates are plotted against the total heater input (tank and neon loop heaters) in Table 47 and Figure 179, and the behavior is well represented by a line. The pressurization rates from Test 2 are then also compared to Test 3 and an offset is observed. Within Test 3, the oxygen flow coming in is accounted for via the change in enthalpy

of 383 J/g. The offset between Test 2 and Test 3 series is ~15 W. It is not fully understood where this 15 W comes from, although it could be due to some extraneous heating of the system due to the incoming GO₂ or precooling of the gas by the cold wall (the incoming gas would have to be pre-cooled to ~225 K to account for the 15-W difference). This is important to note given the importance in the thermal balance in the liquefaction system operations. Using the results from Test 2 for the expected pressurization rates was a part of the reason it was necessary to reperform Test 29.

Additionally, pressurization was caused by introducing GO₂ into the ullage during Test 1a and Test 1a-2 while the tank was locked up. The tests were run so that a constant flow of gas was injected until the desired pressure was reached. Then the gas was allowed to cool down until it reached a fairly stable

pressure or the pressurization rate reached 0. During Test 1a, as shown in Figure 180, the pressure was raised from 206.9 kPa (30 psia) to 276.2 kPa (40 psia) over a 3.21-h duration with the fill level at 45 percent full with a gas flow rate of 0.349 g/s. The pressurization rate started at ~30 kPa/h (4.35 psia/h) and dropped to 17.5 kPa/h (2.54 psia/h) after Hour 142. The ullage collapsed to 270.4 kPa (39.2 psia) over the next 1.48 h. The total mass input was 4.08 kg of oxygen. During Test 1a-2, as shown in Figure 181 and Figure 182, the pressure was raised from 184.0 kPa (26.7 psia) to 253.7 kPa (36.8 psia) over a duration of 6.67 h with the fill level at 15 percent full, with a GO₂ flow rate of 0.305 g/s. The pressurization rate was fairly stable at 10.4 kPa/h (1.5 psia/h) for most of the test. After the gas flow was cut off, the ullage collapsed to 252.1 kPa (36.6 psia). The total mass input for Test 1a-2 was 7.21 kg of oxygen.

TABLE 47.—PRESSURIZATION RATES FOR DIFFERENT PHASES OF TEST 2X

Test no.	Tank heater, W	Loop heater, W	Total, W	Flow rate, g/s	dP/dt, psia/h	Flow power, W	Total power, W	T _{start} , h	T _{end} , h
2/2a	90.27	57.5	147.8	−0.01	0	−3.4	144.4	-----	-----
2b	0	0	0	0	−0.573	0.0	0	814	818
2c	136.7	65.67	202.37	0	0.263	0.0	202.37	840	860
2e	20.27	27.37	47.64	0	−0.394	0.0	47.6	885	905
2g	130.1	44.96	175.06	0	0.164	0.0	175.1	985	1,000
2g-1	114.83	59.87	174.7	0	0.15	0.0	174.7	1,020	1,060

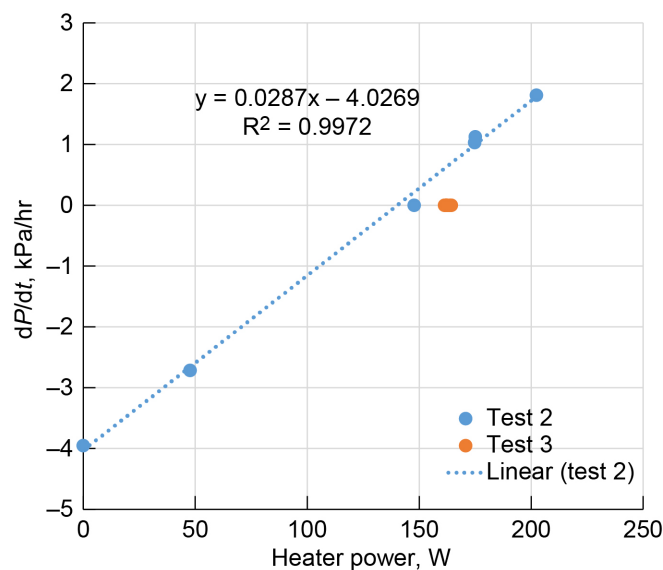


Figure 179.—Pressurization rates versus total heat input for Tests 2a to 2g compared to Test 3.

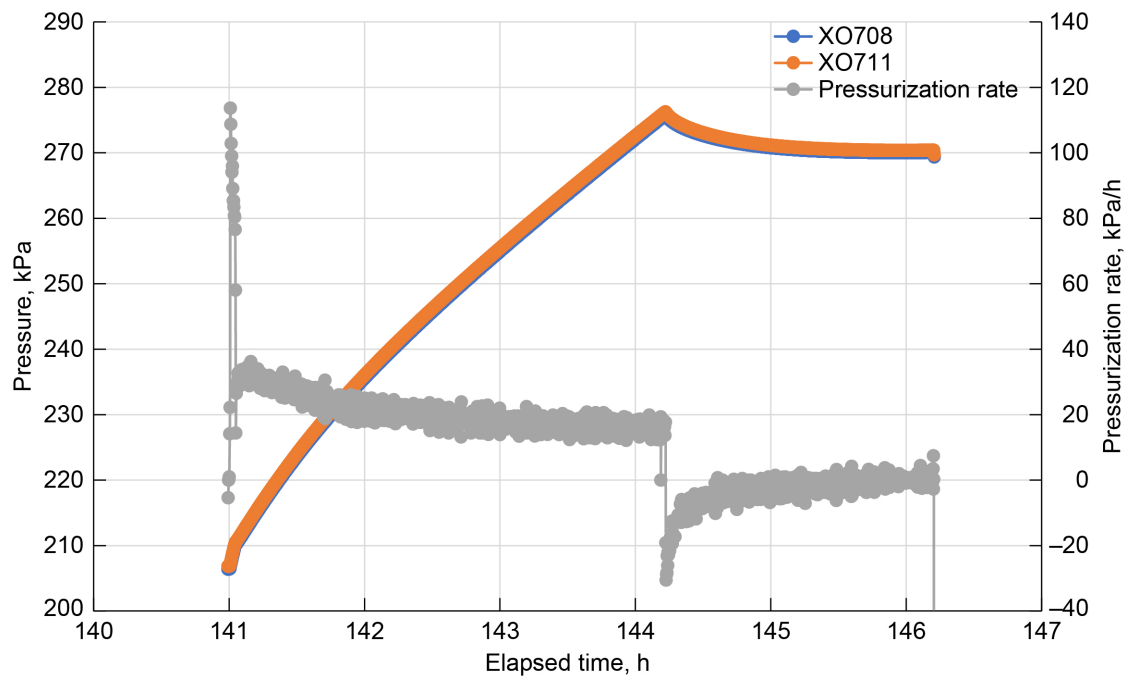


Figure 180.—Tank pressure and pressurization rate for Test 1a.

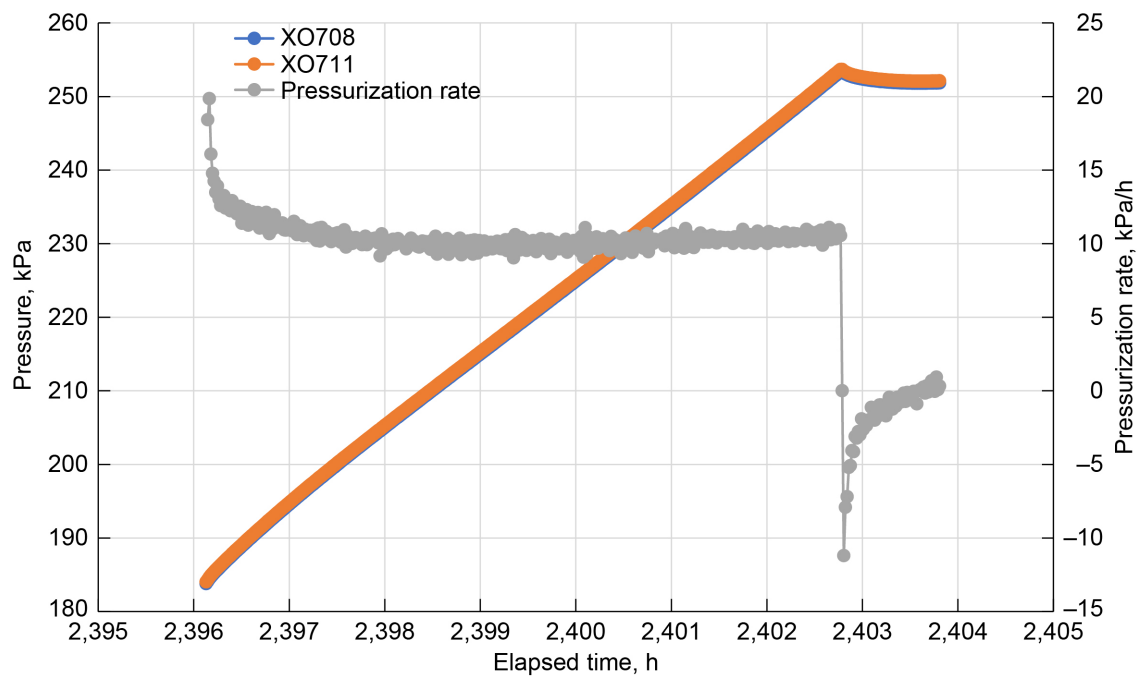


Figure 181.—Tank pressure and pressurization rate for Test 1a-2.

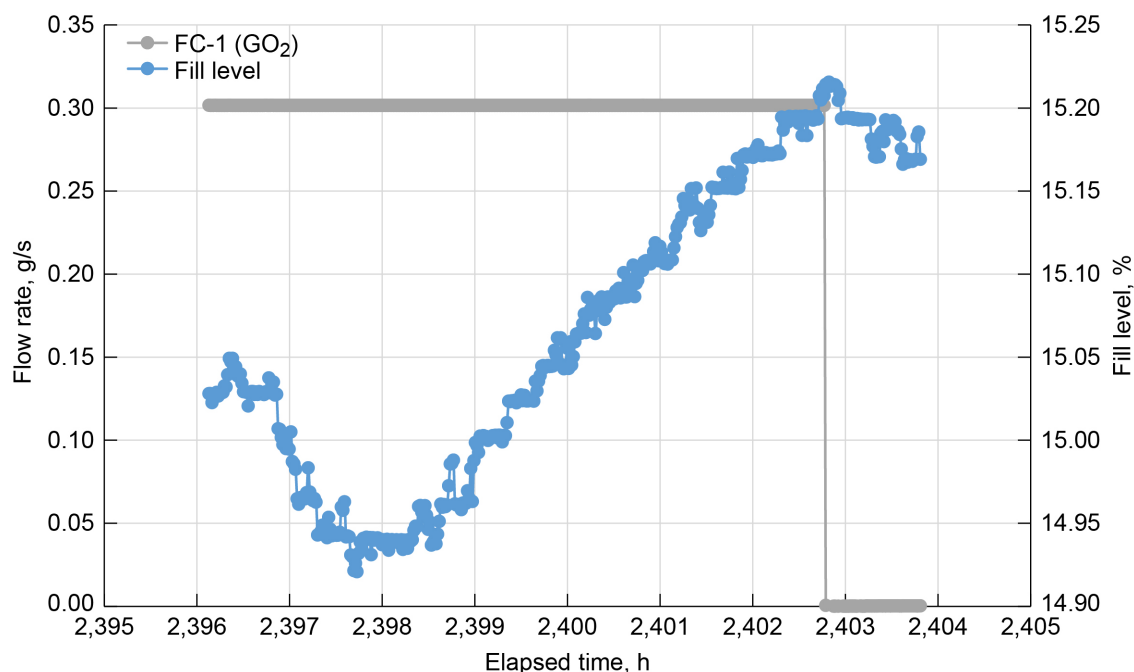


Figure 182.—GO₂ mass flow rate and tank fill level for Test 1a-2.

TABLE 48.—SUMMARY OF TEST 8 TO TEST 10

Test no.	Pressure, kPa	T _{start} , h	T _{end} , h	FC-1, slpm	FC-1, g/s	Fill-cap, %-start	PS-2, kPa	Flow, kg/h
8	206.9	1,220	1,245	11.59	0.276	7.37	432	0.99
9	275.8	1,120	1,175	12.76	0.304	7.10	449	1.09
10 prefill	137.9	1,249	1,251	10.75	0.256	5.58	417	0.92
10 postfill	137.9	1,330	1,380	10.4	0.247	0.13	501	1.02

5.8 Effect of Liquefaction Pressure

For Test 8, Test 9, and Test 10, the pressure was held constant at various pressure levels to determine the effects of the tank pressure on liquefaction rates. As mentioned in Section 4.0, the order of the tests was Test 9 followed by Test 8. Then Test 10 ended up being run twice due to a power failure in the facility. Test 9 was carried out at 206 kPa (40 psia), Test 8 was carried out at 207 kPa (30 psia), and Test 10 was carried out at 138 kPa (20 psia). The liquefaction rates are shown in Table 48 and plotted in Figure 183. The change in liquefaction rate is compared to the change in enthalpy in the fluid to liquefy it in Table 49. Several inconsistencies are worth noting between Test 10 prerefill and postrefill. The first one was the starting fill level was not the same for each test, so the percentage of energy entering the fluid versus the ullage could be slightly different, but because this test was held to an ~5 percent fill level, the variation is assumed to be minimum. The second variation was in the second run of Test 10 the pressure in the neon cooling

loop was increased and this resulted in an unexpected increase in liquefaction rate.

A comparison between the change in liquefaction rates and the change in enthalpy at the different pressures is shown in Table 49. It is clear that the liquefaction rates changed much more than would just be expected from the change in enthalpy. This must be due to the change in integrated cryocooler system efficiency across the saturation temperature range associated with the tank pressure range. The cryocooler efficiency changes with the cold temperature and as the cold temperature increases, the heat removal from the cryocooler increases (see the right side of Figure 16). Calculating the Carnot efficiencies for a 93 K and 101 K refrigeration system with 300 K heat rejection, the ideal efficiency jumps from 44.9 percent at 93 K to 50.8 percent at 101 K, a change of ~12 percent. The combined 4 percent change in enthalpy and 12 percent change in expected cryocooler efficiency increase approaches the measured 17 percent change in liquefaction rate.

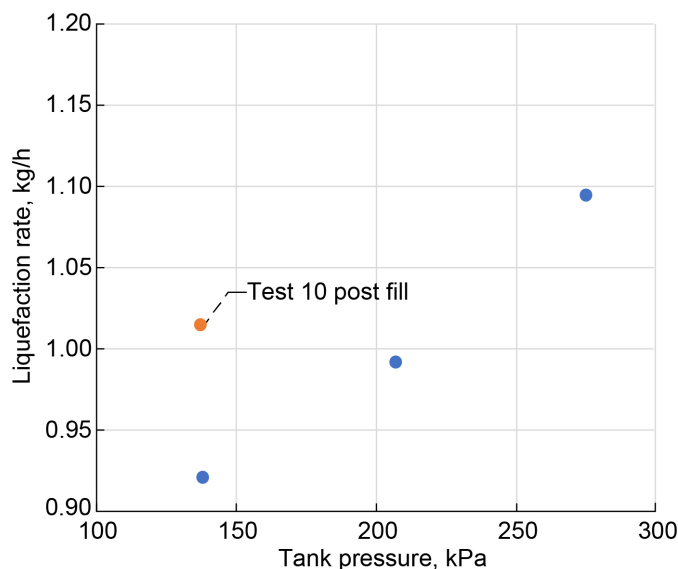


Figure 183.—Liquefaction rate versus tank pressure for Test 8 to Test 10.

TABLE 49.—LIQUEFACTION RATES FOR DIFFERENT PRESSURES COMPARED TO ENTHALPY CHANGES FOR OXYGEN FLOW AT THOSE PRESSURES

Test pressure, kPa	Demonstrated liquefaction rate, kg/h	Demonstrated relative liquefaction rate, %	Enthalpy change for inlet temperature at 300 K, J/g	Analytical liquefaction rate (constant cryocooler), %
138	0.93	93	412	98
207	0.99	100	404	100
275	1.09	110	397	102

The liquefaction heat load is equal to the Δ change in the specific enthalpy in the tank multiplied by the mass flow rate being liquefied (Eq. (26)). One assumption made by the team was that change the pressuring the neon loop would result in little to no change in the ΔT or change in the c_p of the neon loop (as shown in Eq. (27)). This was the reason for increasing the pressure in the neon loop was after the first attempt was terminated early due to power outage. Figure 183, indicates that this assumption was wrong and the liquefaction rate went up beyond statistical error when neon loop was increased 490 kPa

(71 psia) from 414 kPa (60 psia). This increase in liquefaction rate means that the enthalpy removed from the tank is tied to the pressure in the neon loop. This is an area that could be studied more in phase two of the test program.

$$\frac{Q_{GO_2} = Q_{tankheater} + Q_{neonheater} + Q_{parasiticloads}}{\dot{m}_{neon}} = \Delta h_{tank} \quad (26)$$

$$\Delta h_{tank} = (C_p)(\Delta T_{tankcooling}) = \frac{Q_{tankcooling}}{\dot{m}_{neon}} \quad (27)$$

Based on a review of the properties of neon in the two tests, the heat load comparison is shown in Table 50. The change in liquefaction rate was 11 percent compared to 15 percent change in neon density and the same as the 11 percent change in neon heat removal across the tank. Thus, the change in the liquefaction rate was as expected, the same as in the change in the heat load in the neon loop (indicating a very small change in the parasitic loads) and very similar to the change in neon density.

5.9 Maximum Liquefaction Rate

The maximum liquefaction rate testing was performed at constant pressure (pressure held constant at 275.8 kPa (40.0 psia)) as shown in Figure 184. Averaging the oxygen flow rate between Hour 2,276 and Hour 2,324 (48 total h) gave a flow rate of 0.434 g/s (1.56 kg/h), the minimum flow was 0.421 g/s and the maximum of 0.444 g/s, a variation of 2.4 percent/–3.0 percent. The variations in the flow were not seen in the cryocooler heat removal (Figure 185) and so must be driven by the neon loop diurnal temperature oscillation as seen in Figure 144. Figure 186 shows the variation in the ambient temperature on the oxygen flow coming in and the neon loop accumulator. The difference, or phase lag, between the two is due to the thermal mass of the neon loop accumulator and cryocooler itself that takes a small amount of time to respond to the input heat.

Turning the heaters off (~47 W) and using the change in energy of 387 J/g (average oxygen inlet temperature of 293.4 K), the change in liquefaction rate should have been 0.12 g/s. The actual change was 0.13 g/s (0.434 g/s from Test 40 and 0.304 g/s from Test 9). Thus, the actual change was very close to the as-tested change.

TABLE 50.—NEON LOOP COMPARISON FOR FLOWS DURING TEST 10, PREFILL AND POSTFILL

Test 10	PS-22, kPa	Neon flow, g/s	SD-2, K	SD-3, K	Neon cp in, J/g/K	Neon cp out, J/g/K	Q neon, W	Neon density, kg/m ³	Liquefaction rate, kg/h
Prefill	417	7.70	94.38	70.4	1.05	1.06	195.9	14.55	0.92
Postfill	501	8.74	97.1	73.7	1.05	1.06	217	16.71	1.02
Change							11%	15%	11%

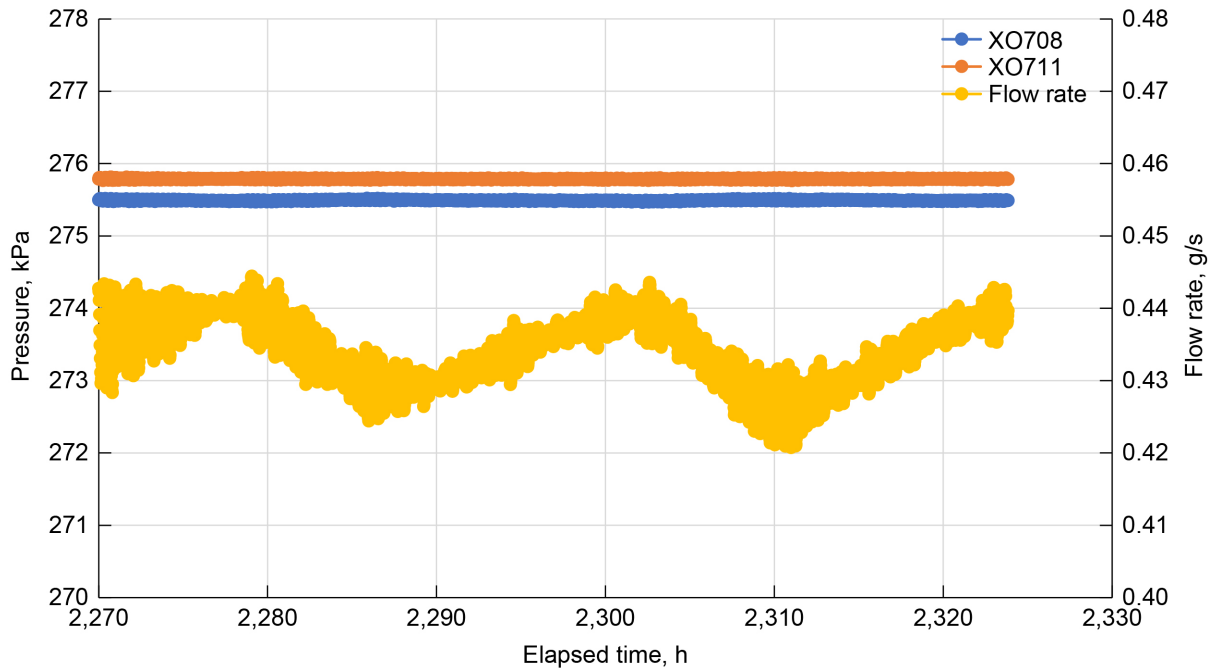


Figure 184.—Tank pressure and incoming mass flow rate during maximum liquefaction testing.

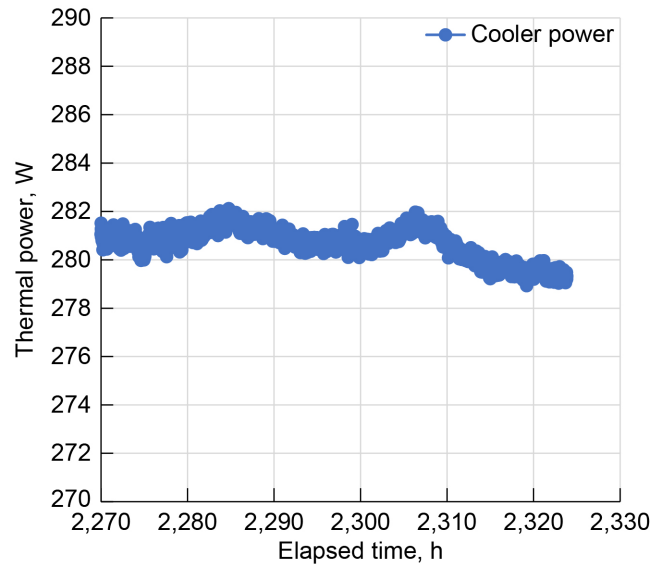


Figure 185.—Cryocooler heat removal during Test 40.

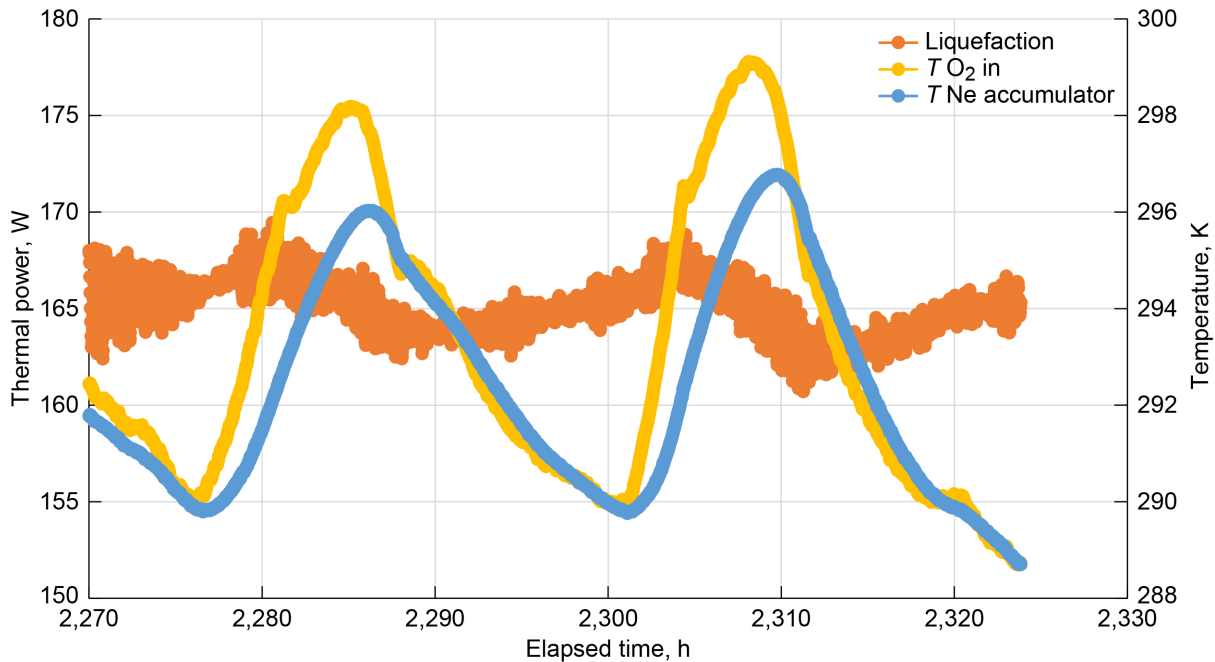


Figure 186.—Liquefaction power required and ambient temperatures during Test 40.

5.10 Transient System Operations Based Off of Analysis of Previous Testing

The transient system operations gave the team an opportunity to use the data from previous testing periods to predict repeatable testing sequences. The requirement for the repeatability of the transient testing was to get within 10 percent of pressure (and associated temperatures), which really is to monitor the pressurization rates. The transient data could then be used by computer models to demonstrate their ability to predict performance in a nonsteady-state manner.

Test 27, the variation of the GO_2 mass flow rates were calculated based on the results from Tests 11 to 13. The pressurization rate equation derived in Figure 165 was used along with durations of 7 h during the day and 17 h during the night to determine the mass flow rates for the cyclical inputs. The target rate of 1.6 kg/h was used as it gave an expected pressurization rate of 6.5 kPa/h (0.94 psia/h), which over 7 h would yield an expected tank pressure increase of 45.5 kPa (6.6 psia). Solving the inverse problem over 17 h gives a depressurization rate of -2.7 kPa/h (-0.39 psia/h), which accordingly should require a flow rate of 0.86 kg/h. The input flow rates as a function of time (1.6 kg/h for 7 h and 0.86 kg/h for 17 h) for two cycles are shown in Figure 187. The actual pressurization rates and depressurization rates are plotted as a function of time in Figure 188 and are shown averaged over half-cycles in Table 51. Although the pressurization and depressurization rates from the input flow rates were both slightly higher than

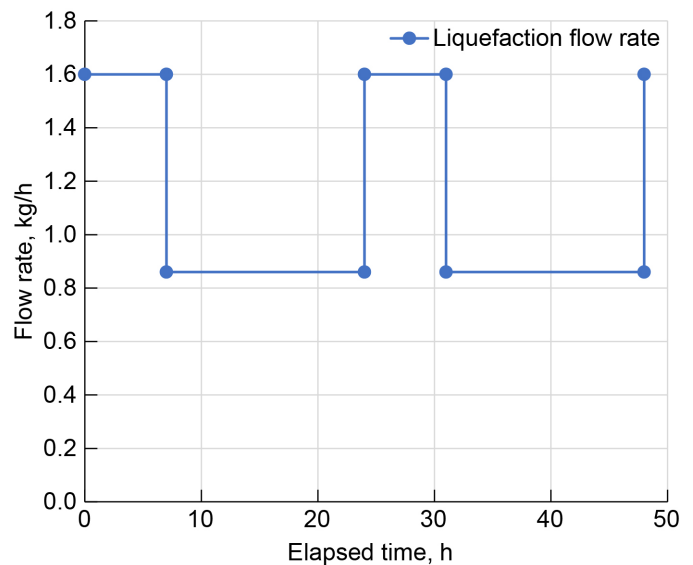


Figure 187.—Flow variation inputs for transient case on Test 27.

predicted, they were repeatable within 6% of the average over the three cycles. The average pressurization rate over the full half-cycle was 7.2 kPa/h (1.04 psia/h) and the average depressurization rate was -3.0 kPa/h (-0.44 psia/h). The pressurization rates do change over the duration of a single cycle, with a slight curvature in the pressure traces over time, but that change is small relative to the magnitude of the actual rate. It is interesting that the pressurization rates decrease slightly as the fill level increases but the depressurization rates do not show trends

with fill level. The cause for the trend in pressurization rate decreasing with fill level is not fully known but could be driven by the slight increase in thermal mass of the liquid that would be absorbing heat and releasing heat as the saturation conditions changed.

Test 29 and Test 29-2 used the neon loop heater and tank heater (Test 2g in Section 4.1, Figure 47, showed that both heaters provided the same effect of parasitic loading to the tank) to simulate the cryocooler delivering less power to the tank via trimming its input power. From Test 2c (between Hours 840 and 860), the maximum pressurization rate was 1.8 kPa/h (0.26 psi/h) at 202.4 W. Testing at those powers over 7 h would cause a pressurization of 12.5 kPa (1.82 psi). Using the data in Figure 179, the heater power during the depressurization was calculated by determining the value that would cause the average heater power to be 144 W over a 24-h cycle. This was solved to be ~123 W. The parasitic thermal heat load associated with incoming GO₂ at 1.1 kg/h was calculated to be ~133 W with the gas at 300 K and 101 kPa (14.65 psia) using nitrogen properties. This was then offset with 25 W seen in differences between Tests 2 and 3 in Figure 179. It is unfortunate that the parasitic thermal heat load due to the liquefaction flow was originally calculated using nitrogen and at 101 kPa (14.65 psia),

it should have been 120 W using oxygen properties at 207 kPa (30 psia). Nevertheless, the total power from heaters were set to 94 W (64 W on the tank and 30 W on the neon loop) for 7 h and 15 W (only on the neon loop) for 17 h. The heater input and pressure results are shown in Figure 189. The instantaneous pressurization rates are shown in Figure 190, there it can be seen that the pressurization rates were very repeatable, but the total pressure values drifted down over the 3 days. The 15 W for 17 h allowed for too high of a depressurization rate compared to the 94 W for 7 h. Figure 191 shows the pressurization rate as a function of heater power and Figure 192 shows pressurization rate as a function of pressure. Similar to previous testing, the pressurization rate at decreasing pressures is a function of the pressure for the two different flow rates, but the pressurization rate at increasing pressure is fairly constant. The average pressurization rate is 5.8 kPa/h (0.84 psia/h) and the average depressurization rate is -3.8 kPa/h (-0.55 psia/h). Table 52 shows the variation in average pressurization and depressurization rate of each cycle. Figure 193 shows an interesting phenomenon where the tank pressure kept increasing for ~0.1 h after the heaters were turned down. This was observed in all three high heat load heater power changes with the third cycle lasting longer (~0.2 h) due to the higher residual heater power.

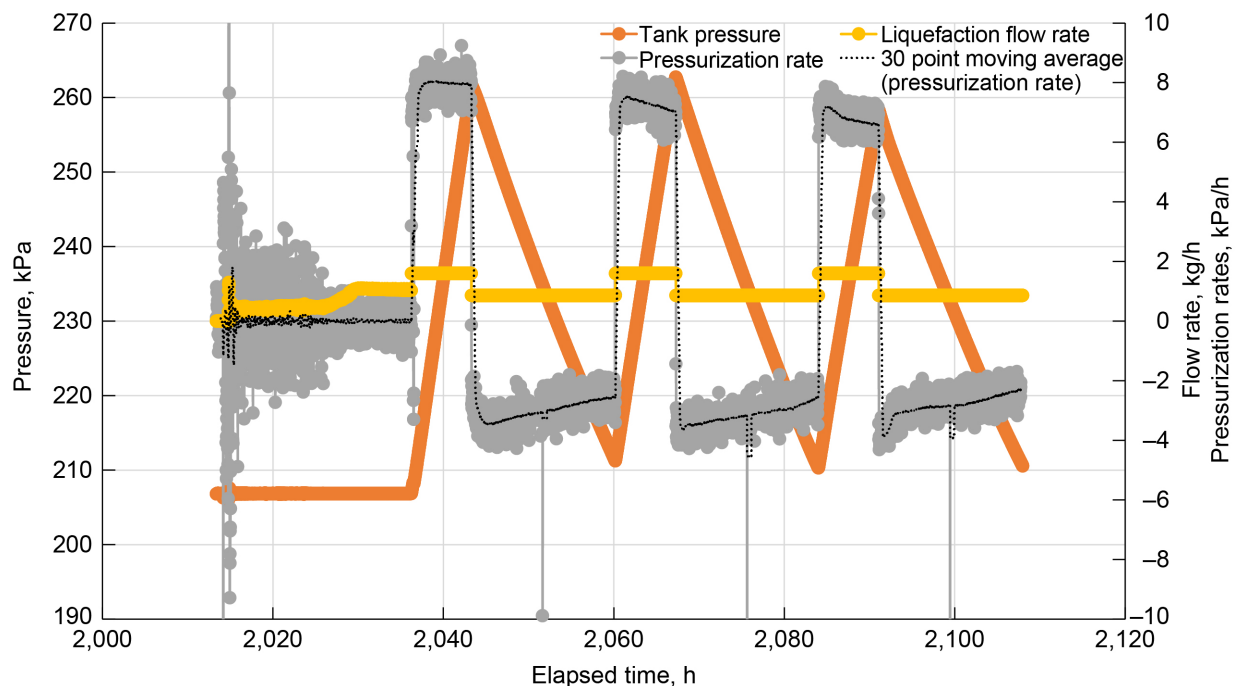


Figure 188.—Pressure and pressurization rate data from Test 27.

TABLE 51.—PRESSURIZATION RATE DATA FROM TEST 27

	Max. pressure, kPa	Min. pressure, kPa	Pressurization rate, kPa/h	Depressurization rate, kPa/h	High flow rate, kg/h	Low flow rate, kg/h	Change from average, pressurization, %	Change from average, depressurization, %
Cycle 1	261.3	211.0	7.7	−3.0	1.59	0.86	6.0	0.1
Cycle 2	262.4	210.1	7.2	−3.1	1.59	0.86	0.1	5.1
Cycle 3	258.1	210.4	6.8	−2.8	1.59	0.86	−6.1	−5.2
Simulated	261.8	192.9	6.5	−2.7	1.6	0.86	−10.2	−9.3

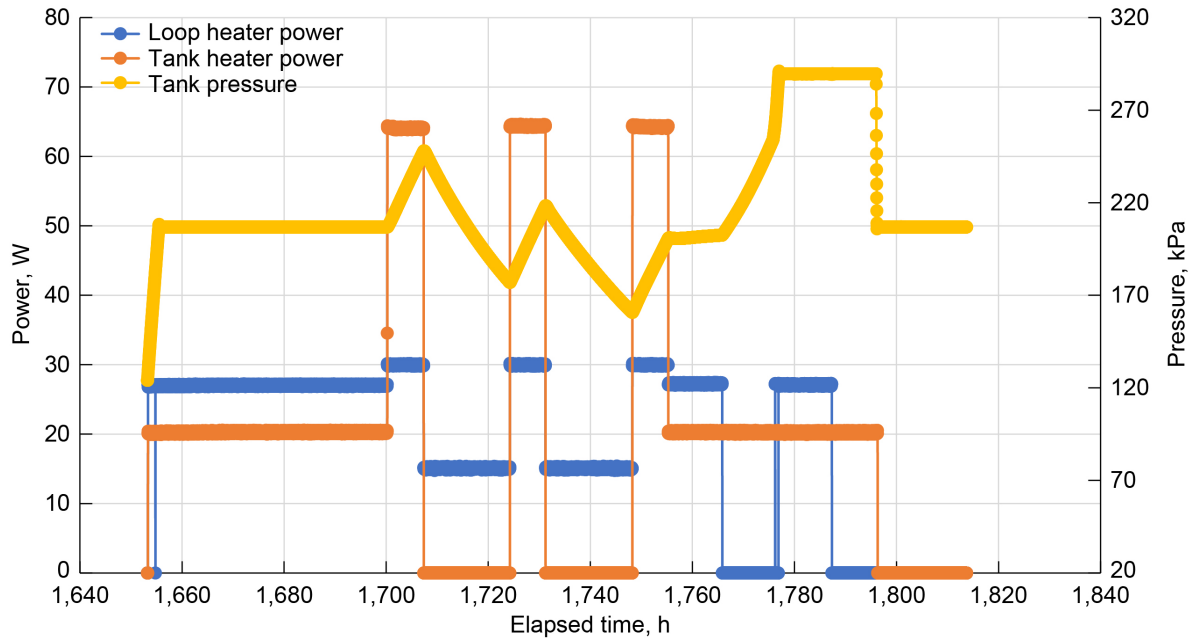


Figure 189.—Heater input and pressure response during Test 29.

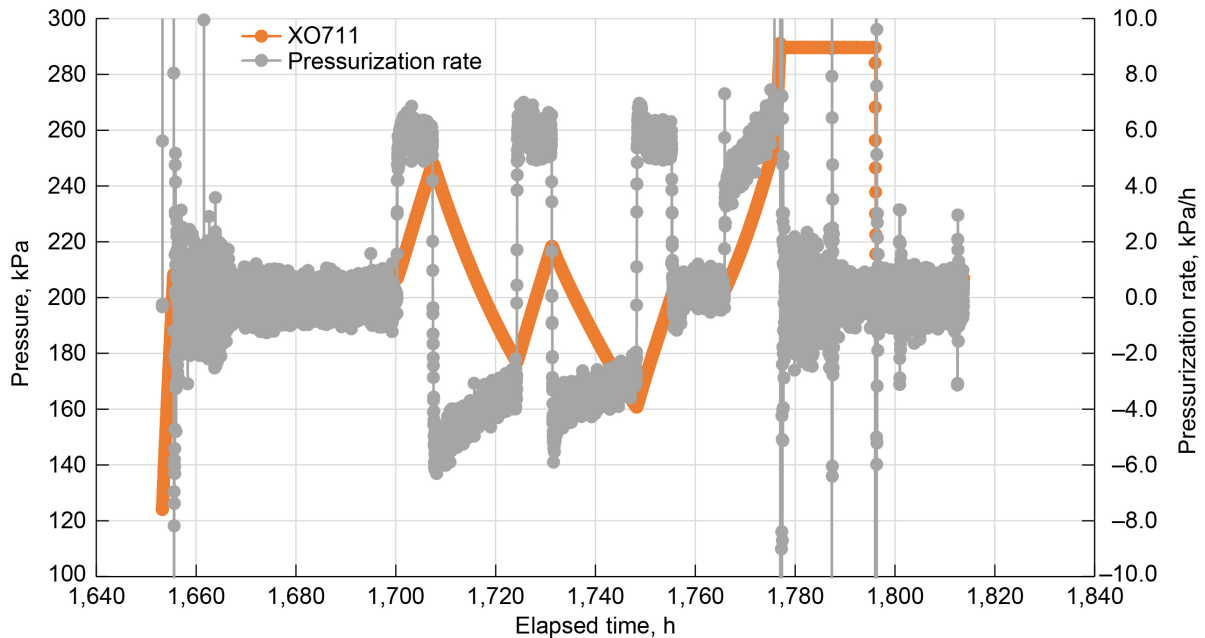


Figure 190.—Tank pressure response and pressurization rate during Test 29.

TABLE 52.—PRESSURIZATION RATE DATA FROM TEST 29

	Max. pressure, kPa	Min. pressure, kPa	Pressurization rate, kPa/h	Depressurization rate, kPa/h	High heater power, W	Low heater power, W	Change from average, pressurization, %	Change from average, depressurization, %
Cycle 1	247.7	176.8	5.8	-4.2	93.4	15.09	0.07	-10.8
Cycle 2	218.1	160.5	5.9	-3.4	93.3	15.08	-2.0	10.8
Cycle 3	200.5	n/a	5.7	n/a	93.8	n/a	2.0	n/a

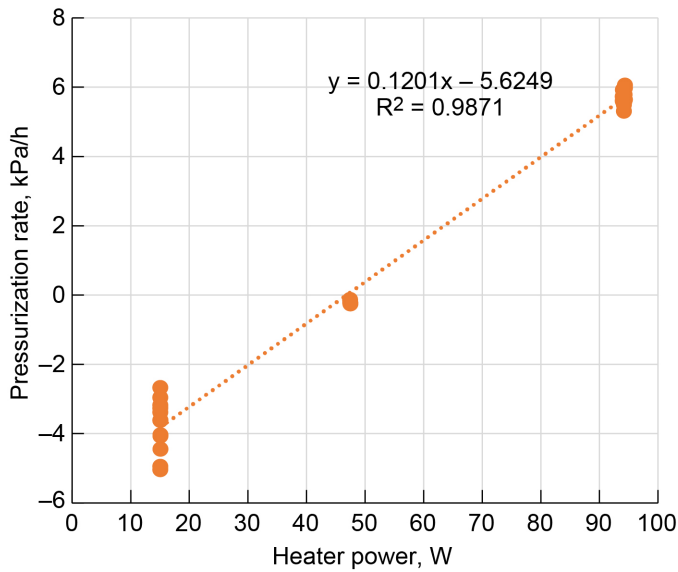


Figure 191.—Tank pressurization rate as function of heater power during Test 29.

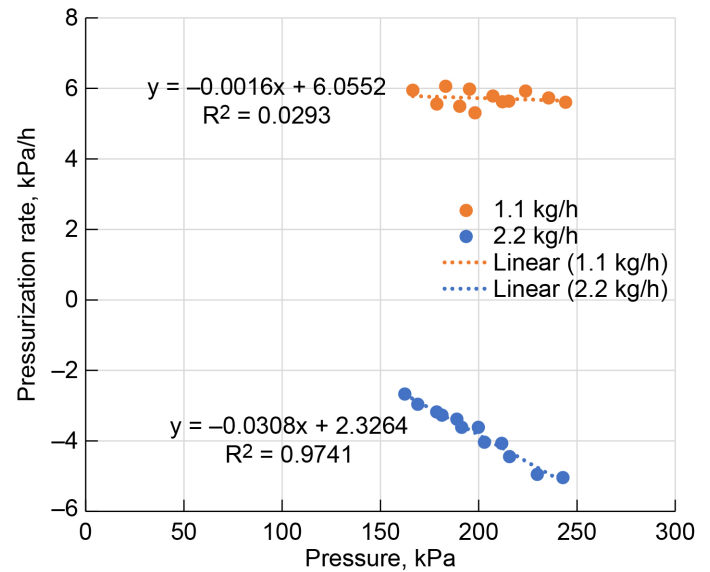


Figure 192.—Tank pressurization rate during Test 29.

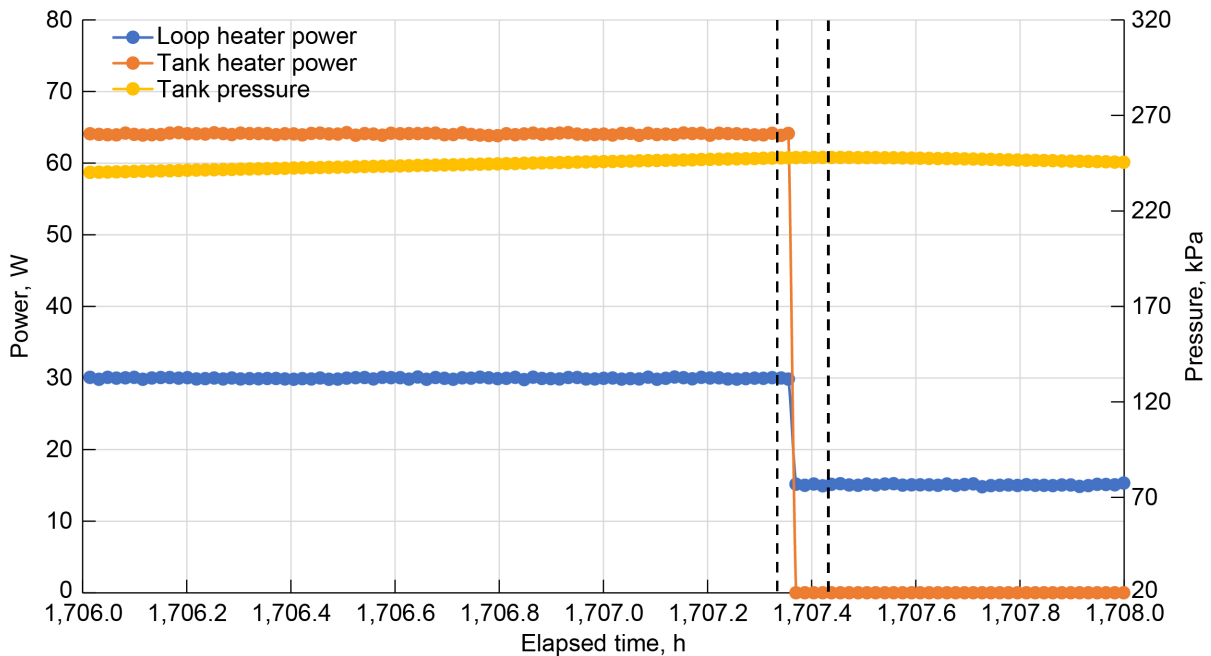


Figure 193.—Tank pressurization rate coasting up for ~0.1 h after heaters turned down during Test 29 as indicated by dashed lines, first for heater changer and second for tank pressure direction change.

For a repeat of Test 29, Test 29-2 used the pressurization curve generated in Figure 191 to set the target pressurization and depressurization rate to -5.6 kPa/h (-0.81 psia/h). This required the heater settings during pressurization to be set to 93.5 W and during depressurization they were 0.2 W . The tank pressure and pressurization rate are shown in Figure 194. The average values for each cycle are shown in Table 53. The average pressurization rate was 6.0 kPa/h (-0.87 psia/h) and the average depressurization rate was -5.2 kPa/h (-0.75 psia/h). The pressurization rates varied by a maximum of 12.6 percent from the average and the depressurization rates varied by a maximum of 6.8 percent from the average, but 3 of the cycles are within 10 percent of the average. Although Cycle 2 from a

total pressure perspective appears to be the outlier, Cycle 3 is the largest outlier from the average for both pressurization rate and depressurization rate. Much as was seen in Test 29, on the top of the pressure rises, the pressure continued to rise for $\sim 0.05 \text{ h}$ after the heaters were turned off.

For Test 31, the cold wall temperatures were varied between 290 K for 7.5 h and 225 K for 16.5 h as shown in Figure 195. The range was calculated based on a desire to get relatively large environmental temperature swings and still average out at 250 K . The time averaged temperature was calculated per Equation (28).

$$T_{avg} = \sqrt[3]{\frac{T_h^3 t_h + T_c^3 t_c}{24}} \quad (28)$$

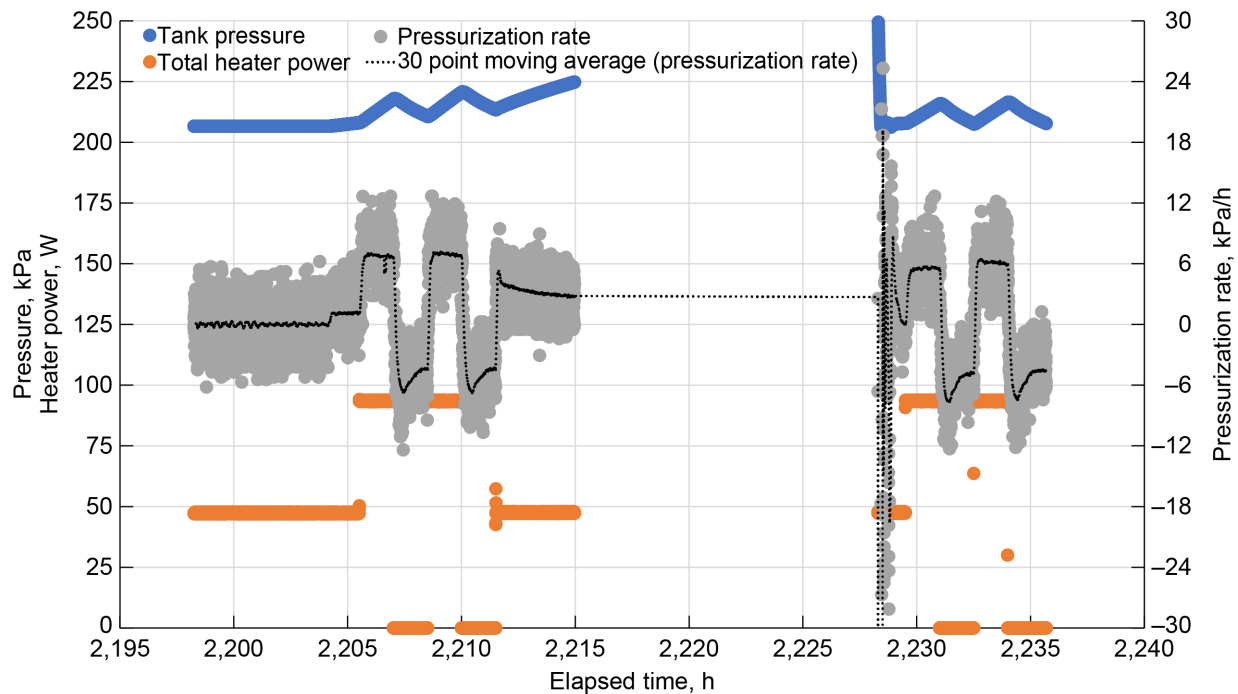


Figure 194.—Tank pressure response and pressurization rate during Test 29-2.

TABLE 53.—PRESSURIZATION RATE DATA FROM TEST 29-2

	Max. pressure, kPa	Min. pressure, kPa	Pressurization rate, kPa/h	Depressurization rate, kPa/h	High heater power, W	Low heater power, W	Change from average, pressurization, %	Change from average, depressurization, %
Cycle 1	217.9	210.6	6.4	-5.1	89.8	0.2	5.6	-3.4
Cycle 2	220.7	215.6	6.6	-5.0	90.7	0.1	9.3	-4.5
Cycle 3	215.8	207.5	5.3	-5.6	91.4	0.5	-12.6	6.8
Cycle 4	216.5	207.7	5.9	-5.3	90.9	0.0	-2.3	1.2

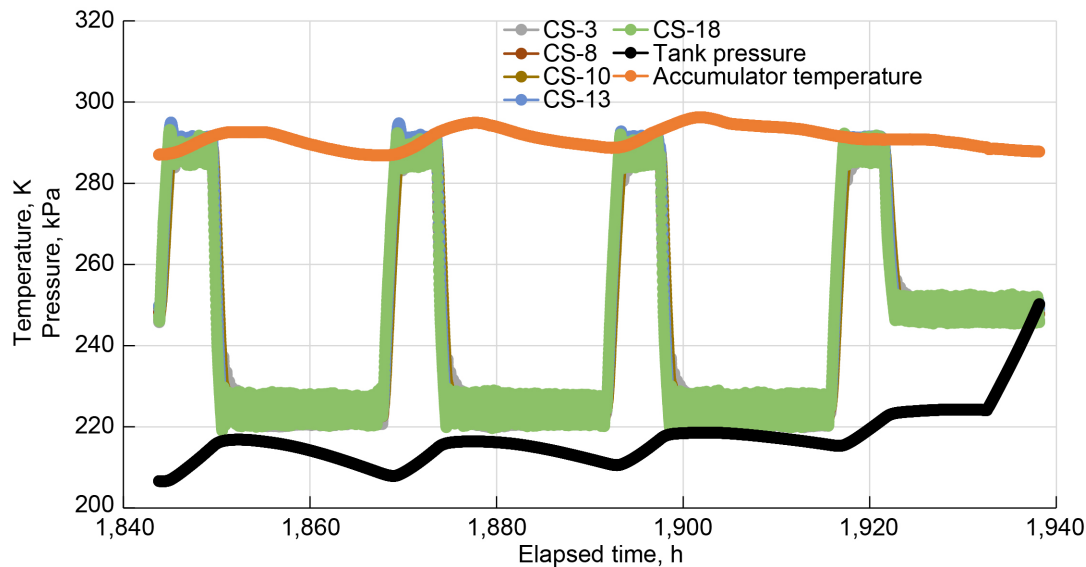


Figure 195.—Cold wall temperature and tank pressure as function of time for Test 31. Spike in tank pressure at end of test is due to power outage.

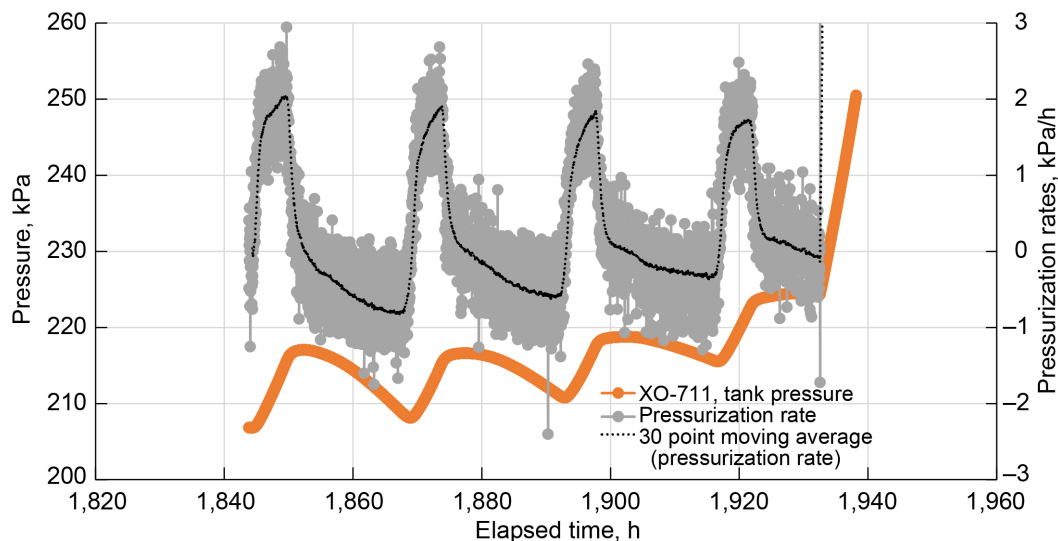


Figure 196.—Tank pressurization rate as function of time for Test 31. Spike in tank pressure at end of test is due to power outage.

As can be seen in Figure 196, the pressurization response is much more complicated for this transient than the other transient responses. The average pressure rate rise during the four pressurization phases was 1.67 kPa/h (0.24 psia/h) and the average depressurization rate during the three depressurization phases was -0.49 kPa/h (-0.07 psia/h). The divergence, especially on the depressurization rates was quite large as seen in Table 54. The data is broken down in more detail in Table 55. Similar, but much more pronounced, there was a delay in response in the pressure to the temperature changes. This often took several hours and is captured in the middle rows of each cycle in Table 56. On the pressurization portion of the cycles,

the first cycle was ~11 percent higher than the average, whereas the other three were slightly less than average and within a few percent of each other. It does appear that the ambient temperature of the accumulator may have played a role in the depressurization rates being less consistent (accumulator temperature shown in Figure 195). Figure 197 shows the linear nature of the pressurization rate in response to different temperature testing between Tests 31 and 11. There is significant spread in the test results due to the curvature in pressurization rates during depressurization on both tests. However, there is a general linear response over the three temperatures that were tested (the third being during Test 11) as shown in Figure 197.

TABLE 54.—PRESSURIZATION RATE DATA FROM TEST 31

	Max. pressure, kPa	Min. pressure, kPa	Pressurization rate, kPa/h	Depressurization rate, kPa/h	Average cold wall temperature, warm, K	Average cold wall temperature, cold, K	Change from average, pressurization, %	Change from average, depressurization, %
Cycle 1	216.1	207.8	1.86	−0.65	286.3	225.4	11	33
Cycle 2	215.8	210.5	1.63	−0.53	282.7	227.9	−2.8	8.3
Cycle 3	217.9	215.3	1.59	−0.28	284.6	226.5	−4.9	42
Cycle 4	223.0	n/a	1.61	n/a	286.9	n/a	−3.6	n/a

TABLE 55.—DETAILED PRESSURIZATION RATE DATA FROM TEST 31

Cycle no.	T _{start} , h	T _{stop} , h	Cold wall, K	P _{min} , kPa	P _{max} , kPa	P _{rate} , kPa/h
Cycle 1	1,846.6	1,850.2	286.29	209.4	216.1	1.86
	1,852.06	1,852.66	225.38	216.80	216.82	−0.02
	1,856.66	1,868.96	226.59	207.87	215.81	−0.65
Cycle 2	1,870.96	1,874.52	282.68	210.04	215.83	1.63
	1,874.94	1,877.1	225.93	216.05	216.37	−0.15
	1,877.1	1,878.1	225.01	216.35	216.37	−0.02
	1,886.1	1,892.89	227.91	210.53	214.10	−0.53
Cycle 3	1,894.89	1,898.29	284.62	212.51	217.92	1.59
	1,899.77	1,902.2	225.30	218.38	218.53	−0.06
	1,908.2	1,916.74	226.53	215.28	217.70	−0.28
Cycle 4	1,918.74	1,922.24	286.90	217.38	223.03	1.61
	1,925.7	1,929.8	249.57	223.95	224.24	−0.07
	1,929.8	1,932.57	249.54	224.09	224.24	−0.05

TABLE 56.—PRESSURIZATION RATE DATA FROM TEST 33. NOTE THAT
AVERAGES ARE ONLY OF FIRST THREE TESTS

	Max. pressure, kPa	Min. pressure, kPa	Pressurization rate, kPa/h	Depressurization rate, kPa/h	High flow rate, kg/h	Low flow rate, kg/h	Change from average, pressurization, %	Change from average, depressurization, %
Cycle 1	236.9	206.8	7.62	−12.1	1.59	0.86	−3.1	−3.5
Cycle 2	238.9	207.2	7.63	−12.2	1.59	0.85	−3.0	−2.7
Cycle 3	240.3	206.2	8.34	−13.3	1.59	0.85	6.0	6.2
Cycle 4	205.2	202.9	0.68	−0.71	1.59	0.85	n/a	n/a

Test 33 used the same test approach and GO_2 mass flow rates as Test 27, however the fill level was changed to start the test at ~90 percent full and the durations of each period were shortened. For each cycle, the high flow of 1.6 kg/h was input for 4 h, followed by 2.5 h of depressurization at 0.86 kg/h. The first three cycles run used ullage insertion of the gas and the fourth cycle used the dip tube to insert the gas. The flow rate, pressure response, and pressurization rate are shown in Figure 198 with a zoomed-in view in Figure 199. The mass flow rate values were calculated both during full pressurization and depressurization cycles and over hour-long time periods that were during solely a pressurization cycle or a depressurization cycle. The averaged data over the whole pressurization and depressurization portions of the cycles are shown in Table 56. The average pressurization rate for the three cycles with the gas inserted into the ullage was 7.86 kPa/h (1.14 psia/h) and the depressurization rate average was -12.5 kPa/h (-1.81 psia/h). These varied by less than 6.5 percent across the three cycles. However, the pressurization rates are not constant through a cycle like what was seen in the lower fill level tests. To compare the pressurization rates more closely through the three cycles, hourly averages were taken during the pressurization periods (as seen in Figure 200) and half-hourly averages were taken during depressurization (as seen in Figure 201). These breakouts show that most of the variation in response was seen in the first time period (Cycle 3 was >10 percent different than the other two) where the initial pressurization and depressurization spikes occurred in the test pressurization rates. As shown in Figure 202, there was significant stratification in the liquid during these three cycles as

both LL19 (ullage) and LL18 (just submerged) warm up by more than 1 K in a manner that is similar to the tank pressure.

The fourth cycle, using the dip tube showed a much lower pressurization rate (as demonstrated in Figure 198 and Table 56). Looking at the fluid temperatures throughout the oxygen (see Figure 202), with the dip tube, the entire bulk liquid was warmed up and cooled down slowly. This indicates that the bubbling through the dip tube creates excellent mixing within the tank and is similar to what was seen in Brassboard testing (Ref. 9).

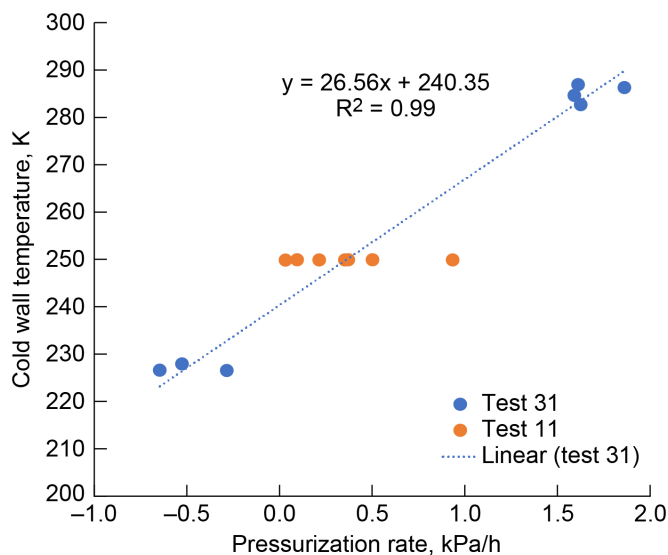


Figure 197.—Pressurization rate as function of environmental temperature (as represented by CS-10) from Tests 31 and 11 for mass flow rate of 1.1 kg/h.

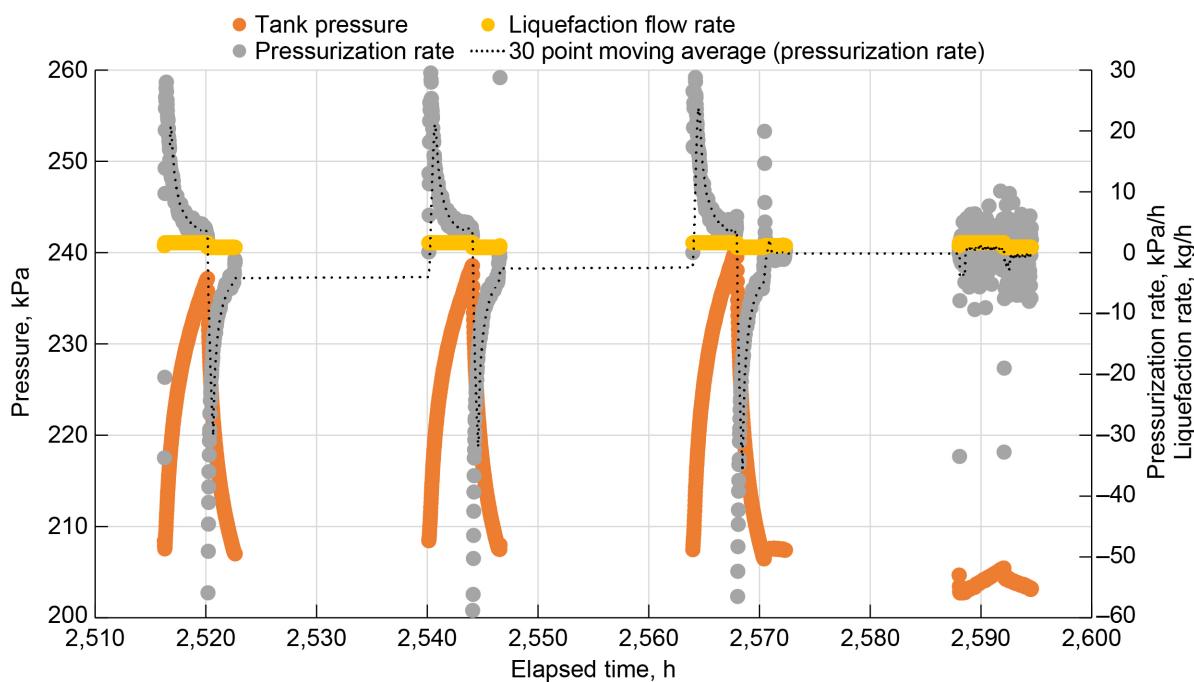


Figure 198.—Pressure and pressurization rate for Test 33.

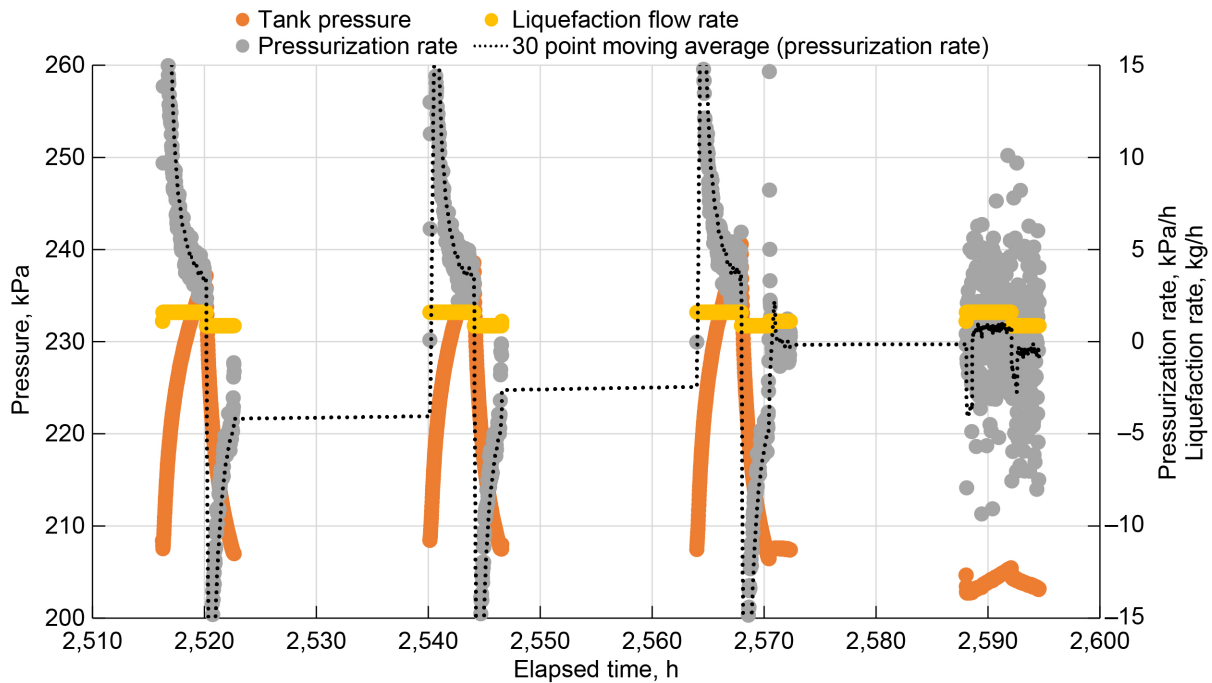


Figure 199.—Zoomed-in pressurization rate for Test 33.

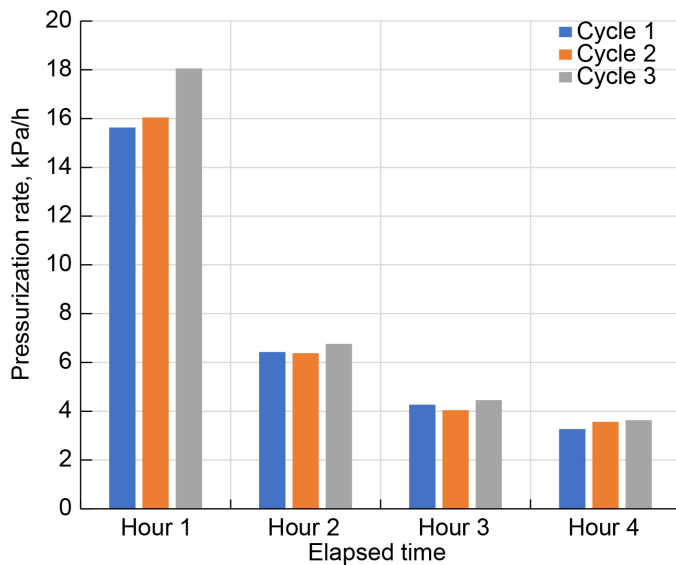


Figure 200.—Pressurization rate for Test 33 broken up by hour after test initiation for first three cycles.

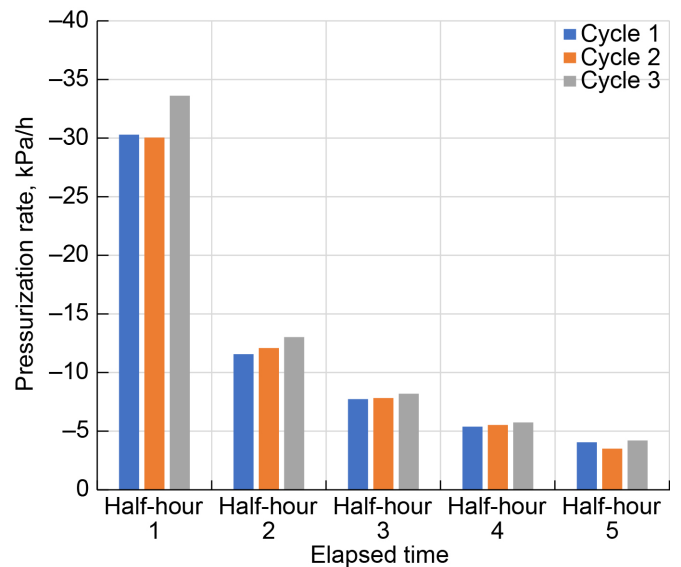


Figure 201.—Depressurization rates for Test 33 broken up by half-hour after test initiation for first three cycles.

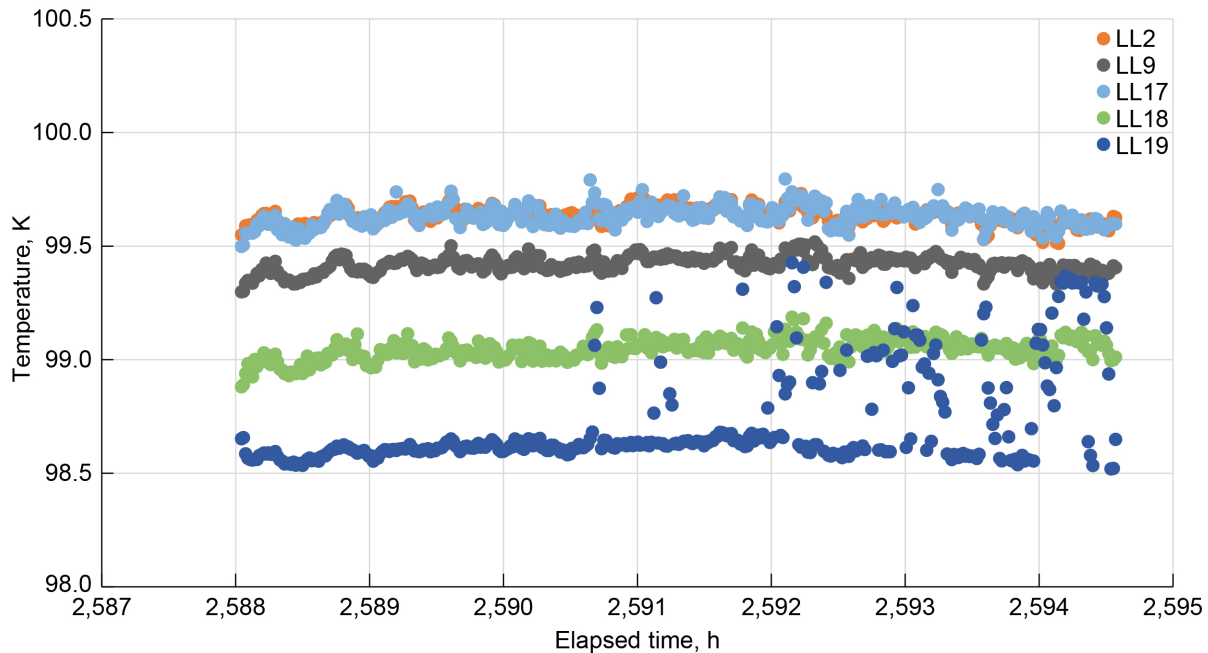


Figure 202.—Oxygen temperatures during fourth cycle of Test 33.

5.11 FOSS Results

Data obtained from FOSS (Fiber Optics Sensing System) are considered as a noncritical data that supplements existing and co-located silicon diode temperature data. In this section, results for selected testing are discussed.

Figure 203 shows the temperature measurement shift during Test 1's boil-off testing, where the FOSS data (circle) fits nicely with respect to the silicon diode's data (triangle) from the eighteenth hour to the thirtieth hour, where the ullage is slowly cooling to the LO₂ temperatures. Figure 204 and Figure 205 show the time-history of Test 1 liquefaction via selective sensors from silicon diode and FOSS data, respectively. The data shown in FOSS is in agreement with the silicon diode data, in which the ullage temperatures settled at a set temperature stratification above the 50 percent fill level, while below the 50 percent fill level, the temperatures converged to a LO₂ bulk temperature of approximately 97 K. The fiber data is immune to the effect of EMI-caused interference, whereas turning on the fluorescent lights during the daytime causes a false indication of a measured temperature increase that can be seen on the silicon diode data.

With the deluge of data from all the liquefaction test, a LabVIEW® program is created to visualize the temperature change with respect to silicon diode and FOSS sensor data. Figure 206 shows the LabVIEW® front end visualizing Test 1, where at different elapsed times (Hour 50 and Hour 110, respectively), the high spatial density nature of the 138 FOSS sensors data fills out the data that are missing with the 19 silicon diodes, which serves as a precursor for the remaining tests throughout the series.

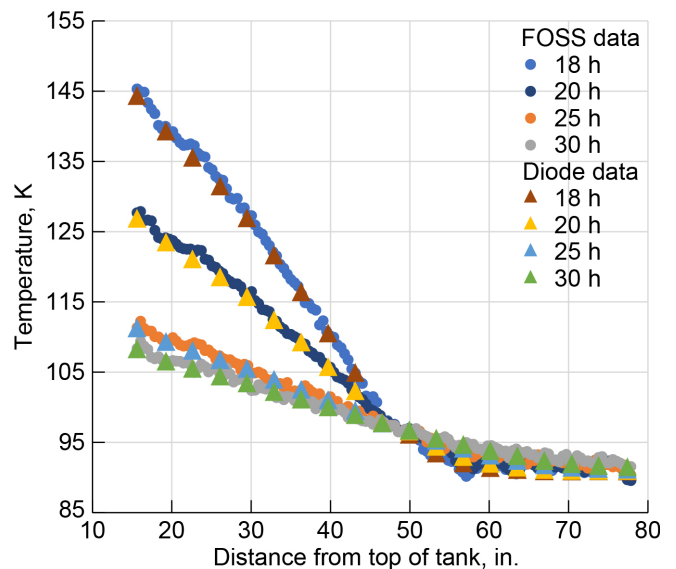


Figure 203.—Test 1 shows FOSS sensor array temperature corresponds to silicon diode temperature at specific time.

Test 4 is a very interesting experiment where there is ullage stratified in the tank when the cryofan turns off. Figure 207 is the elapsed time for both silicon diode and FOSS, where the stratified ullage is clearly seen. Also from Figure 207, temperature response from FOSS sensors heat up similarly to the silicon diodes. FOSS sensors are immune to the effects of EMI that are exhibited on the silicon diodes. Figure 208 showcases the higher spatial density ability to map out the stratified temperature.

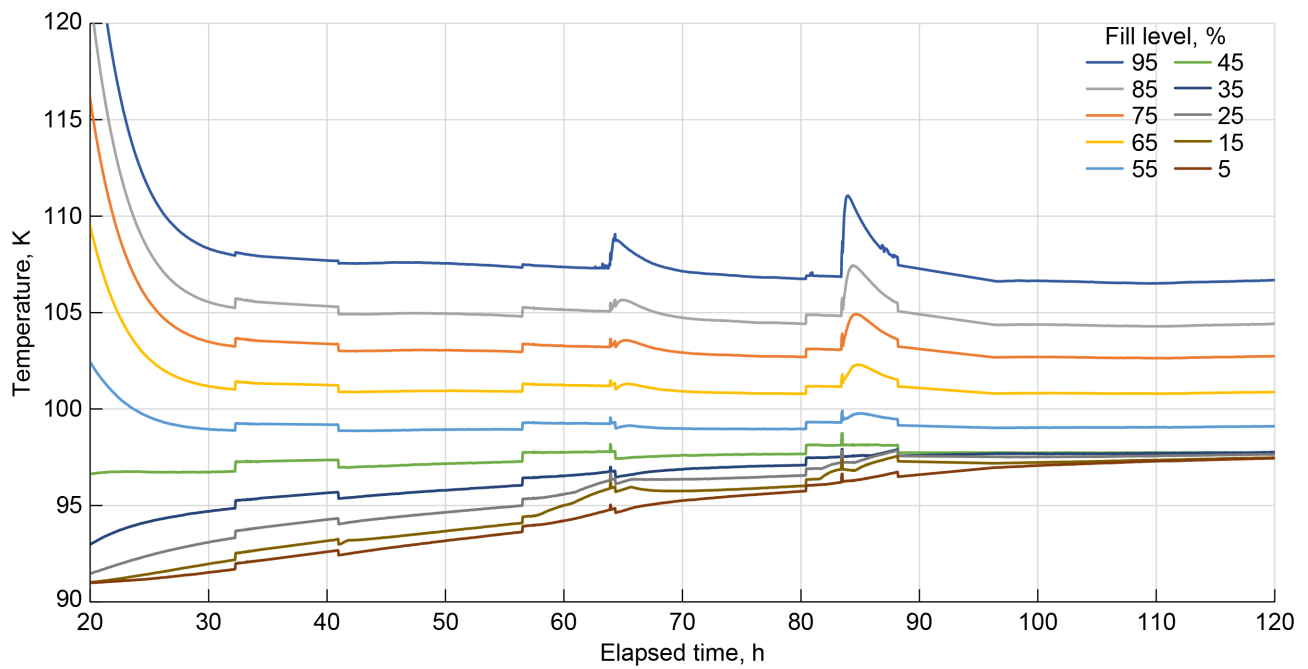


Figure 204.—Time-history of Test 1 liquefaction from selective silicon diodes.

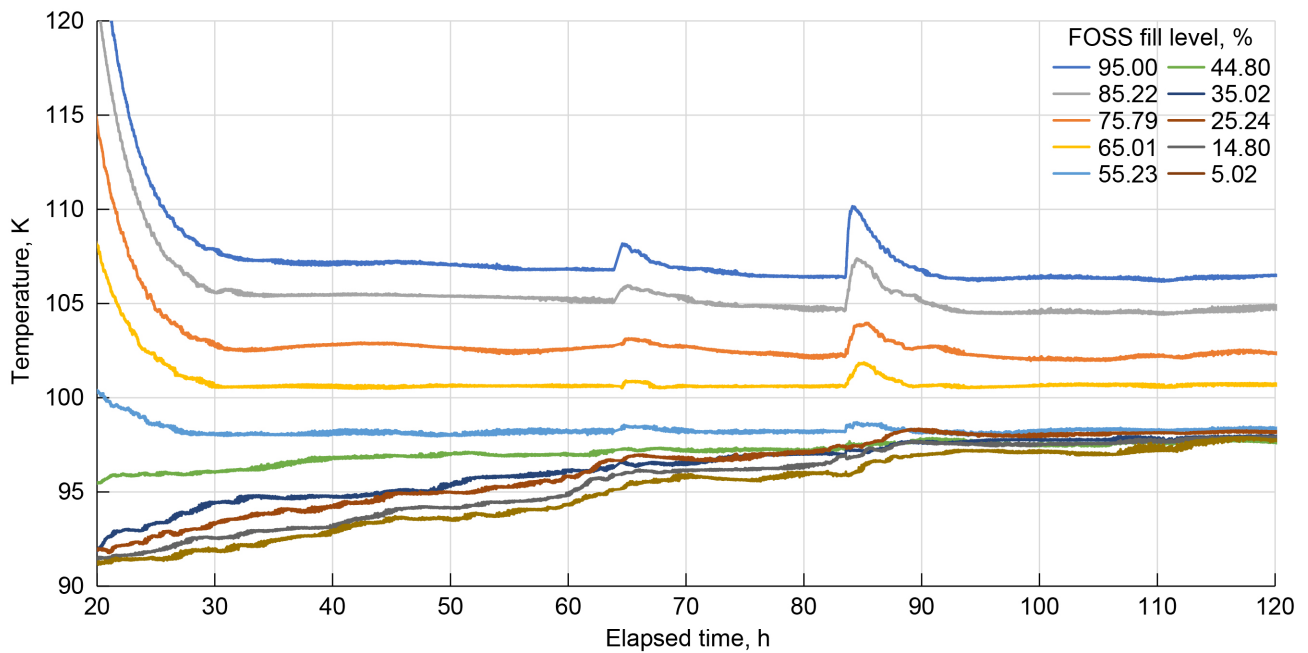


Figure 205.—Time-history of Test 1 liquefaction via selective FOSS grating corresponding to adjacent silicon diode, for comparison.

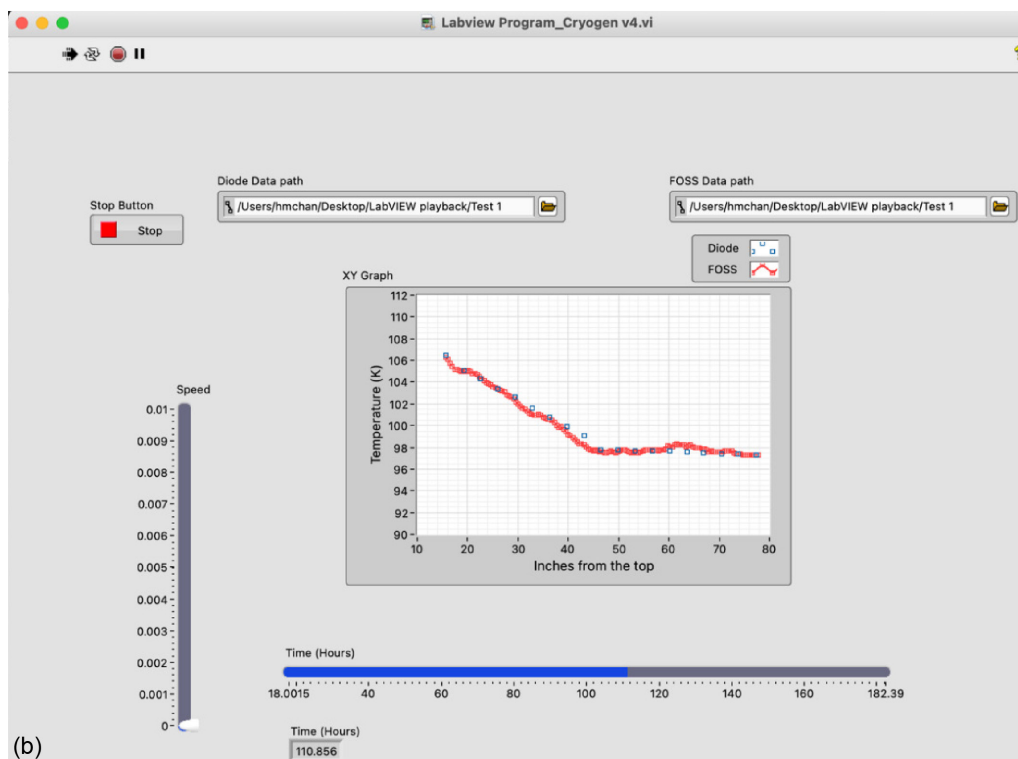
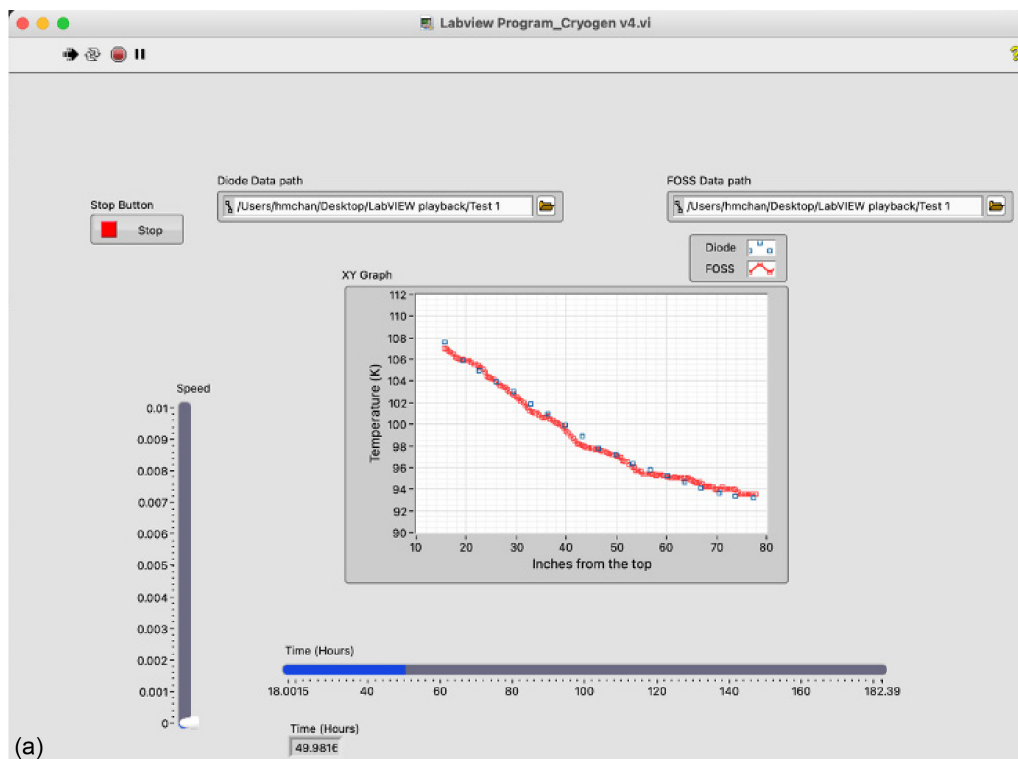


Figure 206.—LabVIEW® data visualization software to distinguish between 138 FOSS sensors (red dots) versus 19 silicon diodes (blue dots) for Hour 50 (top) and Hour 110 (bottom).

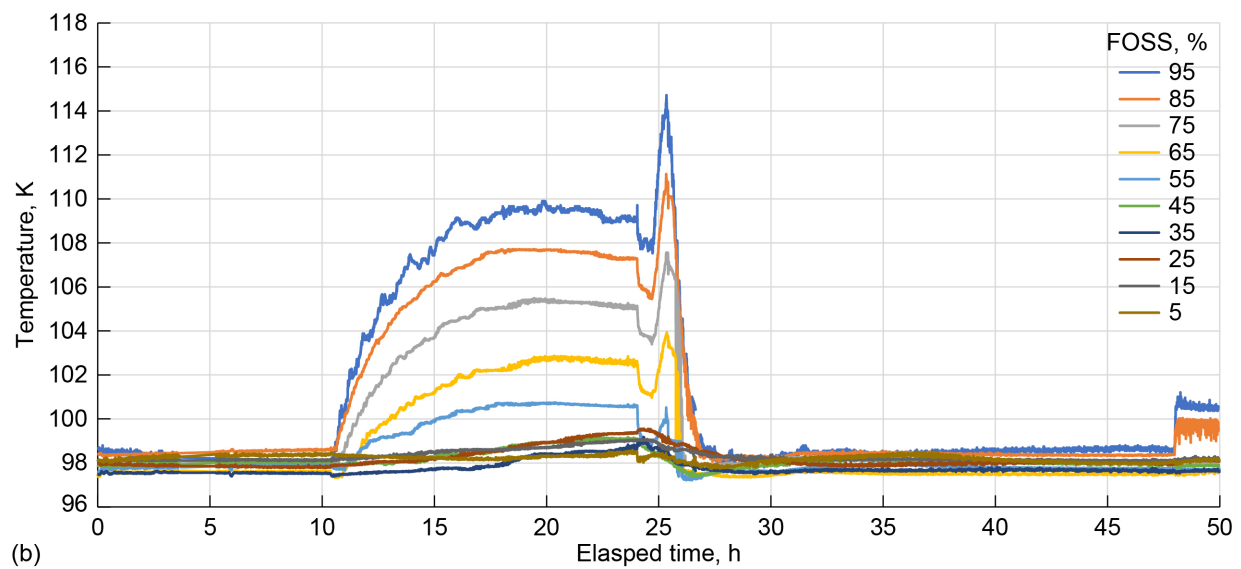
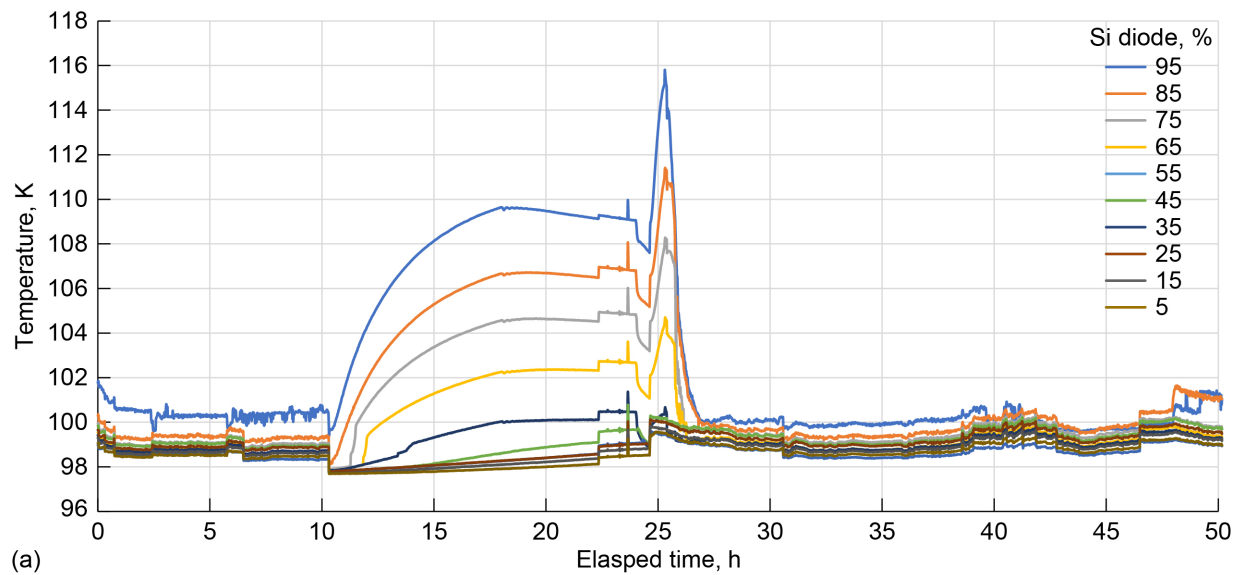


Figure 207.—Test 4 progression of silicon diode (top) versus co-locating FOSS sensors (bottom) under same elapsed time.

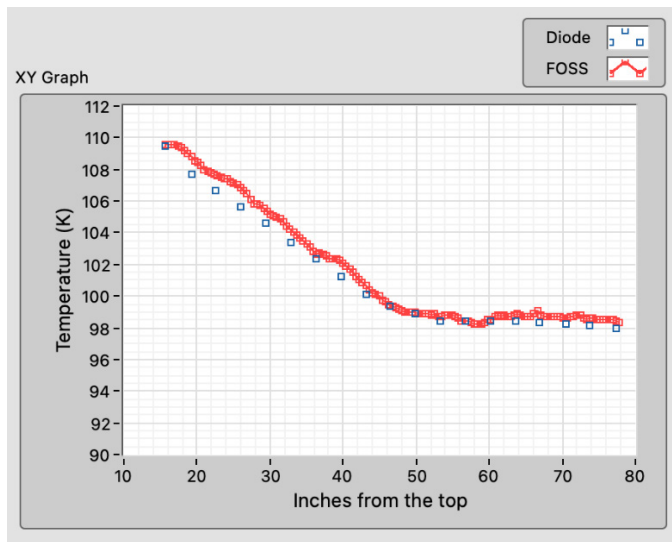
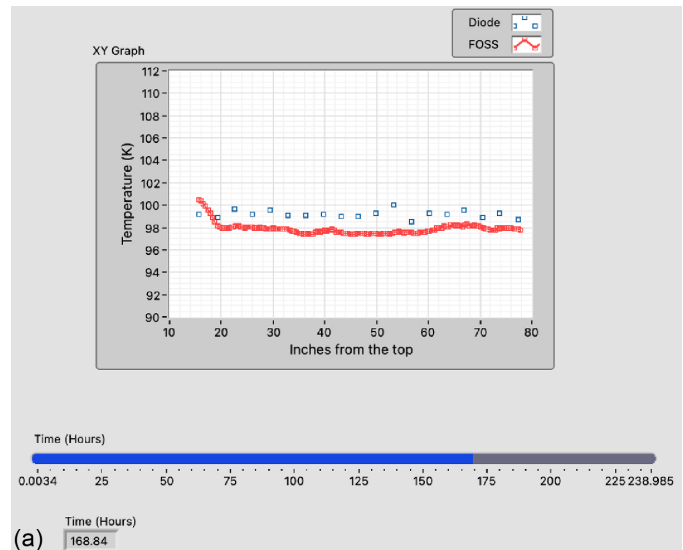


Figure 208.—Test 4 data representation for silicon diode and FOSS at Hour 20.

One of the questions to be answered in this test was the accuracy of the FOSS sensors with respect to silicon diode data, without the effect of EMI caused by either the cryofan or fluorescent lights. Due to the various EMI caused by the lights in the first five tests and the cryofan when the cryocooler is operating, Test 6 provides the best extended period of comparison between the two temperature sensors. On Test 6, for constant liquefaction from 90 percent fill level, the first 100 h is the conditioning phase to 207 kPa (30 psia). Figure 209 shows the temperature status between representative silicon diodes and the co-locating FOSS sensors. The FOSS sensor is again tracking well with respect to silicon diode level.

First, the hourly silicon diode data (LL01 to LL19) are collected from Hour 0 to Hour 70. Then, the co-locating fiber sensor data is compared, and the temperature difference (ΔT) from the silicon diode is recorded, assuming silicon diode is the truth source. Figure 210 is the representation of data that is on the top of the tank (LL19, FOSS-G20) and the bottom of the tank (LL01, FOSS-G158). The plots show that the sensors are within 0.75 K of the silicon diode temperature throughout the test.

Figure 211 is the representation of average (blue bar) and standard derivation (error bar) of temperature difference between FOSS and silicon diode, for the first 70 h. The best-case scenario is with LL08 and FOSS-G70 pair, where it is located at 40 in. from top of tank, with ± 0.2 K of uncertainty. The worst-case scenario is with LL02 and FOSS-G27 pair, where high temperature swing during tank compression leads



(a)

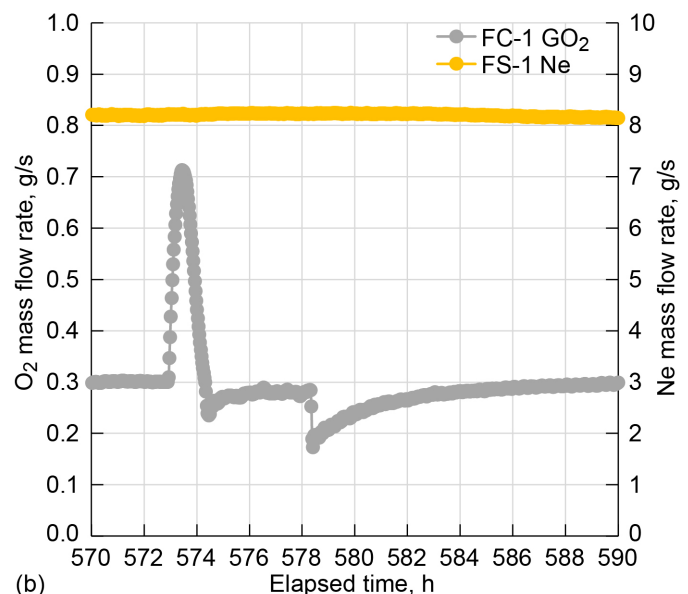


Figure 209.—Test 6 for silicon diode and FOSS data for selected location from first 100 h, that is conditioning the tank to 30 psia with 90 percent LO₂ fill.

to large temperature difference of 1.0 ± 0.3 K of uncertainty. Overall average is that temperature variation for this test show FOSS and silicon diode difference is 0.36 ± 0.2 K of uncertainty.

At the 100-plus hour of elapsed time, where the liquefaction stage of Test 6 occurs, the temperature recorded at the fiber data is consistent lower than the silicon diode data, due to the constant liquefaction and the turning on of the cryofan, as seen at Figure 212.

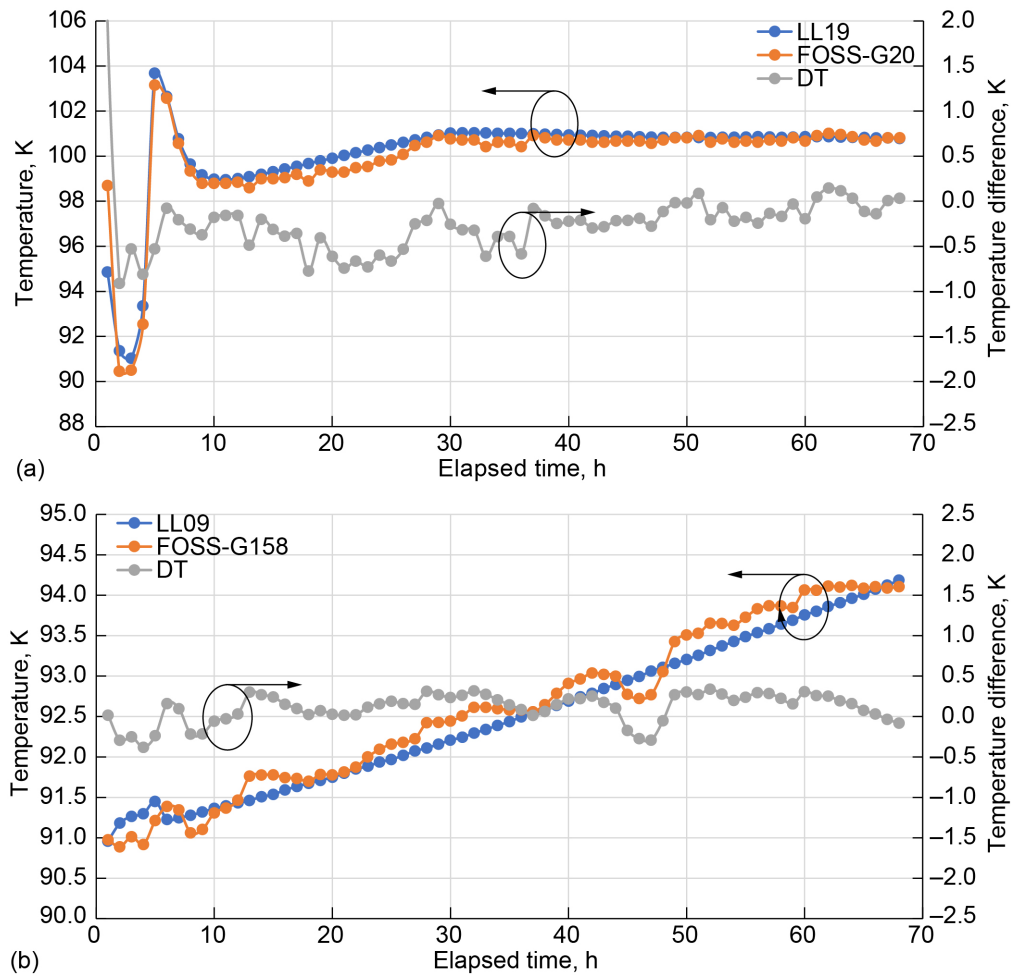


Figure 210.—Temperature measured from representative sensors (top, LL19; bottom, LL01) from start of Test 6 during conditioning phases (left horizontal axis), and temperature difference between diode and fiber (right horizontal axis).

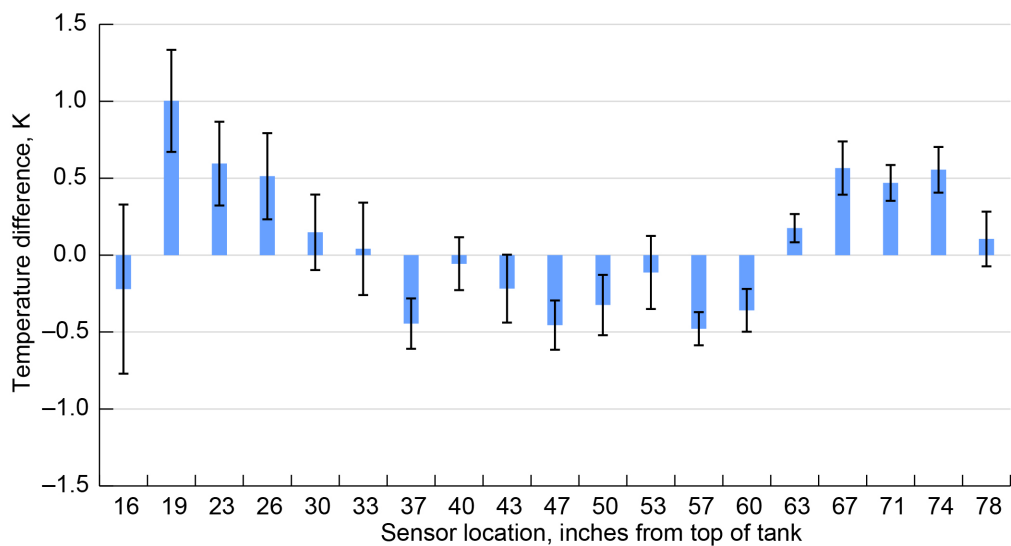


Figure 211.—Average measured temperature difference from Test 6 for each representative sensor pair, and error bar shows standard derivation.

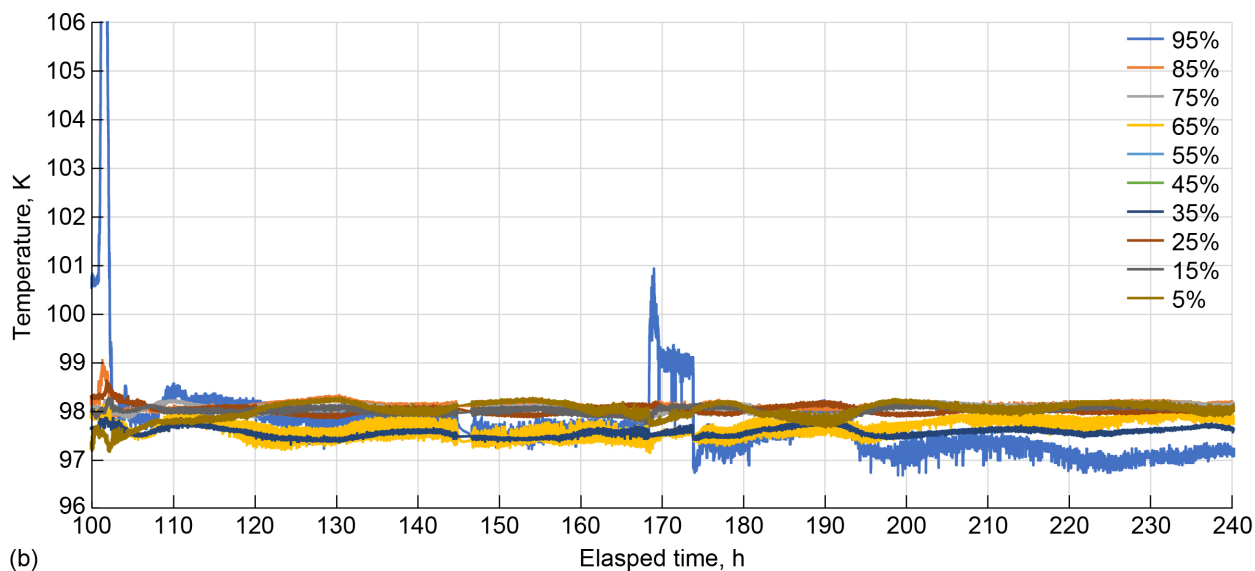
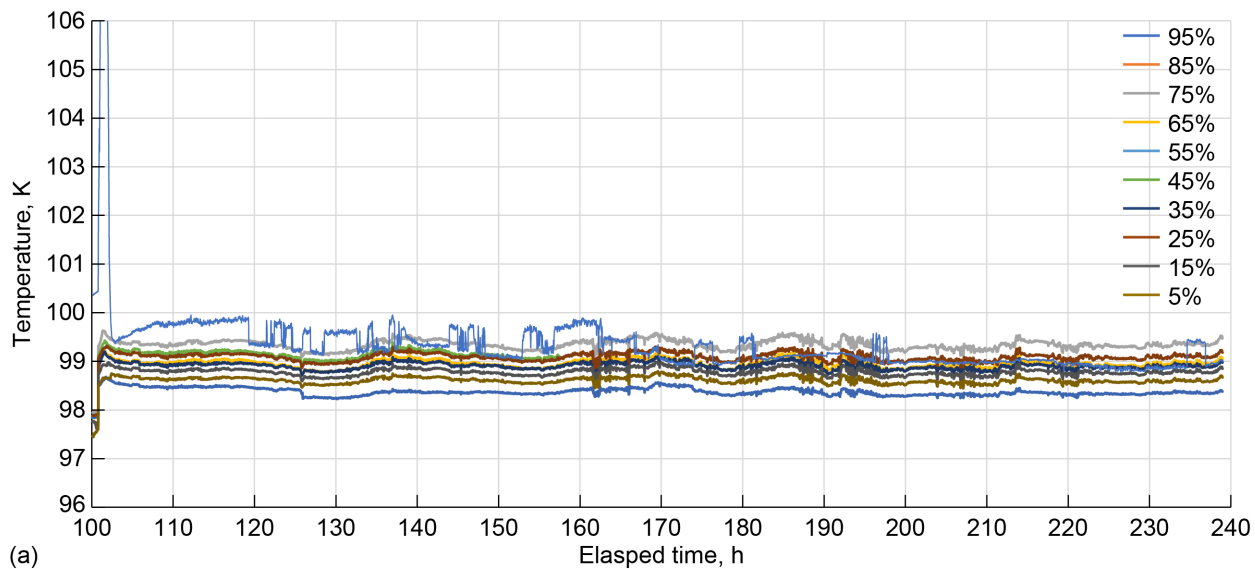


Figure 212.—Test 6 for both silicon diode and FOSS during liquefaction stage. Temperatures from (a) silicon diodes were consistently higher (99 K) than (b) fiber sensors (98 K) due to effect of EMI from cryofan.

In Figure 213, the fiber response to ullage temperature stratification in the top 5 percent of the tank caused by increase GO_2 flow rate at Hour 168 of Test 6's elapsed time (or Hour 572 of total elapsed time). Due to the FOSS sensor density and count, it is able to observe the stratification, but the lack of silicon diodes in that part of the tank prevent them from doing so. Once the GO_2 flow returns to a normal level, the ullage temperature returns to its unstratified conditions.

FOSS was utilized on the transient GO_2 feed testing, specifically in this report Test 27 with 5 percent liquefaction and

Test 33 with 95 percent liquefaction will be concentrated. Figure 214 is the temperature distribution from selective silicon diode and fiber sensors, respectively for Test 27, under 5 percent tank fill. Both sensors experience the same amount of heating due to increase of pressure from increase of GO_2 flow, with the temperature increase around 3 K for all three separate instants of liquefaction. Fiber sensors are more sensitive to temperature changes because there is no heat load, unlike silicon diode; therefore, there is more variation to the fiber temperature swing versus silicon diode temperature.

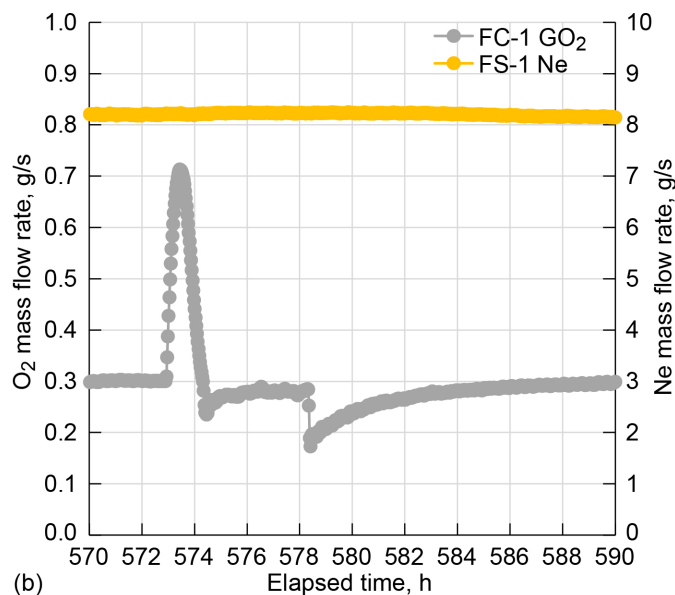
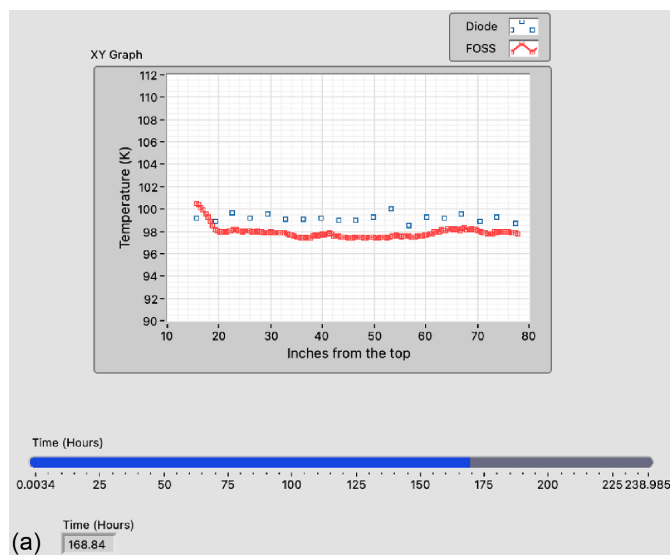


Figure 213.—On Hour 573 (Hour 169 of Test 6), GO_2 flow rate increase triggers temperature stratification above the 95% fill level, where FOSS sensors can capture event.

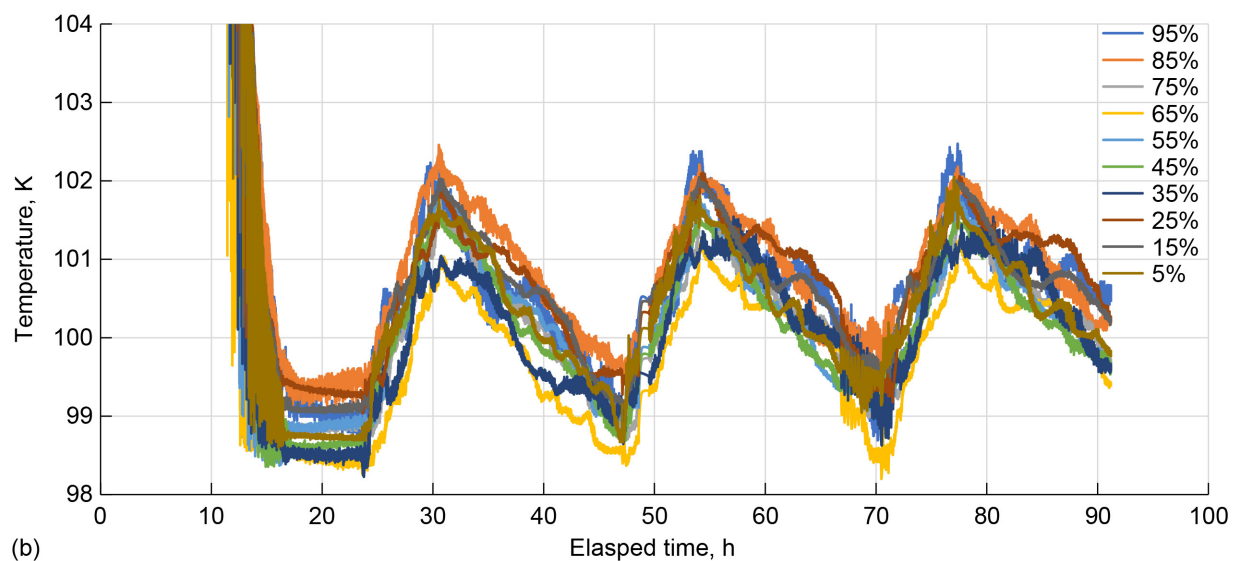
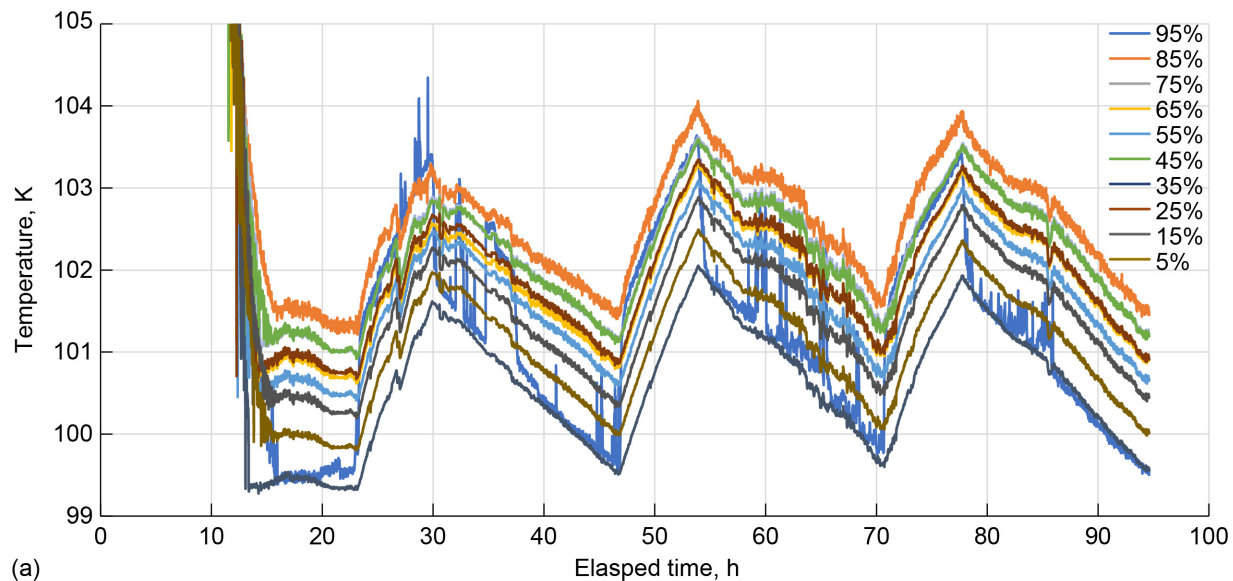


Figure 214.—Test 27 tank temperature under during liquefaction to 5 percent tank fill level, for representative (a) silicon diode and (b) FOSS sensors, respectively.

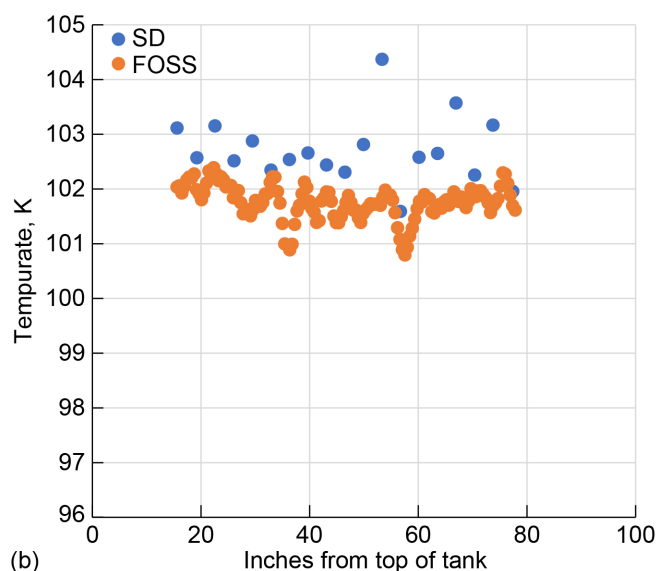
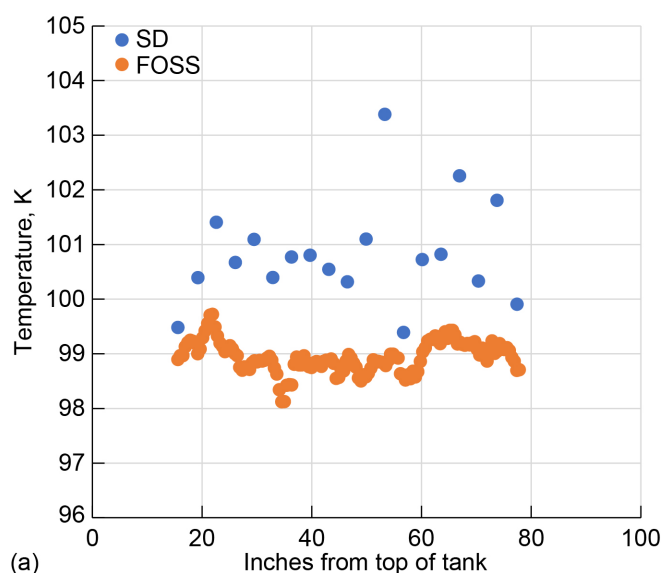


Figure 215.—Temperature change recorded on both silicon diode (blue) and FOSS sensors (orange) during Test 27's first increase in GO_2 flow, from elapsed time of Hour 20 (a) to Hour 30 h (b).

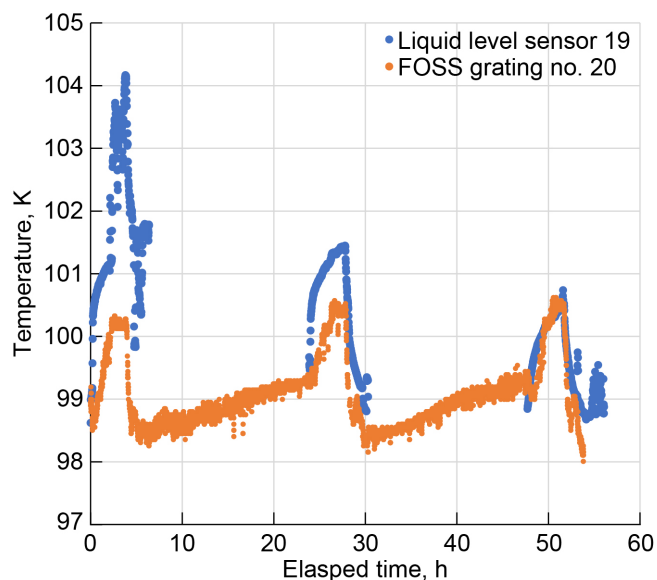


Figure 216.—Test 33 elapsed time shows three separate liquefaction events at 90 percent tank fill level, where ullage stratification is recorded from top sensor from both silicon diode (blue) and fiber sensor (orange).

Figure 215 shows the changes from the minimum and the maximum temperature values during the tank transient testing during Test 27, where again due to EMI from the cryofan, the silicon diode temperature is consistently higher than the FOSS sensor data. The FOSS sensors show that the fluid in the tank was fairly isothermal at both conditions with only a few degrees of stratification, even less stratification is seen on the FOSS than in the silicon diodes.

On Test 33, there are three liquefaction events when tank is filled to 90 percent. Figure 216 shows the three liquefaction events from the top sensor from silicon diode and FOSS, respectively. It shows that stratification is recorded from diode and FOSS data, from the ullage section. Figure 217 shows the three liquefaction events where the high spatial density of the FOSS sensor can see the stratification event from the tank well in Hour 27 when the flow is higher and pressure rising, while the limited number of sensors, as well as the EMI effect of the cryofan, limits the resolution of the diodes. The high-fill-level transient test (Test 33) shows much more stratification in the ullage at the 95 percent full level than the low-fill-level transient test.

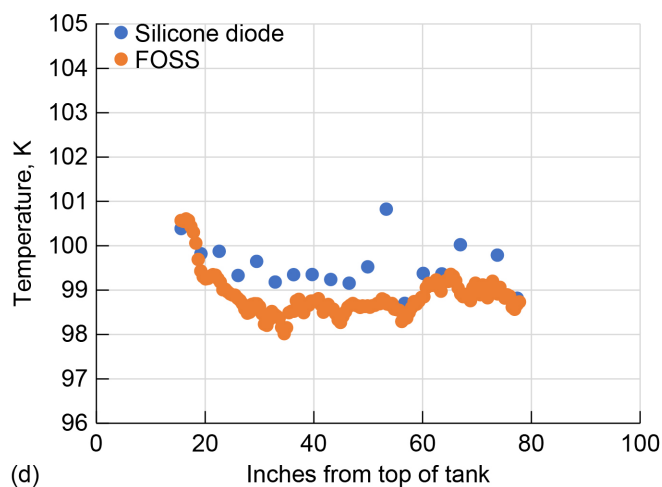
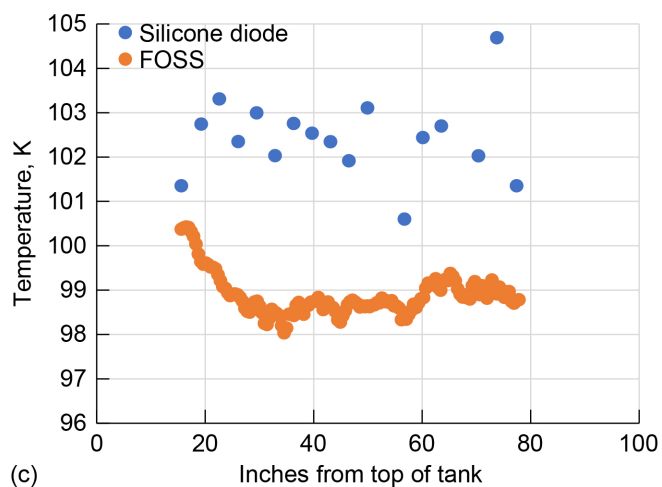
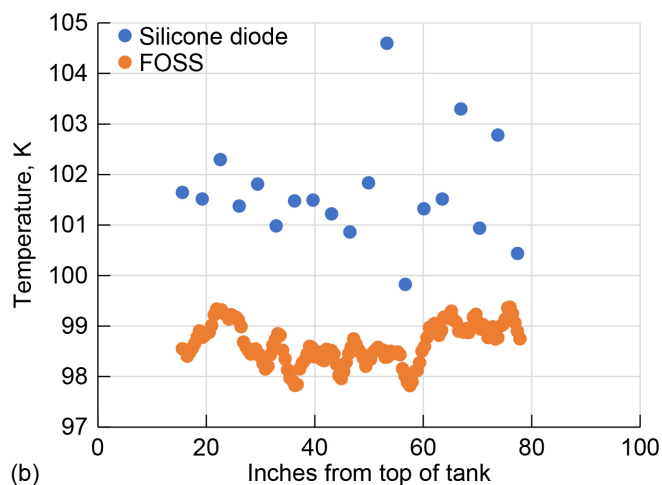
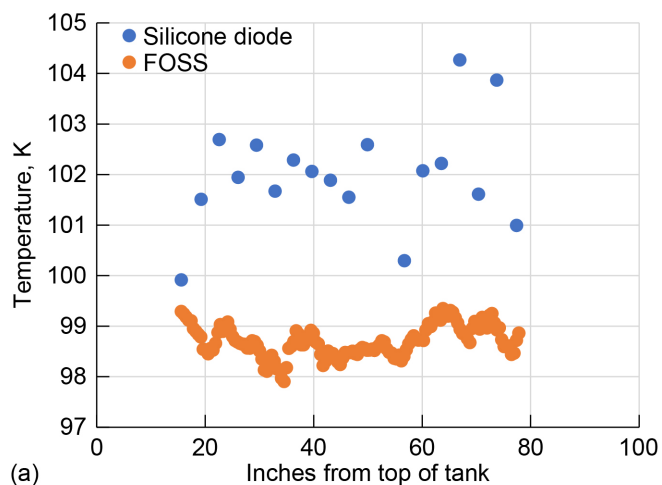


Figure 217.—Test 33 temperatures as measured with silicon diodes and fiber sensors. (a) Test 33 at Hour 3, both sensor systems show stratification in ullage from incoming gas, but are offset by 2-3 K. (b) When GO_2 flow slows down, both temperature sensor systems indicate fluid returned to a destratified condition at Hour 5.0. (c) Stratification increase evident at Hour 20 on second liquefaction is much more readily seen in FOSS data. (d) Stratification increase evident at Hour 51 on third liquefaction is much more readily seen in FOSS data and temperatures are consistent with each other.

Finally on Test 6c, there was interest to see if FOSS can differentiate fill-level data. Because FOSS's calibrated data set ends at 95 percent silicon diode level, and although there are data, these are not calibrated temperature data. Wavelength shift data at the top of the grating, during Test 6c, shown in Figure 218, indicates about a 0.7-nm shift (from -4.2 to -4.9 nm), which from the calibration for grating 20 would indicate a temperature rise of ~34 K. This suggests that the incoming GO₂ is cooling significantly in the fill/drain port of the tank. During the 55 h of liquefaction testing, the wavelength shift is steady and does not change much and it does not appear that the fill-level changes are indicated in the FOSS data.

Figure 219 shows FOSS-G02 (7.5 in. from top of tank, at the 100 percent fill level)'s wavelength shift behavior throughout the complete fill process of Test 6c as the tank approached 100 percent full, where there is little warming for the first 60 h as the constant pressure test maximum fill liquefaction test was run. Once the test was completed, the tank was pressurized to for draining. Due to the pressurization and drain, the sensors warm back up to nearly room temperature, indicating that despite being uncalibrated, the sensors are functional.

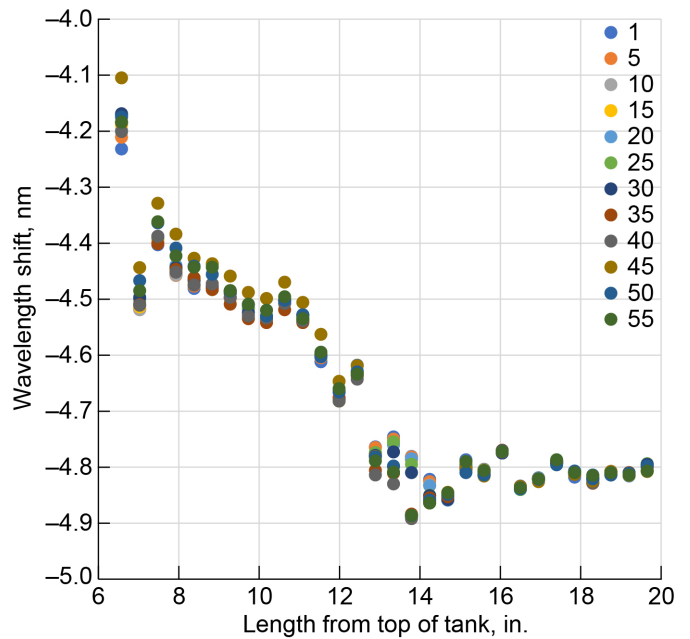


Figure 218.—Wavelength shift of each FOSS sensor at elapsed time of 1 h to 55 h (or Hour 2,595 to Hour 2,649). Because these sensors are not calibrated, no absolute temperature value is indicated.

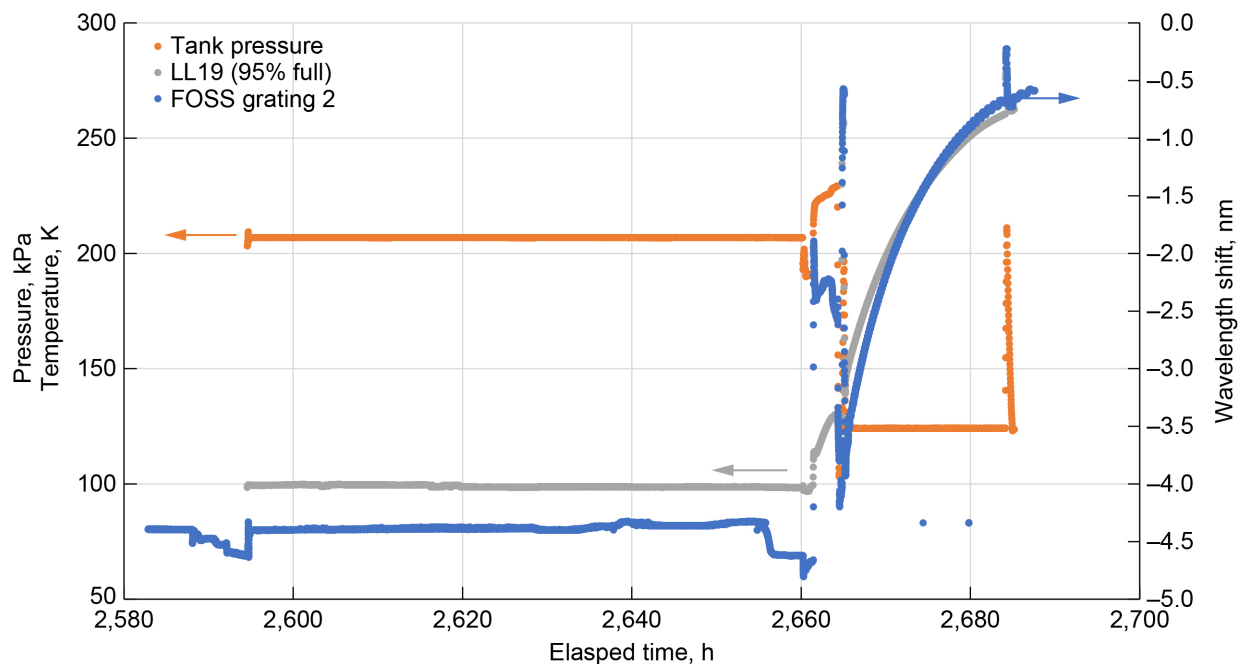


Figure 219.—Total elapsed time of Test 6c with particular grating (FOSS-G02), at 7.5 in. from top of tank, showing wavelength change on cooling and purge event with tank pressure and 95 percent full fluid temperature.

6.0 General Summary and Lessons Learned

6.1 General Summary

Four months of oxygen liquefaction testing on a system that is scalable, both geometrically and environmentally, to initial lander-sized tanks was completed. Testing included the determination of the nominal system performance, parameterization of the system during constant liquefaction operations, and performing transient liquefaction testing. The Nominal Performance phase included determination of system sensitivities to multiple operational parameters and demonstrated the capability to liquefy 1.1 kg/h in multiple configurations. During the Constant Liquefaction phase, the testing demonstrated the effect of liquid level and tank pressure on liquefaction rate, as well as the effect of inlet gas flow rate on tank pressurization rate at a constant cryocooler operating condition. The system was then set to maximize liquefaction and a rate of 1.6 kg/h was achieved. The Transient Liquefaction phase included dynamically changing liquefaction flow rate, effective cryocooler input power, environmental temperatures, and liquefaction pressure over shorter periods of time. The results verify the sensitivities of the liquefaction system in response to key parameters that simulate an in-situ resource utilization system as it responds dynamically to operational scenarios. The test hardware also included an experimental Fiber Optic Sensing System (FOSS) set up to measure fluid stratification within the tank. These tests met all of the CryoFILL Prototype Key Performance Parameters (KPPs) Threshold values, as shown in Table 57.

The nominal performance determination of the CryoFILL system was key to allowing the test team to understand the performance of the system. By observing the system under controlled testing, the operational impacts of the different control knobs could be slowly explored. This gave the test team confidence in the operation of the system so that when the more dynamic testing was performed, the team was comfortable with

the complex operations required for transient testing. This allowed for a successful, repeatable series of transient tests. This also allowed the team to isolate the larger-than-expected impact of the circulation loop pressure and temperature.

During the conditioning of the oxygen tank to higher pressures, several ways to decrease the conditioning time were observed. In addition to the obvious use of the tank heaters, bubbling GO₂ through the liquid was very effective in increasing the temperature of the bulk fluid and in increasing the mixing within the liquid. This made it possible to reduce the time from 5 days (207 kPa (30 psia), 50 percent full) to 3 days (207 kPa (30 psia), 90 percent full) to appropriately condition the bulk liquid to saturation, even when increasing the fill level. Furthermore, it was observed that the stratification in the tank was greatly reduced and nearly eliminated with the cryocooler operating.

Although several loss-of-power incidents occurred during testing, none of them damaged the test hardware due to the extensive pretest safety review. This allowed the system to be operated safely and continuously while unattended overnight for the 4-month test duration. When the loss-of-power incidents did occur, the system safed itself appropriately and informed the operators of the issue.

Results of the testing also verified the observation made during the CryoFILL Brassboard testing that liquid level does not play a large role in the rate of liquefaction. It expounded on the data by showing that starting at essentially 0 percent full was readily achieved. Additionally, with the tube-on-tank manifold inlet on the vent tube, the tank was easily filled more than 95 percent full without a decrease in liquefaction rate.

Gains for liquefying at higher pressures were observed to be substantially greater (15 percent increase in liquefaction rate) than the decrease in enthalpy (4 percent). This is due to the increased efficiency of the integrated cryocooler system at the slightly higher pressure. This increase in performance at higher pressures will have to be weighed against engine performance, which may be better at lower pressures.

TABLE 57.—CRYOFILL TESTING KEY PERFORMANCE PARAMETERS (KPPs) WITH FINAL STATUS

KPP ID	Description	State of the art	Threshold value	Project goal	Final status
Liq-1	Liquefaction rate with integrated cryocooler in flightlike configuration	<0.1 kg/h	1.1 kg/h averaged over daily cycle	2.2 kg/h averaged over daily cycle	1.6 kg/h constant liquefaction over 48-h period
Liq-3	Variations of gas inlet cycles	Constant flow rate	Demonstrate tank operation with 2 different cyclical flows	Demonstrate tank operation with 3 different cyclical flows	Demonstrated tank operation with transient environment, cryocooler, and flow rate
Liq-4	Liquefaction demonstration at a number of fill levels		3 fill levels (including <10%, >90%)	5 fill levels (including <10%, >90%)	Demonstrated liquefaction at <10, 50, and >90% fill levels

Transient testing yielded several key observations. Varying the environmental temperature did not drive large pressurization rates compared to the heater and mass flow transient. This indicates that the environmental temperature swings are less impactful on integrated system performance than the other two factors. The heater power and mass flow transients were very similar; being able to control both may be important to help offset each other. The mass flow transient had much higher pressurization rates when injecting into the ullage at 95 percent full. When injecting into the bottom of the liquid, the pressurization rates are much more muted as the injected gas causes mixing and destratification of the full liquid mass. This suggests that at some point, if there are known to be transients in the system, it may be desirable to switch from an ullage fill to a dip tube-like fill or even to sacrifice a small amount of performance to dampen the pressure responses.

This series of liquefaction testing was the first time that FOSS sensors with enhanced cryogenic sensitivity were able to conduct cryogenic LO₂ sensing. With the high spatial density and immunity to errors caused by EMI, FOSS sensors can complement existing silicon diode liquid-level sensors. Accuracy of the sensors is calculated to be within 0.36 ± 0.2 K of a typical silicon diode at 100 K.

6.2 Lessons Learned

Throughout the CryoFILL testing, multiple lessons were learned, both in the operation of the liquefaction system and through examining the test data.

Several of these lessons were learned in relationship to temperature sensors; most of these lessons are not new. Early on, several occurrences of EMI with temperature measurements were observed; these tended to affect RTD temperature measurements on the top of the tank and not the bottom of the tank. During Test 5, it was discovered that the lights in the workspace next to the test cell were one of the EMI culprits. Another culprit was found to be the cryofan wiring, the temperatures were seen several times to change when the fan speed changed or when it would be shut down in a loss-of-power scenario. This appeared to affect the silicon diodes on the temperature rake inside the tank, as well as the thermocouples on the outside wall of the tank. There were also much smaller measurement indications within the neon loop related to EMI offsets.

The installation of the RTDs on the test tank provided a mixed result. The RTDs on the bottom of the tank read well and showed that the neon was very close to the saturation temperature of the

oxygen as it approached the exit manifold. Figure 220 shows the temperature of the RTDs on the top and bottom of the manifold during Test 3 and Figure 221 shows a similar diagram from the LN₂ checkout testing. During Test 3, the oxygen tank pressure was 207 kPa (30 psia) and the associated saturation temperature is 97.6 K. It is seen that the temperatures on the top of the tank are much higher than the saturation temperature of oxygen and the neon coming into the top tank manifold is coming from the cryocooler so it should be colder than that exiting at the bottom (SD-3A showed the neon coming in at 74.9 K). Similarly, this was observed during the LN₂ checkout testing. Observation of the sensors also showed from Test 7 that the RTDs responded in a period fashion (as seen in Figure 222). Figure 223 shows that the periodic response is similar to the environmental shroud temperatures, but with a phase shift. The phase shift could simply be regarded as the thermal impedance of the MLI on the tank. However, for the sensors to be responding to the environmental shroud and not the neon tube upon which they were epoxied, the epoxy joint would have to have been broken. Similar epoxy fixtures for temperature sensors have been used by multiple test programs, including SHIIVER on the tank and the forward skirt without seeing this issue (Ref. 27). Images of the instrumentation prior to closeout with MLI indicated appropriate thermal contact between the sensor and the tube (or at least similar to the tank bottom and other tank sensors). Perhaps the leading probable cause of the offset is the EMI mentioned in the previous paragraph, although other causes are not ruled out.

In a similar fashion, it was observed that during liquefaction testing, the silicon diodes within the tank did not operate successfully in wet/dry mode. The response of all the internal tank temperature sensors was observed to not respond in way that allowed determining if a sensor was dry as they did when liquefaction operations were not happening. Whether this was due to EMI from the cryocooler cryofan or from fundamental changes within the tank due to liquefaction operations, the driving cause cannot be ascertained.

Although the test was not a calorimeter or heat load-based test, instrumentation was put on the bottom and top structural support load paths. The calculated heat loads coming down those paths was seen to vary widely as reported in Section 5.1. The difference in heat load calculation was due to large variances in temperatures being measured along the conduction paths. As such, more care should have been taken to perform due diligence on placement and allocation of exterior thermocouples in order to capture any structural heat loads as accurately as possible.

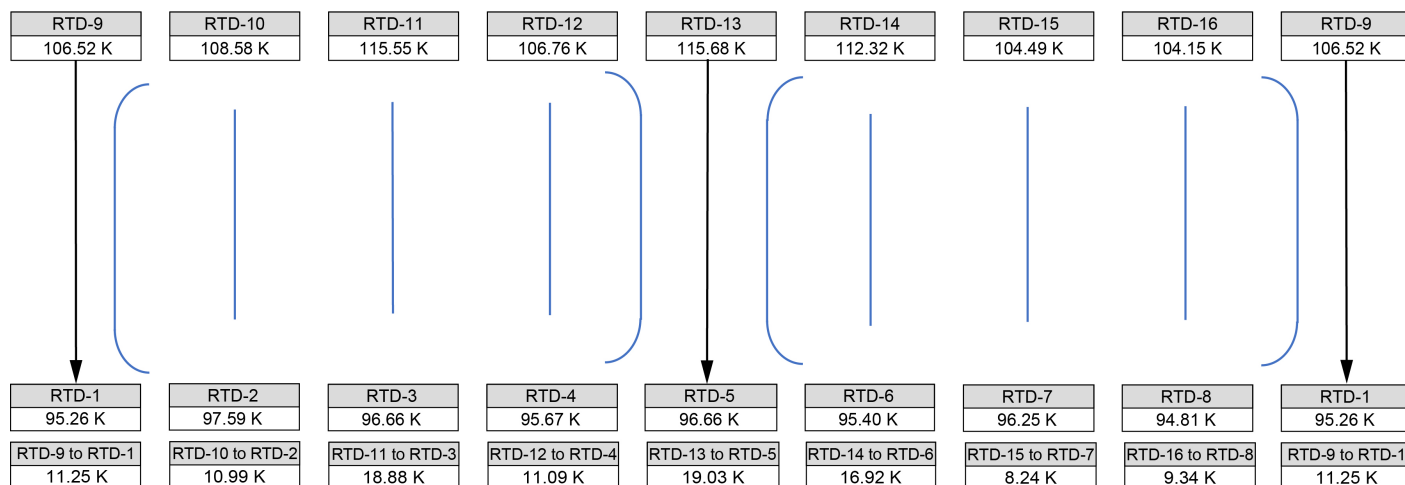


Figure 220.—RTD temperatures during Test 3, test tank oxygen pressure was 207 kPa, with saturation temperature of 97.6 K.

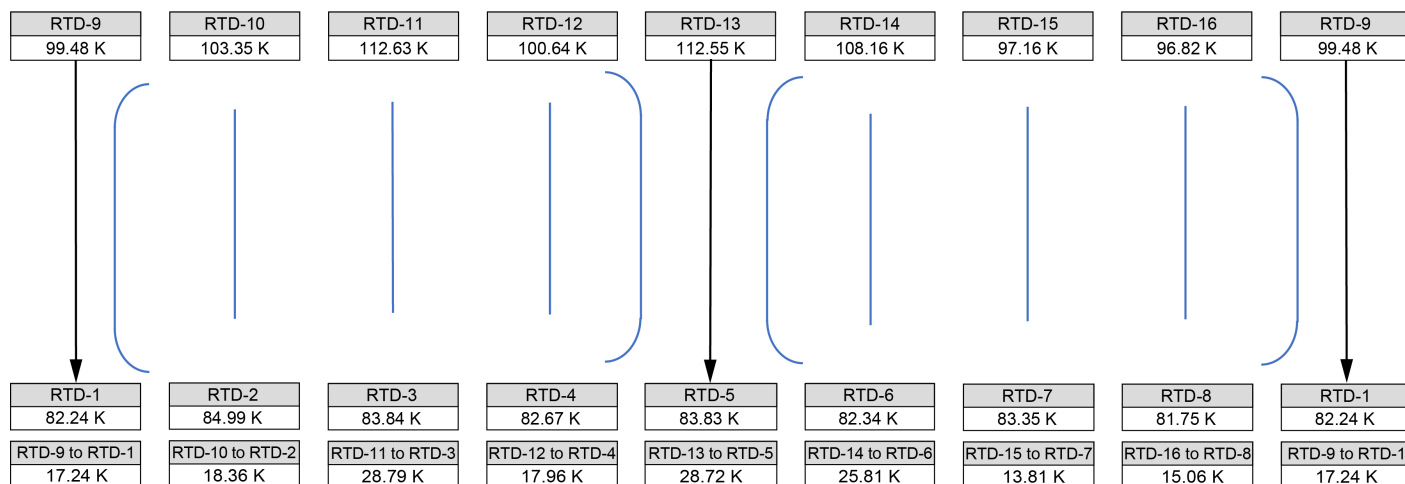


Figure 221.—RTD temperatures during LN₂ checkout testing, test pressure was 207 kPa, with saturation temperature of 83.8 K.

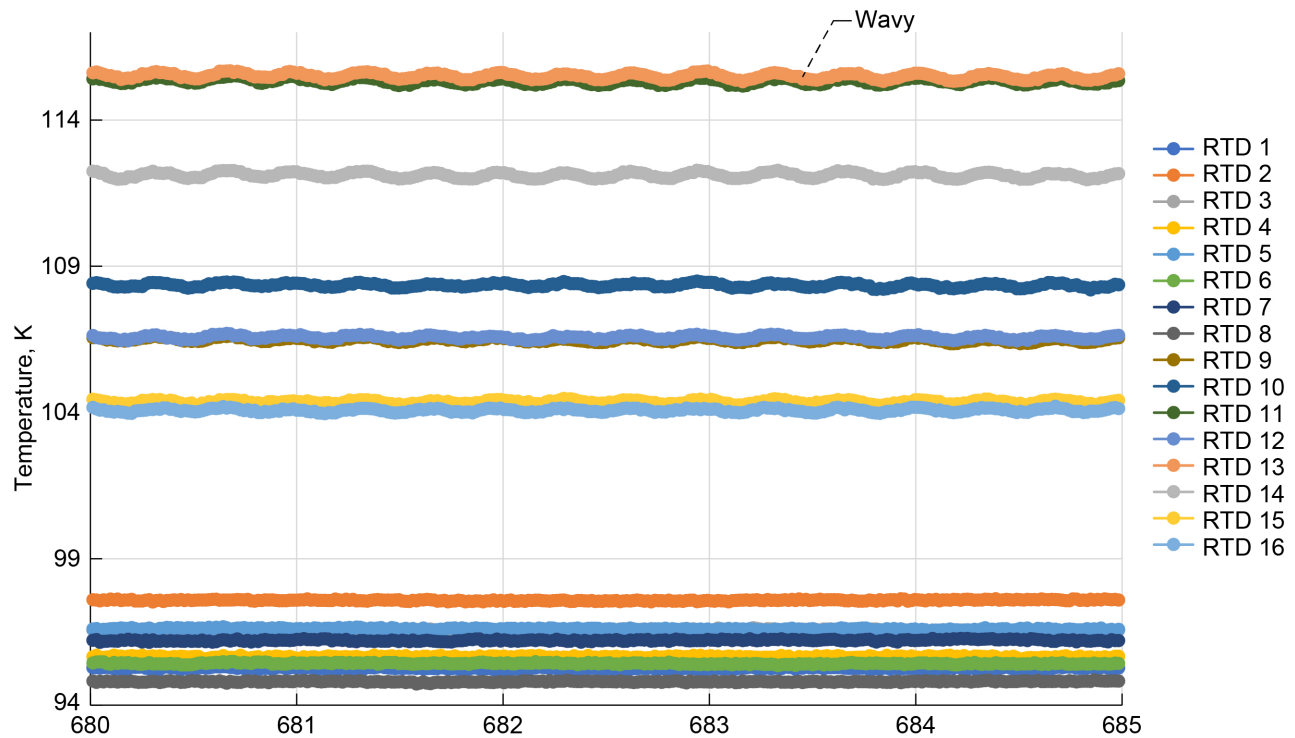


Figure 222.—RTD temperatures during Test 7; test tank oxygen pressure was 207 kPa, with saturation temperature of 97.6 K. Wavy sensor signals are from those on top of tank; flat sensor signs are from those on bottom of tank.

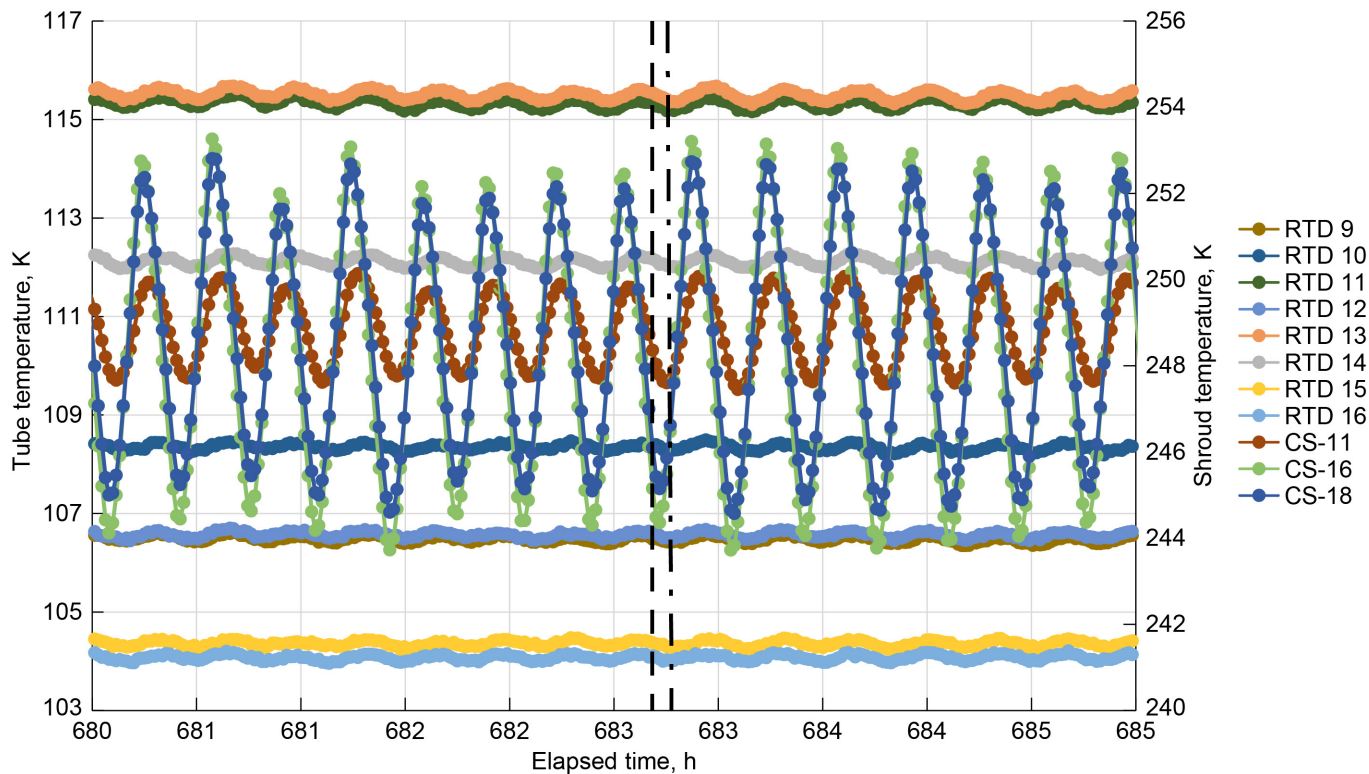


Figure 223.—RTD temperatures from Test 7 with environmental shroud temperatures. Black lines denote phase shift between environmental shroud (dashes) and RTDs (dash-dot).

Another interesting observation, noted several times throughout this report, is that the accumulator temperature on the integrated cryocooler system had a much higher driving force on the system than expected. The accumulator for the neon loop was not under vacuum and had direct exposure to surrounding outside temperature. The daily swings in temperature as it affected the accumulator were readily noticeable in system operations. Although a layer of insulation was added to the accumulator after Test 6 and the swings were observed to decrease, they did not go away. These temperature swings affected the pressure in the cryocooler loop, which would affect the mass flow rate and ultimately the integrated cryocooler system heat removal capability. In future systems, this will need to be better accounted for. Also, there was a small neon leak within the cryocooler system; this caused the pressure in the loop to slowly decrease over time. The team had to recharge the cryocooler neon approximately once per month after the pressure decreased from ~480 kPa (69.62 psia) to 410 kPa (59.47 psia) over time. The change in the neon pressure was shown to affect the integrated cryocooler system heat removal capacity.

The CryoFILL test system was originally designed to circulate neon from the bottom of the tank to the top as it was expected that this might allow for more heat removal. However, approximately a month before checkout testing began, it was proposed to flip the direction of the neon flow (to be from top of the tank to the bottom). This was agreed upon for two reasons: first, it would be more likely to prevent the buildup of stratification in both the liquid and vapor spaces (this was observed to be correct during testing) and second, the manifold at the bottom of the tank was perceived to be at risk for maldistribution of the neon due to its design. The limitations in test space in the shroud meant the manifold was simply a disk with gas passage holes drilled into it. During the discussion, questions arose about the effect on the flow loop systems already installed and none were identified. However, during testing, it became apparent that the Coriolis flow meter was not working properly (see Section 5.2). It was observed that the entrance to the Coriolis flow meter had a very short path after a sharp 90° elbow in the flow. The new upstream direction (previously was downstream) had significant straight length flow to mitigate the flow divergences. However, this had not been caught in the discussion. The flow meter was known to be bidirectional, but the pre-entrance fluid dynamics were not accounted for.

A few positive lessons were also learned. The forward neon manifold was placed directly on the tank vent line. This allowed

the cooling from the cryocooler to be integrated at greater than 100 percent full of the tank. This was a major reason the tank could be filled to 100 percent full in Test 6c while still liquefying at the nominal 1.1 kg/h. This design feature should be captured on future operational hardware. Additionally, very little stratification was observed in the liquid and ullage during liquefaction operations (less than a few kelvin). Clear initiation of stratification was seen, especially in the ullage on several power failure events, with the maximum temperature difference between the top of the tank and the liquid reaching as much as 15 K without the cryocooler running.

A final observation was that due to the tight packaging of the inlets and outlets to the tank and associated lack of insulation around the 6-way cross at the top, there was a significant change in heat load when gas was coming in for liquefaction compared to when it was not. This value was observed to be ~15 W.

7.0 Conclusions

The CryoFILL Prototype testing successfully demonstrated the liquefaction of oxygen in a prototypical lander tank using tube-on-tank integration of a cryocooler. The CryoFILL Prototype hardware consists of the tank, tubes on the tank for integrating of the cryocooler for heat removal, and an industrial cryocooler system. The hardware is scaled by half of the surface area to a 10 mT Mars lander while liquefying oxygen at over half of the required rate by the associated Mars architecture. The system was fully instrumented with temperature, pressure, and flow measurement devices to understand both the mass and heat transfer processes being tested.

Testing on the CryoFILL hardware was completed in both quasi-steady state and transient modes, demonstrating system performance as a function of fill level, oxygen mass flow rate, cryocooler system performance, and environmental temperatures. Transient tests with flow rate, cryocooler system performance and environmental temperatures showed that the transient system could be predicted by the results from the quasi-steady state performance.

As demonstrated in this report, the CryoFILL Prototype hardware can be used to demonstrate the liquefaction operations as they might be performed on the lunar or martian surface. Continued evolution of the hardware should serve as a platform to continue to mature ISRU and surface-based CFM technologies, along with their integration into full ISRU plants and landers.

Appendix A.—CryoFILL Instrumentation List

TABLE 58.—SILICON DIODES AND PLATINUM RTDS

PID name	Description	Location	Manufacturer	Model number
LL1	Instrument rake 5%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL2	Instrument rake 10%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL3	Instrument rake 15%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL4	Instrument rake 20%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL5	Instrument rake 25%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL6	Instrument rake 30%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL7	Instrument rake 35%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL8	Instrument rake 40%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL9	Instrument rake 45%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL10	Instrument rake 50%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL11	Instrument rake 55%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL12	Instrument rake 60%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL13	Instrument rake 65%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL14	Instrument rake 70%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL15	Instrument rake 75%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL16	Instrument rake 80%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL17	Instrument rake 85%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL18	Instrument rake 90%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL19	Instrument rake 95%	Rake	Lake Shore Cryotronics	DT-670B-SD
LL20	Tank vent temperature	Tank vent outlet	Lake Shore Cryotronics	DT-670B-SD
RTD-1 ^a	Bottom tank cooling lines at 22.5°	Bottom tank cooling lines at 22.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-2 ^a	Bottom tank cooling lines at 67.5°	Bottom tank cooling lines at 67.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-3 ^a	Bottom tank cooling lines at 112.5°	Bottom tank cooling lines at 112.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-4 ^a	Bottom tank cooling lines at 157.5°	Bottom tank cooling lines at 157.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-5 ^a	Bottom tank cooling lines at 202.5°	Bottom tank cooling lines at 202.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-6 ^a	Bottom tank cooling lines at 247.5°	Bottom tank cooling lines at 247.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-7 ^a	Bottom tank cooling lines at 292.5°	Bottom tank cooling lines at 292.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-8 ^a	Bottom tank cooling lines at 337.5°	Bottom tank cooling lines at 337.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-9 ^a	Top tank cooling lines at 22.5°	Top tank cooling lines at 22.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-10 ^a	Top tank cooling lines at 67.5°	Top tank cooling lines at 67.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-11 ^a	Top tank cooling lines at 112.5°	Top tank cooling lines at 112.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-12 ^a	Top tank cooling lines at 157.5°	Top tank cooling lines at 157.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-13 ^a	Top tank cooling lines at 202.5°	Top tank cooling lines at 202.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-14 ^a	Top tank cooling lines at 247.5°	Top tank cooling lines at 247.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-15 ^a	Top tank cooling lines at 292.5°	Top tank cooling lines at 292.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
RTD-16 ^a	Top tank cooling lines at 337.5°	Top tank cooling lines at 337.5°	Innovative Sensor Technology	P0K1.232.4W.Y.010
SD-1	Neon loop flow meter inlet temperature	At neon loop flow meter (FS-1)	Lake Shore Cryotronics	TP-6-2NQ-N-2-SOA
SD-2A	Neon loop tank cooling outlet temperature—Diode A	At neon loop tank outlet	Lake Shore Cryotronics	XTP-6-4NF-N-2-SOA
SD-2B	Neon loop tank cooling outlet temperature—Diode B	At neon loop tank outlet	Lake Shore Cryotronics	XTP-6-4NF-N-2-SOA
SD-3A	Neon loop tank cooling inlet temperature—Diode A	At neon loop tank inlet	Lake Shore Cryotronics	XTP-6-4NF-N-2-SOA
SD-3B	Neon loop tank cooling inlet temperature—Diode B	At neon loop tank inlet	Lake Shore Cryotronics	XTP-6-4NF-N-2-SOA
SD-4	Neon loop heater inlet temperature	Neon loop—heater location	Lake Shore Cryotronics	TP-6-2NQ-N-2-SOA
SD-5	(RTD) Cryomech HX inlet temperature	Outside tank	Honeywell	HEL-707-U-1-12-00
SD-6	(RTD) Cryomech outlet temperature	Outside tank	Honeywell	HEL-707-U-1-12-00
SD-7	(RTD) Cryomech HX temperature	Outside tank	Honeywell	HEL-707-U-1-12-00

^aDegree symbols in RTD-1 to RTD-16 indicate the sensor's position on the tank circumference.

TABLE 59.—THERMOCOUPLES

Name	Description	Type	Manufacturer	Model
Inside vacuum tank				
T/C-1	Tank wall at 0%	E	Omega Engineering	5TC-TT-E-24-72
T/C-2	Tank wall at 5%	E	Omega Engineering	5TC-TT-E-24-72
T/C-3	Tank wall at 10%	E	Omega Engineering	5TC-TT-E-24-72
T/C-4	Tank wall at 15%	E	Omega Engineering	5TC-TT-E-24-72
T/C-5	Tank wall at 20%	E	Omega Engineering	5TC-TT-E-24-72
T/C-6	Tank wall at 25%	E	Omega Engineering	5TC-TT-E-24-72
T/C-7	Tank wall at 30%	E	Omega Engineering	5TC-TT-E-24-72
T/C-8	Tank wall at 35%	E	Omega Engineering	5TC-TT-E-24-72
T/C-9	Tank wall at 40%	E	Omega Engineering	5TC-TT-E-24-72
T/C-10	Tank wall at 45%	E	Omega Engineering	5TC-TT-E-24-72
T/C-11	Tank wall at 50%	E	Omega Engineering	5TC-TT-E-24-72
T/C-12	Tank wall at 55%	E	Omega Engineering	5TC-TT-E-24-72
T/C-13	Tank wall at 60%	E	Omega Engineering	5TC-TT-E-24-72
T/C-14	Tank wall at 65%	E	Omega Engineering	5TC-TT-E-24-72
T/C-15	Tank wall at 70%	E	Omega Engineering	5TC-TT-E-24-72
T/C-16	Tank wall at 75%	E	Omega Engineering	5TC-TT-E-24-72
T/C-17	Tank wall at 80%	E	Omega Engineering	5TC-TT-E-24-72
T/C-18	Tank wall at 85%	E	Omega Engineering	5TC-TT-E-24-72
T/C-19	Tank wall at 90%	E	Omega Engineering	5TC-TT-E-24-72
T/C-20	Tank wall at 95%	E	Omega Engineering	5TC-TT-E-24-72
T/C-21	Tank wall at 25%_180°	E	Omega Engineering	5TC-TT-E-24-72
T/C-22	Tank wall at 25%_270°	E	Omega Engineering	5TC-TT-E-24-72
T/C-23	Tank wall at 25%_90°	E	Omega Engineering	5TC-TT-E-24-72
T/C-24	Tank wall at 50%_180°	E	Omega Engineering	5TC-TT-E-24-72
T/C-25	Tank wall at 50%_270°	E	Omega Engineering	5TC-TT-E-24-72
T/C-26	Tank wall at 50%_90°	E	Omega Engineering	5TC-TT-E-24-72
T/C-27	Tank wall at 75%_180°	E	Omega Engineering	5TC-TT-E-24-72
T/C-28	Tank wall at 75%_270°	E	Omega Engineering	5TC-TT-E-24-72
T/C-29	Tank wall at 75%_90°	E	Omega Engineering	5TC-TT-E-24-72
T/C-30	MLI outer layer #1 (top)	E	Omega Engineering	5TC-TT-E-24-72
T/C-31	MLI outer layer #2 (mid)	E	Omega Engineering	5TC-TT-E-24-72
T/C-32	MLI outer layer #3 (mid)	E	Omega Engineering	5TC-TT-E-24-72
T/C-33	MLI outer layer #4 (mid)	E	Omega Engineering	5TC-TT-E-24-72
T/C-34	MLI outer layer #5 (bot)	E	Omega Engineering	5TC-TT-E-24-72
T/C-35	Right support (facing)	E	Omega Engineering	5TC-TT-E-24-72
T/C-36	Right support (facing)	E	Omega Engineering	5TC-TT-E-24-72
T/C-37	Right support (facing)	E	Omega Engineering	5TC-TT-E-24-72
T/C-38	Middle support (facing)	E	Omega Engineering	5TC-TT-E-24-72
T/C-39	Middle support (facing)	E	Omega Engineering	5TC-TT-E-24-72
T/C-40	Middle support (facing)	E	Omega Engineering	5TC-TT-E-24-72

TABLE 59.—THERMOCOUPLES

Name	Description	Type	Manufacturer	Model
Inside vacuum tank				
T/C-41	Left support (facing)	E	Omega Engineering	5TC-TT-E-24-72
T/C-42	Left support (facing)	E	Omega Engineering	5TC-TT-E-24-72
T/C-43	Left support (facing)	E	Omega Engineering	5TC-TT-E-24-72
T/C-44	Bottom tank feet	E	Omega Engineering	5TC-TT-E-24-72
T/C-45	Bottom tank feet	E	Omega Engineering	5TC-TT-E-24-72
T/C-46A	Bottom tank feet	E	Omega Engineering	5TC-TT-E-24-72
T/C-47	Bottom tank feet	E	Omega Engineering	5TC-TT-E-24-72
T/C-48	Bottom tank feet	E	Omega Engineering	5TC-TT-E-24-72
T/C-49	Bottom tank feet	E	Omega Engineering	5TC-TT-E-24-72
T/C-50	Tank heater zone W (Brown)	E	Omega Engineering	5TC-TT-E-24-72
T/C-51	Tank heater zone X (Yellow)	E	Omega Engineering	5TC-TT-E-24-72
T/C-52	Tank heater zone Y (Orange)	E	Omega Engineering	5TC-TT-E-24-72
T/C-53	Tank heater zone Z (Black)	E	Omega Engineering	5TC-TT-E-24-72
T/C-54	Fill line TC above tank	E	Omega Engineering	5TC-TT-E-24-72
T/C-57	Cross surface temperature	E	Omega Engineering	5TC-TT-E-24-72
T/C-58	Cross internal vent temperature	E	Omega Engineering	5TC-TT-E-24-72
T/C-59	Neon flow loop temperature	E	Omega Engineering	5TC-TT-E-24-72
T/C-60	Neon loop heater control skin temp	E	Omega Engineering	5TC-TT-E-24-72
Outside vacuum tank				
T/C-61	GO ₂ feed temperature A at FC-1	E		
T/C-62	GO ₂ feed temperature B at FC-1	E		
XO712	Vent line temperature after heat exchanger	E		
XO714	Vent line temperature before heat exchanger	E		
XO714A	Vent line temperature before heat exchanger	E		
XO728	Temperature for flow meter XO727	E		
Cryoshroud				
CS-1	Bottom section center fin	E		
CS-2	Bottom section middle diameter fin	E		
CS-3	Bottom section outer diameter fin	E		
CS-4	Middle section upper fin	E		
CS-5	Middle section upper fin	E		
CS-6	Middle section upper fin	E		
CS-7	Middle section center fin	E		
CS-8	Middle section center fin	E		
CS-9	Middle section center fin	E		
CS-10	Middle section lower fin	E		
CS-11	Middle section lower fin	E		
CS-12	Middle section lower fin	E		
CS-13	Middle section center fin – control TC	E		
CS-14	Middle section inlet manifold	E		

TABLE 59.—THERMOCOUPLES

Name	Description	Type	Manufacturer	Model
Cryoshroud				
CS-15	Middle section outlet manifold	E		
CS-16	Top pancake	E		
CS-17	Top pancake	E		
CS-18	Top pancake	E		
CS-19	Top pancake	E		
CS-20	Top pancake	E		

TABLE 60.—PRESSURES, HEATERS, FLOWS, VACUUM, AND FILL LEVELS

PID name	Description	Manufacturer	Model no.	Range	Location
Neon loop					
PS-1	Neon loop flow meter inlet pressure	Setra	205-2	0 to 500 psia	Neon loop – inside chamber
PS-2	Neon loop tank cooling inlet pressure	Setra	205-2	0 to 500 psia	Neon loop tank cooling loop inlet
PS-3	Neon loop tank cooling delta pressure	Setra	239	0 to 10 psid	Neon loop tank inlet to outlet
PS-4	Neon loop cryofan delta pressure	Dwyer	636D	0 to 10 psid	Cryocooler cold box
FS-1	Neon loop Coriolis flow meter	Micro Motion	CMF025	0 to 302.4 g/s	Neon loop – inside chamber
	Transmitter	Micro Motion	2700		Upper test cell
LOOP_HTR	Neon loop heater power output	-----	-----	On/Off	Neon loop – inside chamber
CRYOFAN_SP	Neon loop cryofan speed setpoint	-----	-----	0 to 100%	Neon loop – upper test cell
PT-CAN	Vacuum pressure on cryofan “Can”	Setra		0 to 25 psia	Cryocooler cold box
Oxygen system					
XO711	Tank pressure (high)	Rosemount	3051S	0 to 100 psia	Upper test cell panel 18
XO708	Tank pressure (low)	Rosemount	3051S	0 to 50 psia	Upper test cell panel 18
FC-1	GO ₂ flow control valve meter SP	Brooks	SLAMf50 MFC	0 to 30.15 slpm	Upper test cell
	GO ₂ flow control valve meter FB				
XO715	Tank vent pressure to flow meters	Setra	205-2	0 to 100 psia	Tank vent – lower test cell
XO602	LO ₂ fill pressure	Setra	205-2	0 to 300 psia	Upper test cell
XO602A	LO ₂ fill pressure	Setra	205-2	0 to 300 psia	Upper test cell
XO607	Flash tank delta pressure	Setra	239	0 to 5 psid	O ₂ flash tank
XO726	Boil-off flow meter	Brooks	SLAMF60	0 to 20 slpm	Tank vent – lower test cell
XO727	Boil-off flow meter	Brooks	SLAMF60	0 to 1.5 slpm	Tank vent – lower test cell
GO604	GO ₂ feed pressure on outside panel	Setra	204	0 to 3,000 psig	Outside GO ₂ panel
GO606	GO ₂ feed pressure upstream of controller	Setra	204	0 to 3,000 psig	Upstream of GO ₂ flow control valve
GO615	GO ₂ feed pressure downstream of controller	Setra	205-2	0 to 100 psia	Downstream of GO ₂ flow control valve
CP-1	LO ₂ tank level	American Magnetics		0 to 100%	Inside tank
Vacuum system					
V047A	V047A ion gage	Granville Phillips	274006		Lower test cell vacuum instrument cable V110
V047B	V047B ion gage	Granville Phillips	274006		Lower test cell vacuum instrument cable V111
Test tank					
HTR_W	Tank heater zone W (brown)			On/Off	Test tank external (in VC)
HTR_X	Tank heater zone X (yellow)			On/Off	Test tank external (in VC)
HTR_Y	Tank heater zone Y (orange)			On/Off	Test tank external (in VC)
HTR_Z	Tank heater zone Z (black)			On/Off	Test tank external (in VC)

Appendix B.—Full CryoFILL Test Matrix

TABLE 61.—FULL CRYOFILL TEXT MATRIX

Test no.	Test description	Fill level, %	Cold wall temperature, K	Initial tank pressure, kPa	GO ₂ flow, kg/h	Heaters, W	Neon loop fan speed, krpm	GO ₂ injection method
1	Boil-off test	50	250	207	n/a	n/a	n/a	n/a
1a	Autogenous pressurization test	50	250	207 to 276	1.1	n/a	n/a	Vent line
1a-2	Autogenous pressurization test	15	250	185 to 253	1.1	n/a	n/a	Vent line
2	ZBO	50	250	207	n/a	155	20	n/a
2a 2b 2c 2d 2e 2f 2g	Tank pressurization/depressurization	50	250	^a 170 to 240	n/a	0 to 212	20	n/a
3	Initial liquefaction	50	250	207	1.1	47*	20	Vent line
3a	Neon loop heater variations	50	250	207	^a 1.1	7 to 57 in 10-W increments	20	Vent line
4	Neon loop flow variations	50	250	207	^a 1.1	47	15, 17.5, 20, 22.5	Vent line
4z -2 -3	Neon loop flow variations, control flow	<5, 15, 90	250	^a 207	1.1	47	15, 16.25, 17.5, 20	Vent line
5	Effect of dip tube	50	250	207	^a 1.1	47	20	Dip tube
5a	Effect of heater settings with dip tube	50	250	207	^a 1.1	7, 17, 37	20	Dip tube
6	High fill level	90	250	207	^a 1.1	47	20	Vent line and dip tube
6c	Max. fill level	95 to 100	250	207	^a 1.1	47	20	Vent line
7	Medium fill level	50	250	207	^a 1.1	47	20	Vent Line
8	Low fill, medium pressure	<10	250	207	^a 1.1	47	20	Vent line
9	Low fill, high pressure	<10	250	276	^a 1.1	47	20	Vent line
10	Low fill, low pressure	<10	250	138	^a 1.1	47	20	Vent line
11	Constant flow, nominal	<10	250	^a 207	1.1	47	20	Vent line
12	Constant flow, low	<10	250	^a 207	0.5	47	20	Vent line
13	Constant flow, high	<10	250	^a 207	2.2	47	20	Vent line
26	Set initial conditions	<10	250	207	^a 1.1	47	20	Vent line
27	Variable GO ₂ flow rate	<10	250	^a 207	0.9 to 1.6	47	20	Vent line
28	Set initial conditions	<10	250	207	^a 1.1	47	20	Vent line
29	Variable cryocooler lift	<10	250	^a 207	1.1	15 to 94.4	20	Vent line
29–2	Variable cryocooler lift	<10	250	^a 207	1.1	0 to 93.5	20	Vent line
30	Set initial conditions	<10	250	207	^a 1.1	47	20	Vent line
31	Variable environmental temperature	<10	225 to 290	^a 207	1.1	47	20	Vent line
32	Set initial conditions	90	250	207	^a 1.1	47	20	Vent line
33	Variable GO ₂ flow rate	90	250	^a 207	0.9 to 1.6	47	20	Vent line and dip tube
40	Max. liquefaction rate	0 to 5	250	276	^a 1.6	0	20	Vent line
41	Pressure collapse test	0 to 5	250	276 to ^a 210	1.1	47	20	Vent line

^aNominal value given, but test allowed this variable to respond to all other inputs.

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