Test Data Analysis of the CRYOTE TVS-Augmented Top Spray Injector Liquid Nitrogen Transfer Experiments

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Abstract

Traditionally, a tank must be pre-chilled to some "target" temperature before the main vent valve can be closed to attempt a non-vented fill (NVF) of cryogenic liquid propellant. This methodology is particularly attractive for performing in-space transfer of cryogens due to the unknown location of the liquid/vapor interface and the high propensity of venting liquid if the vent valve is opened during transfer. This paper presents in-depth test data analysis of a Thermodynamic Vent System (TVS) augmented injector used for cryogenic tank chilldown and fill experiments of the CRYOgenic Orbital TEstbed (CRYOTE) tank. Eight tests were conducted using liquid nitrogen across a range of inlet conditions and boundary conditions, and three different chilldown/fill methods. For four of the tests, the injector sprays liquid into the tank as normal, but also uses a TVS system to cool the metallic injector as well as the main incoming liquid stream. Results show that using the TVS augmented injector simplifies transfer operation at the cost of sacrificing a small amount of propellant.

1.0 Introduction

Future long duration human and robotic missions beyond Low Earth Orbit will likely require high specific impulse cryogenic propulsion systems. Cryogenic propellants are an attractive alternative to storable propellants due to lower toxicity, higher energy density, and unmatched level of performance. However, cryogenic propellants, which are gases at room temperature, are highly susceptible to boiling due to low normal boiling point (NBP) and difficult to transfer single phase liquid due to low NBP and low surface tension. Several different cryogenic fluid management (CFM) technologies will be required, depending on the mission and mission duration (Johnson and Stevens 2018).

One concept that is particularly attractive for enabling long duration missions is the cryogenic fuel depot, defined as an Earth-orbiting propellant storage vessel that can house cryogenic propellant for an indefinite duration of time and then transfer the propellant to any other orbiting vehicle. The orbiting vehicle could launch with enough propellant to break the Earth gravity well, rendezvous and dock with the fuel depot, and then refill en route to the final destination. This process is analogous to refueling an automobile at a gas station on the ground. Large fuel depots can therefore contain a large percentage of the propellant required for a deep space mission, thus allowing more dry mass launched into orbit.

There are stages to the refueling process, including (1) acquisition of the storage tank liquid despite microgravity of space, (2) chilldown of the connecting transfer line, (3) chilldown of the receiver tank, and (4) fill of the receiver tank. Due to the projected cost to launch and store propellant in LEO, the chilldown process and transfer of propellant to the customer receiver tank must be optimized so that high final fill fractions (>95%) in the customer receiver tank are possible. Therefore depot line and tank to tank chilldown must be optimized to minimize evaporation and venting of mass. To do so, a number of mass-savings transfer methods have been proposed, such as pulse flow (Schuster et al. 1996, Hartwig et al. 2016, Chung et al. 2019) and charge-hold-vent (CHV) (Chato and Sanabria 1991, Keefer et al. 2016, Kartuzova and Kassemi 2017). In CHV, a small amount of liquid charges the tank, the liquid is held until it boils off completely and the tank walls and cold fluid reach equilibrium via sensible energy exchange (hold), and then vented. The overall goal of this transfer is to achieve a high fill fraction at a final pressure lower than the maximum allowable working pressure (MAWP) of the receiver tank, while sacrificing as little propellant as possible during chilldown in the microgravity of space.

As traditionally envisioned for in-space cryogenic propellant transfer in the absence of settling thrusting maneuvers, a receiver tank must be pre-chilled to some "target" temperature before the main vent valve can be closed to attempt a non-vented fill (NVF) of cryogenic liquid propellant. This methodology is particularly attractive due to the unknown location of the liquid/vapor interface and the high propensity of venting liquid if the vent valve is opened during transfer. The goal is to be able to remove as much thermal energy as is needed from the tank walls such that when the vent valve is closed, the fill is permissible beyond 90%. There are multiple competing heat transfer rates involved: (1) residual boil-off of incoming liquid in contact with the walls and subsequent pressure rise, (2) ullage cooling due to heat transfer between incoming droplets and warm ullage, (3) pressure rise due to droplet evaporation, and (4) pressure collapse due to condensation at the tank liquid/vapor interface. Well-designed injection systems will counteract the residual boiling and thus permit initiation of a NVF at a tank wall temperature well above the incoming liquid saturation temperature. This target temperature can be predicted reasonably well using zeroth order (Clark and Hartwig 2021). However, chilling the system down to this target temperature using a method like CHV requires complex valve cycling and proper timing so that liquid is never vented.

The purpose of this paper is to present test data analysis of recent cryogenic fluid transfer experiments using a new type of injector, a Thermodynamic Vent System (TVS) augmented top spray injector used for cryogenic tank chilldown and fill experiments of the CRYOgenic Orbital TEstbed (CRYOTE-2) tank. Preliminary data analysis as well as design details on the injectors have been provided by Stephens (2018) and Mireles et al. (2020), respectively. Eight tests were conducted using liquid nitrogen across a range of flow rates, inlet conditions, and boundary conditions, for three different chilldown methods. The goal of this short test series was to provide proof-of-concept and determine operational limits of the new TVS augmented injector. The outline of the paper is as follows: First a short background section is given to summarize cryogenic transfer tests to-date. Then the experimental design section outlines the hardware and instrumentation. Next the experimental methodology is described, along with the test matrix. Finally experimental results are presented for the three different transfer methods along with discussion.

2.0 Background

To date, cryogenic propellant has never been transferred in reduced gravity. Only ground testing has been performed. For a detailed description of previous historical NVF tests, please refer to Hartwig et al. (2021). Following is a brief description of the testing. In the 1990s numerous chilldown and fill tests were performed using LH_2 and LN_2 on various sized tanks (Chato et al. 1990, Chato 1991, Moran et al. 1991, Moran and Nyland 1992, Chato et al. 1993, Hartwig et al. 2021). Emphasis of testing was on proving the feasibility of CHV (Chato and Sanabria 1991) and NVF methods and to compare the performance of different injectors, such as top spray, spray bar, bottom jet, etc. In the 2000's, No-Vent Top-Off (NVTO) testing was successfully demonstrated in Flachbart et al. (2013). In 2016, Kim et al. performed 16 parametric NVF tests on a small cylindrical tank using a methane surrogate fluid using a dip tube bottom fill injector. Initial tank wall temperature, incoming liquid temperature, mass flow rate, and supply tank pressure were all varied. The most recent set of testing occurred between 2014 – 2017 on the CRYogenic Orbital Testbed Experiment (CRYOTE) tank (Hartwig et al. 2021). The CRYOTE-2 tests consisted of more than 53 tests demonstrating NVF, varying many parameters such as injector type, supply tank pressure, initial fill level, and initial tank temperature. The majority of these tests were conducted using vented chill/NVF, in that the receiver tank vent valve remained opened during the majority of chill down, and different target temperatures were used to commence NVF. While this method accelerates the transfer process, a vented chilldown would likely not work in the microgravity of space unless it was possible to constantly settle the propellant.

NVF and NVTO has been successfully demonstrated across a range of tanks, fluids, and initial system conditions and boundary conditions. Meanwhile CHV was successfully demonstrated for chilling down a tank to the target temperature, despite the added complexity of valve cycling. The motivation for the new test campaign in the current work is to investigate the feasibility of performing a combined tank chilldown and tank fill with a new TVS augmented injector.

3.0 Experimental Design and Methodology

The objective of the CRYOTE TVS Augmented Injector ground tests was to fill the receiver tank (CRYOTE) with LN_2 from the Vibro-Acoustic Test Article (VATA) supply tank to a fill fraction of greater than 90% using the new TVS-augmented injector. Eight tests took place during April 2018. Following is the description of test hardware, instrumentation, and test procedure.

3.1 Supply and Receiver Tanks

A detailed description of the test tank and facility are available in Stephens (2018) and Hartwig et al. (2021); only a brief description is given here. VATA is the supply tank that feeds the CRYOTE receiver tank inside of the Exploration Systems Test Facility (ESTF) shown in Figure 1 (Woods and Foster 2013, Rhys et al. 2019). ESTF is a 6.10 m long, 2.74 m diameter multi-purpose vacuum chamber that has been used for numerous CFM experiments at the Marshall Space Flight Center. Multiple ports and interfaces are available for testing, including fill, drain, vent, instrumentation lines, etc. ESTF is capable of pumping down well below vacuum levels (< 1.38 kPa) to reduce gaseous conduction heat leak into test articles. VATA is a 903 kpa ASME stainless steel pressure vessel with a volume of 1.37 m^3 and a wall thickness of 0.476 cm. VATA is thoroughly insulated with foam, multi-layer insulation (MLI), and a broad area cooling (BAC) shield. During the CRYOTE tests, VATA is filled with LN2 initially at 77K and 1 atm and then pressurized to the desired supply tank pressure utilizing gaseous nitrogen.

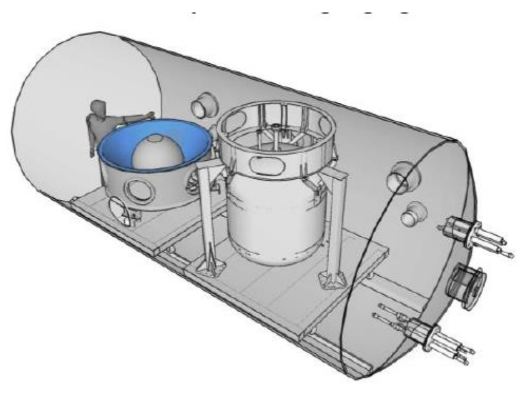


Figure 1 – System Diagram for the TVS-Augmented Injector Transfer Tests. From left to right: CRYOTE tank, VATA tank

The CRYOTE receiver tank depicted in Figure 2 is a spherical 6-4 titanium tank with an outer diameter of 75.44 cm and a wall thickness of 0.127 cm (Johnson et al. 2015). The spherical portion of the tank weighs approximately 10.3 kg. The tank lid, on the other hand, is a cylindrical

304 stainless steel lid that weights approximately 2.9 kg. CRYOTE also includes multi-layer insulation (MLI) and a support skirt, both reduce radiative and conductive parasitic heat leak into the tank. The location of all of the thermocouples is shown in Figure 2 as well.

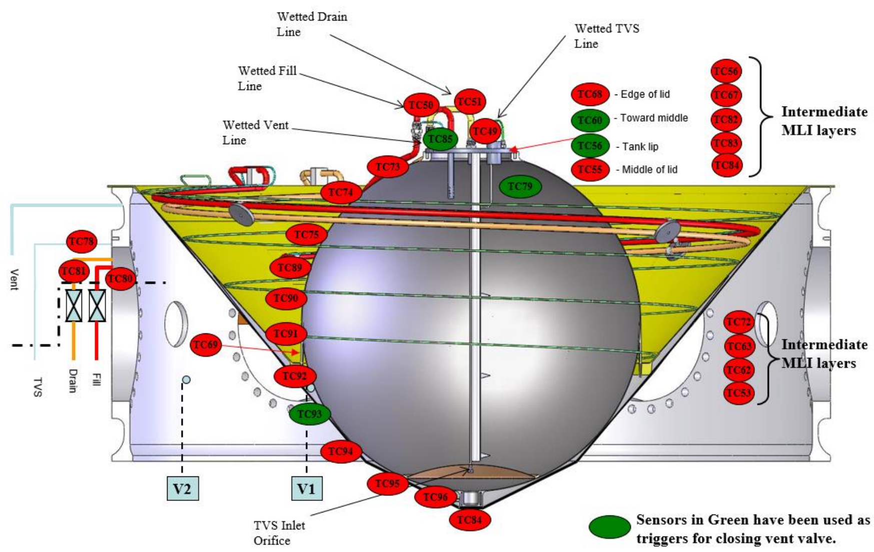


Figure 2: CRYOTE Thermocouple Locations. Note the main tank TVS system was removed for these tests.

3.2 The TVS Augmented Top Spray Injector

There are five components of the new aluminum TVS augmented injector: (1) 4 mm inner diameter (ID) main injection line, (2) 4 mm ID TVS line, (3) Joule-Thomson (JT) orifice, (4) outer metallic matrix, and (5) top spray injector into the tank. Figures 3a and b depict the as-built TVS augmented injector and flow path, respectively. Figure 4 shows the interfaces and instrumentation. The concept of operation is as follows: VATA and CRYOTE are connected via a single transfer line. The flow that enters the CRYOTE tank is then split into two legs, the main injector and the TVS. The liquid flow through the main injector follows the numbers 1-10 in Figure 3b as it winds down and around inside the metal matrix to maximize surface area contact with the TVS gas. Eventually, the flow enters the tank through a top spray nozzle configuration and into the CRYOTE receiver tank. Meanwhile, the split-off portion of flow to the TVS leg is routed to a JT orifice where the flow immediately flashes from liquid into vapor (or two-phase flow depending on the pressure) because the downstream pressure is maintained at vacuum level (~ 1 kPa). The gas continually cools as it expands to the vacuum pressure. The flow path of the gas inside the injector is tortuous; it is routed down along the edges of the metal matrix, and then inward where it flows along the main injection line. Then the flow is routed around the upper outer portion of the metal matrix, and then eventually to vacuum as shown in Figure 3b. The TVS flow path is designed in a way to maximize cooling of the outer metal matrix as well the main injection line. Note that flow through the TVS leg is controlled by a valve and thus can be turned on, off, or cycled on/off during chill and fill to determine operational limits.

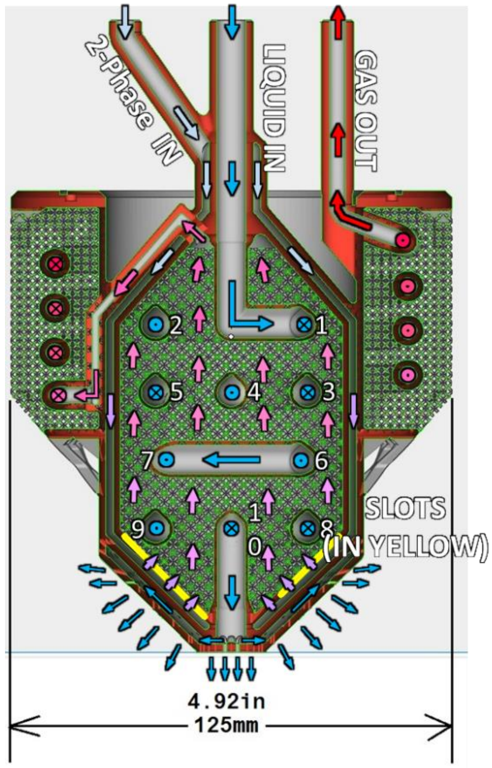


Figure 3: TVS Augmented Injector a) As-Built Device and b) Flow Paths

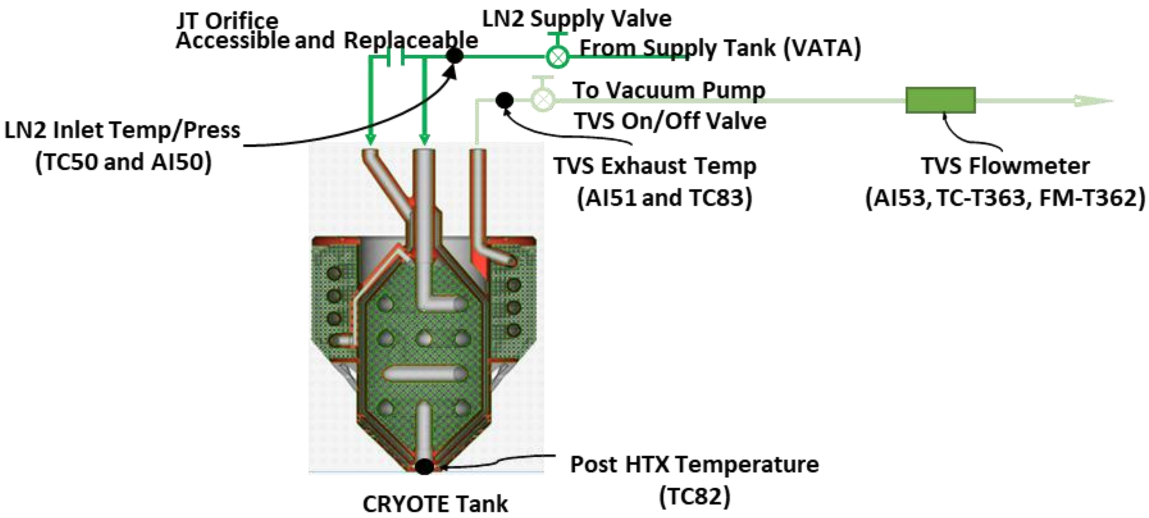


Figure 4: TVS Augmented Injector Interfaces and Instrumentation

The top spray injector portion of the TVS augmented injector consists of numerous holes that, on average, sit about 10 cm from the top of the tank; 80 holes of radius 0.35 mm sit on the vertical cylindrical section of the injector, 215 holes of radius 0.35 mm sit on the conical surface of the injector, and 19 holes of radius 0.25 mm sit on the bottom tip of the injector. Equation 1 can be used to determine the overall coefficient of discharge for a given flow rate, liquid density, and pressure drop across the injector:

$$C_D = \frac{\dot{m}}{A\sqrt{2\rho\Delta P}} \quad (1)$$

Overall, the average single-phase coefficient of discharge for this injector was experimentally determined to be approximately 0.119 across all tests, with little variation test to test.

3.3 Instrumentation

Tables 1-3 outline the instrumentation lists of thermocouples, pressure transducers, load cells, and volumetric flow meters used for VATA, CRYOTE, and the TVS augmented injector, respectively. Figures 2 and 4 illustrate sensor locations for CRYOTE and the TVS augmented injector, respectively. Many of these sensors were in place for the tests outlined in Hartwig et al. (2021). Of particular interest in the current work are thermocouples TC50 and TC83, the wetted fill and vent thermocouples, respectively, which could be used to directly measure the temperature of the incoming and vented fluid of the TVS. For example, with TC85 it can be determined whether or not the vent valve was open, because TC85 would drop sharply if fluid were routed through the vent path. Strain gauge type load cells were used on both CRYOTE and VATA to determine the amount of mass inside the tank as a function of time. D-PT-V616 and PT-T364/AI52 provided the pressures in the VATA tank and in the CRYOTE tanks, respectively. All sensors in raw English units were converted to SI units in the results and discussion section subsequently.

VATA Sensors		
Thermocouple Location Description	**DAQ ID**	**Units**
Tank Surface Bottom	SD008	K
VATA Load Cells	**DAQ ID**	
Load Cell 1	SG001	lbm
Load Cell 2	SG002	lbm
Load Cell 3	SG003	lbm
VATA Pressure Transducers	**DAQ ID**	
VATA Ullage Pressure	D-PT-V616	psia

Table 1: VATA Sensor Names and Locations

CRYOTE Sensors					
Thermocouple Location Description	**DAQ ID**	**Units**	**Thermocouple Location Description**	**DAQ ID**	**Units**
Wetted thru TVS tee at Lid ~ 39.5% fill level	TC49	K	Transfer line TC, 47" from TC 86 (right before Valve Z)	TC87	K
Wetted Fill at Lid	TC50	K	Transfer line TC, 16" from TC 87 (right before tee with CRYOTE drain line)	TC88	K
On skirt inside turn 1 from tank	TC52	K	71.9% fill level, external to tank	TC89	K
On skirt inside turn 4 from tank	TC54	K	57.5% fill level, external to tank	TC90	K
Close to center of lid	TC55	K	42.5% fill level, external to tank	TC91	K
CRYOTE tank lip (at lid but on main tank body)	TC56	K	28.1% fill level, external to tank	TC92	K
On skirt inside turn 2 from tank	TC57	K	15.5% fill level, external to tank	TC93	K
On skirt inside turn 5 from tank	TC58	K	6.0% fill level, external to tank	TC94	K
Tank Lid, half way between edge and center of lid	TC60	K	0.7% fill level, external to tank	TC95	K
TVS turn 5 from tank	TC61	K	0.0% fill level, external to tank	TC96	K
on skirt inside turn 3 from tank	TC64	K			
TVS turn 3 from tank	TC65	K			
TVS turn 4 from tank	TC66	K	**CRYOTE Load Cells**	**DAQ ID**	
Edge of Tank Lid, thicker part	TC68	K	Load Cell 4	SG004	lbm
TVS turn 2 from tank	TC70	K	Load Cell 5	SG005	lbm
99.3% Fill level, external to tank	TC73	K	Load Cell 6	SG006	lbm
94.0% fill level, external to tank	TC74	K			
84.4% fill level, external to tank	TC75	K	**Pressure Transducers**	**DAQ ID**	
CRYOTE Wetted 95% fill level	TC79	K	Inlet Pressure to Injector	AI50	psia
tank fill line at ESPA ring	TC80	K	TVS Vent Pressure	AI51	psia
CRYOTE Spray Temperature	TC82	K	CRYOTE2 Ullage Tap Pressure	AI52	psia
TVS Post-Injector Temperature	TC83	K	TVS Flowmeter Pressure	AI53	psia
Tank sump at base of cup (Very bottom of tank)	TC84	K			
CRYOTE Vent (wet) Temperature	TC85	K	**Flow Meters**	**DAQ ID**	
Transfer line TC, 60" from VATA TC36	TC86	K	TVS Volumetric Flow Meter	FM-T362	ft^3/min

Table 2: CRYOTE Sensor Names and Locations

Details of uncertainty in the raw measurements are as follows: all thermocouples had an error of +/- 2 degrees K. Pressure transducers had a +/- 0.5% BFSL (Best Fit Straight Line) margin of error. Load cells and volumetric flow meters had an uncertainty < 2% full scale. For all tests, measurements were taken every second from test start to test end, and ultimately stored in Excel files.

TVS Specific Sensors		
DAQ ID	**Sensor Name**	**Units**
AI50	Injector Pressure	psia
AI51	TVS Vent Pressure	psia
AI52	CRYOTE2 Ullage Tap Pressure	psia
AI53	TVS Flowmeter Pressure	psia
TC50	Pre-injector Temperature	K
TC82	CRYOTE Spray Temperature	K
TC83	TVS Post-Injector Temperature	K
TC-T363	TVS Flowmeter Temperature	K
PT-T364	CRYOTE Ullage Pressure	psia

Table 3: TVS Augmented Injector Sensor List

4.0 Experimental Methodology, Test Matrix, and Computed Parameters

Tests were generally conducted in the following manner: First, CRYOTE was pre-conditioned to the desired initial condition, typically just ambient pressure and temperature. Second, the liquid in the storage tank VATA was conditioned to the desired temperature, and then filled with pressurant gas to the desired total pressure, typically 380 kPa (55 psia). Since the receiver tank injector was the limiting orifice in the flow path, setting the supply tank pressure sets the maximum allowable flow rate. Once the liquid was properly conditioned, the VATA outlet valve was opened to chill down the transfer line connecting VATA and CRYOTE. Next, liquid would flow directly into CRYOTE 2 to chill down the receiver tank. As detailed below, the tank was chilled down in three different ways: (1) classical CHV, (2) vented chilldown, or (3) non-vented chilldown. Once chilldown was complete, as determined by some trigger point, the CRYOTE vent valve was closed and then a NVF was attempted. For (3), a trigger point was still used to determine when to engage the TVS. A successful fill is indicated by achieving a fill level of >90% at a pressure well below the MAWP. At any point during the test, if it was desired to engage the TVS, then the valve to vacuum was first open to evacuate the line and allow flow through the TVS line.

Table 4 outlines the test matrix. Eight tests were conducted in April, 2018. The first was a check-out test to ensure the system was functioning properly and that all of the sensors were responding. Tests 2 and 3 consisted of normal vented chill/NVF, as was the case in the original CRYOTE 2 tests, transferring fluid with the vent valve open until some trigger point, and then the vent valve was closed and the NVF continued. Tests 4 through 7 were the most crucial of all of these, because no-vent transfers (NVTs) were attempted with the main CRYOTE vent valve closed during the majority of chilldown and fill. For these tests, the TVS was turned on before the main fill initiated, or cycled on/off. Subtle differences in Tests 4-7 were evident as shown in Table 5. Finally, Test 8 was a classical CHV with two cycles, followed by a NVF in order to compare the chilldown time and mass of this classic base method versus the other two chill and fill methods.

TVS Augmented Injector Test Procedures

Test	Date	Configuration	VATA feed Pressure	Procedure
Number	Test Name	-	psia	-
1	20180329	TVS Augmented Injector	-	A check out test
2	20180401	TVS Augmented Injector	55	TVS off, normal chill into fill
3	20180402	TVS Augmented Injector	55	TVS off, normal chill into fill. Fill always on, vent starts closed and is opened from 653-841s.
4	20180403	TVS Augmented Injector	55	TVS on (92-2320s), NVT
5	20180404	TVS Augmented Injector	55	TVS on (915-1872s), NVT
6	20180405	TVS Augmented Injector	55	TVS on (121-1070s &1804-1885s), NVT. TVS turned off after 1st recovery, fill fails, then another attempt is made.
7	20180406	TVS Augmented Injector	55	TVS on (722-915s), NVT
8	20180408	TVS Augmented Injector	55	CHV (1089,1170,1590s & 1971,2040,2544s) with TVS off

Table 4: Summary Table of TVS Augmented Injector Test Procedures

Important Times in TVS-Utilized Tests							
Test	**Date**	**Procedure**	**Fill Start Time**	**Initial Fail Time**	**Fill Recovery Time**	**ccess/Failur**	**Did the Final Fill Attempt Succeed?**
Number	**Test Name**	-	Seconds from start	Seconds from start	Seconds from start	conds from s	Yes/No
4	20180403	TVS on (92-2320s), NVT	803	883	1300	2700	Yes
5	20180404	TVS on (915-1872s), NVT	1237	1331	1800	3268	Yes
6	20180405	TVS on (121-1070s &1804-1885s), NVT. TVS turned off after 1st recovery, fill fails, then another attempt is made.	666	747	1100, 1700	1279, 3038	Yes
7	20180406	TVS on (722-915s), NVT	829	918	1300	1375	No

Table 5: Summary of Important Times during the TVS-Utilized Tests

Table 6 shows a summary of test conditions and important features leading up to the start of a NVF, depending on the initial conditions. To be precise, the TVS-on tests were actually NVTOs, because Table 6 shows that for Tests 4-7, there was a small amount of liquid in the tank (< 1% of tank volume) at the start of vent valve closure. Nonetheless, the mass averaged tank wall temperature was 260-290K for the attempted NVFs with the TVS engaged.

TVS Augmented Injector NVF/NVTO Test Results													
Test	**Date**	**Test Begin Time**	**NVF Start Time/Vent Close Time**	**NVF End Time**	**NVF Duration**	**Average Injector Inlet Pressure during NVF**	**Average Injector Inlet Temp during NVF**	**Average Inlet Pressure during NVF**	**Average Inlet Temp during NVF**	**Initial Inlet Temp at NVF Start**	**Receiver Tank Pressure at NVF Start**	**Receiver Tank Ullage Temp at NVF Start**	**Receiver Tank Liquid Temp at NVF Start**
Number	**Test Name**	Seconds from start	Seconds from start	Seconds from start	seconds	kPa	K	K	K	K	kPa	K	K
1	20180329	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2	20180401	698	920	2035	1115	269.32	85.35	269.319	85.17	86.36	209.48	107.75	84.09
3	20180402	490	841	1943	1102	266.15	85.35	266.146	85.06	85.83	210.09	110.04	84.12
4	20180403	803	863	2700	1837	297.24	90.01	297.24	92.87	93.22	291.98	265.99	87.61
5	20180404	1237	1317	3268	1951	319.61	95.37	319.614	99.21	92.72	256.44	178.53	86.20
6	20180405	666	714	3038	2324	323.38	95.86	323.379	101.1	92.09	204.06	273.95	83.83
7	20180406	829	884	1375	491	370.17	110.83	370.171	123.25	92.06	203.01	263.09	83.78
8	20180408	1095	3112	4222	1110	243.73	85.59	243.729	85.23	86.21	88.59	82.21	76.23
Test	**Date**	**Receiver Tank LL at NVF Start**	**Receiver Tank Mass Vapor at NVF Start**	**Receiver Tank Mass Liquid at NVF Start**	**Receiver Tank Mass Avg Tank Temp at NVF Start**	**Receiver Tank Temperature at NVF End**	**Receiver Tank Pressure at NVF End**	**TVS Energy Removed since Vent Closed**	**Mass Used in TVS at NVF End**	**Receiver Tank LL at NVF End**	**Mass of Fluid in Receiver Tank at 90% Fill**	**Mass Used in TVS at 90% Fill**	**Mass of Fluid in Receiver Tank at NVF End**
Number	**Test Name**	% Fill	kg	kg	K	K	kPa	kJ	kg	% Fill	kg	kg	kg
1	20180329	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
2	20180401	7.96	1.30	13.25	141.63	95.62	373.67	0	0.00	93.43	150.15	0.00	155.80
3	20180402	7.56	1.28	12.59	147.03	95.67	375.51	0	0.00	93.97	150.18	0.00	156.76
4	20180403	0.76	0.79	1.27	287.10	93.29	380.36	-	1.4*	91.08	150.38	1.40	152.15
5	20180404	1.24	1.03	2.07	259.93	96.60	373.05	28.29	0.24	91.00	149.97	0.24	151.62
6	20180405	0.75	0.54	1.25	291.71	95.19	372.61	25.66	0.20	90.25	150.18	0.20	150.54
7	20180406	1.56	0.55	2.55	289.10	194.48	340.94	1.06	0.02	2.42	5.17	Failed	5.17
8	20180408	3.01	0.76	5.01	119.03	92.72	374.31	0	0.00	96.94	150.00	0.00	161.46

Table 6: Initial, Boundary, and Final Conditions. An asterisk implies the quantity is estimated.

Table 6 is included to allow the external community the ability to model these tests via the initial and boundary conditions. Unfortunately for this analysis, two-phase flow always existed during the initial stages of the transfer process, due to transfer line chill down. This means that for most of the chilldown process, the inlet state of the flow into CRYOTE is indeterminable with the sensors utilized in the experiment. Nonetheless, direct comparison with modeling is achievable from the times denoted in Table 6, for the NVF portion of transfer. Unfortunately, there was a lack of critical instrumentation, such as a liquid flow meter in the transfer line, gas flow meter of pressurant into VATA, and gas flow meter on the CRYOTE vent line that did not permit a direct comparison of total LN_2 consumed to chill and fill CRYOTE. This data would have been highly beneficial to be able to assess the efficiency of the three transfer methods against one another. What can be compared between transfer methods is final achievable liquid level, which is a qualitative metric of performance. Nonetheless, the primary goal of the test series was to assess the feasibility of the TVS on transfer operation, and to that end, there is sufficient instrumentation available.

Many of the parameters in Table 6 and throughout are self-explanatory, but some parameters were computed or require further explanation as follows:

1. All calculated fluid properties like fluid density come from the REFPROP equation of state (Lemmon et al. 2010).
2. Data acquisition is initialized at time = 0.
3. "Test Begin Time" is the time at which the liquid withdrawal valve on VATA was opened.
4. "NVF Start Time/Vent Close Time" is the time when the vent valve on CRYOTE-2 was closed to initiate NVF.
5. "NVF End Time" is the end of the test.
6. "Average Injector Inlet Pressure during NVF" is specified by AI50.
7. "Average Injector Inlet Temp during NVF" is specified by TC50.
8. "Average Inlet Pressure during NVF" is specified by AI50, assuming that the flow losses through the main flow line in the injector are minimal.
9. "Average Inlet Temp during NVF" is specified by the average of TC82 over NVF test duration.
10. "Initial Inlet Temp during NVF" is specified by TC82.
11. The thermodynamic state of the fluid going into the TVS augmented injector is specified by TC50 and AI50.
12. The thermodynamic state of the fluid entering the CRYOTE tank is specified using TC82 and AI50.
13. "Receiver Tank Pressure at NVF Start" is specified by AI52.
14. "Receiver Tank Ullage Temp at NVF Start" is the vapor temperature inside CRYOTE at the start of NVF, and is specified by:
    a. The average value of TC49 and TC79 when this value is greater than the saturation temperature based on the ullage pressure AI52.
    b. Otherwise the saturation temperature based on the ullage pressure AI52 is used.
15. "Receiver Tank Liquid Temp at NVF Start" is the liquid temperature inside CRYOTE at the start of NVF, and is specified by:
    a. TC82 when TC82 is less than the saturation temperature based on ullage pressure AI52.
    b. Otherwise the saturation temperature based on the ullage pressure AI52 is used.
16. The thermodynamic state of the vapor in CRYOTE is specified using "Receiver Tank Pressure at NVF Start" and "Receiver Tank Ullage Temp at NVF Start".
17. The thermodynamic state of the liquid in CRYOTE is specified using "Receiver Tank Pressure at NVF Start" and "Receiver Tank Liquid Temp at NVF Start".
18. The thermodynamic state of the fluid at the outlet of the TVS line but upstream of the vacuum vent valve is specified using TC83 and AI51.

19. The thermodynamic state of the fluid downstream of the vacuum vent valve is specified by TC-T363 and AI53.
20. Receiver Tank liquid level in the tank was calculated by dividing the volume of the liquid in the tank by the total tank volume at any point in time, ignoring the small volume change as the tank contracts with colder temperature, after some algebraic manipulation:

21. $$Liquid\ Level = \frac{V_{liquid}}{V_{tank}} = \frac{m_{liquid}}{\rho_{liquid} V_{tank}} = \frac{\left(m_{LC} - m_{CRYOTE}\right) - \rho_{ullage} V_{tank}}{\rho_{liquid} V_{tank} - \rho_{ullage} V_{tank}} \qquad (3)$$

22. "Receiver Tank Mass Vapor at NVF Start" and "Receiver Tank Mass Liquid at NVF Start" are calculated using conservation of mass and a volume constraint:

$$m_{LC} - m_{CRYOTE} = m_{liquid} + m_{vapor} \qquad (4)$$

$$V_{tank} = V_{liquid} + V_{vapor} \qquad (5)$$

where m_{CRYOTE} is the mass of the empty receiver tank. Substituting the known liquid and vapor densities using REFPROP, Equation 5 becomes:

$$V_{tank} = \frac{m_{liquid}}{\rho_{liquid}} + \frac{m_{vapor}}{\rho_{vapor}} \qquad (6)$$

Using the known liquid level:

$$m_{liquid} = \rho_{liquid} V_{tank} LL \qquad (7)$$

$$m_{gas} = \rho_{ullage} V_{tank} \left(1 - LL\right) \qquad (8)$$

23. "Receiver Tank Mass Averaged Tank Temp at NVF Start" was calculated by taking a mass average of the lid and tank walls.
24. The TVS mass flow rate was then simply the gas density specified by TC-T363 and AI53 times the measured volumetric flow rate.
25. "TVS Energy Removed since Vent Closed" is the computed total energy that the TVS removes from the injector (metal matrix plus the main injection line). This is determined by calculating the change in specific enthalpy of the fluid at the inlet and exit of the TVS augmented injector. Assuming isenthalpic flow across the JT orifice (Hendricks 1972), the specific enthalpy downstream of the orifice is approximately the same as the specific enthalpy upstream such that the enthalpy h_1, can be computed using TC50, AI50, and REFPROP. Meanwhile the downstream enthalpy h_2 is computed from TC83, AI51, and REFPROP. Multiplying the change in specific enthalpy by mass flow rate and integrating over total test time yields the overall energy removed from the TVS augmented injector:

$$E_{TVS} = \int_{t1}^{t2} (h_{downstream,measured} - h_{upstream}) \dot{m}\, dt \qquad (2)$$

26. "Mass used in TVS at NVF End" is the total integrated mass that passed through the volumetric flow meter (FM-T362) times the local density specified by the thermodynamic state of the fluid at the outlet of the TVS line.

5.0 Experimental Results and Discussion

5.1 Test 8, Classic Charge Hold Vent/No Vent Fill

Beginning with Test 8 (TVS turned off), 20180408, Figures 5a and b plot pressures and fill level as a function of time from the start of chilldown, respectively while Figure 6 plots CRYOTE wall temperatures at different heights, along with ullage temperature, inlet liquid temperature, saturation temperature based on tank pressure, etc. As shown, two full CHV cycles around 1000 and 2000 seconds were performed to prechill the receiver tank. The tank is vented down to vacuum pressure to remove vapor from the tank. A NVF is performed at 3112 seconds. Figure 5a shows that liquid injection during charging was terminated when the VATA and CRYOTE pressures nearly equilibrated; this is followed by a dramatic reduction in tank wall temperature as the fluid boils and then exchanges heat via boiling and then natural convection. After sufficient time CRYOTE is vented to partial vacuum, and the process is repeated again. At this point, many of the wall thermocouples are near 150K. During NVF, there is a sharp rise in pressure caused by residual boiling of the fluid in contact with the wall due to the temperature difference between wall (150K) and inlet liquid saturation (~80K). Figure 5a shows that during NVF the fluid is constantly flashing because the saturation pressure based on the inlet temperature is consistently higher than the ullage pressure, and also that the fluid is predominately saturated since the saturation pressure and measured pressure are nearly identical. Even though the inlet fluid temperature is warmer than the saturation temperature based on the ullage pressure, Figure 6 shows that the 99.3% ullage temperature location is considerably warmer than the interface (injector spray cannot reach the upper portions of the tank and lid). This finding indicates/implies a net positive condensation rate from the vapor to the liquid that keeps the ullage pressure down during fill.

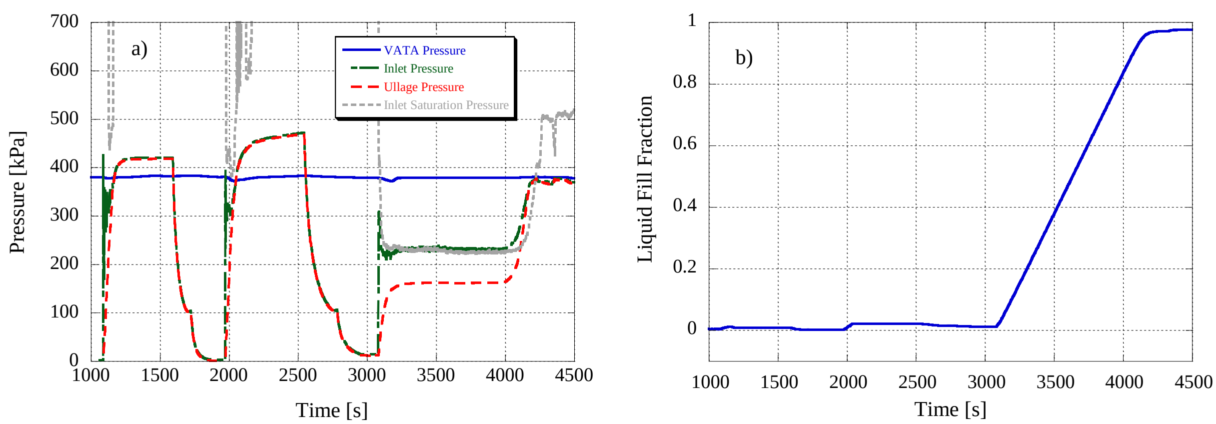


Figure 5: a) Pressure Traces and b) Fill Level versus Time for Test 8, 20180408

Figure 5b shows that once the thermal energy is removed from the walls, the tank fill level varies linearly with time. As the wall temperatures bottom out, the pressure also levels out due to incoming liquid spray condensing the ullage gas. Eventually the pressure rises again due to compressibility of the gas, but by this point the tank is at 96% fill. Note that the CHV/NVF achieves the highest final liquid level of all the three transfer methods tested. This is primarily due to the fact that the tank is vented down to vacuum prior to NVF, allowing more boil-off gas room to expand during the start of the fill. Vented chills begin at ambient pressure, so there is less available delta P margin between receiver tank starting pressure and end pressure. As stated earlier, CHV/NVF is an attractive, albeit most complex in terms of valve cycling, method of chilling down and filling a tank in low-g.

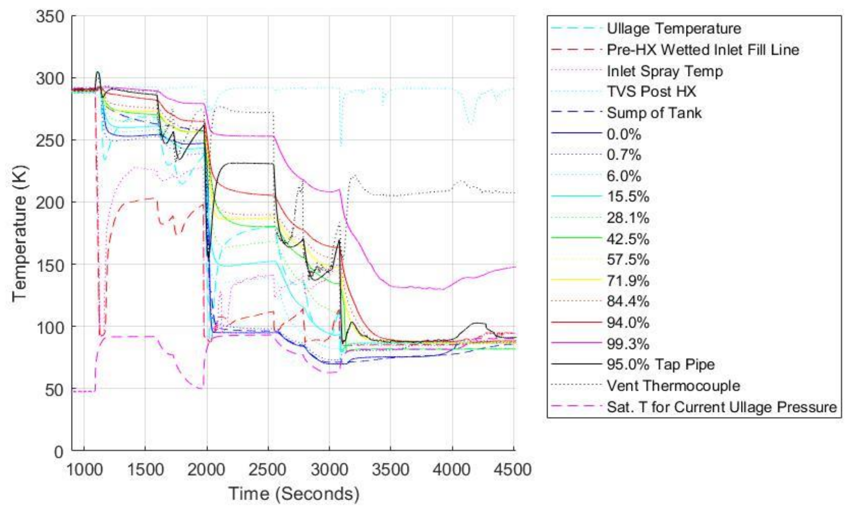


Figure 6: Various Tank Temperatures versus Time for Test 8, 20180408

5.2 Tests 2 and 3 Vented Chill, No-Vent Fill

Figures 7a, 7b, and 8 plot the pressure, fill level, and tank wall temperatures for Test 2, 20180401, respectively. Here the CRYOTE receiver tank vent valve is opened during line and tank chilldown, until around 920s. Then the vent valve is closed and a NVF is successfully completed. Mass accumulates at around 800s after most of the boiling heat transfer has taken place. The "target temperature" for this test was 141K, and results show a successful fill above 90%. Only the highest ullage temperature sensor was still warm at the end of fill, due in part to the thick SS tank lid. Contrary to the CHV/NVF test, here, the inlet state is subcooled throughout fill, probably due to the continuous flow nature of the VC/NVF process. However, the inlet saturation pressure is still above the ullage pressure indicating some flashing throughout transfer. It can be concluded here that there is also a net positive condensation rate due to (1) subcooled inlet state, and (2) warm ullage gas temperature relative to the saturation temperature.

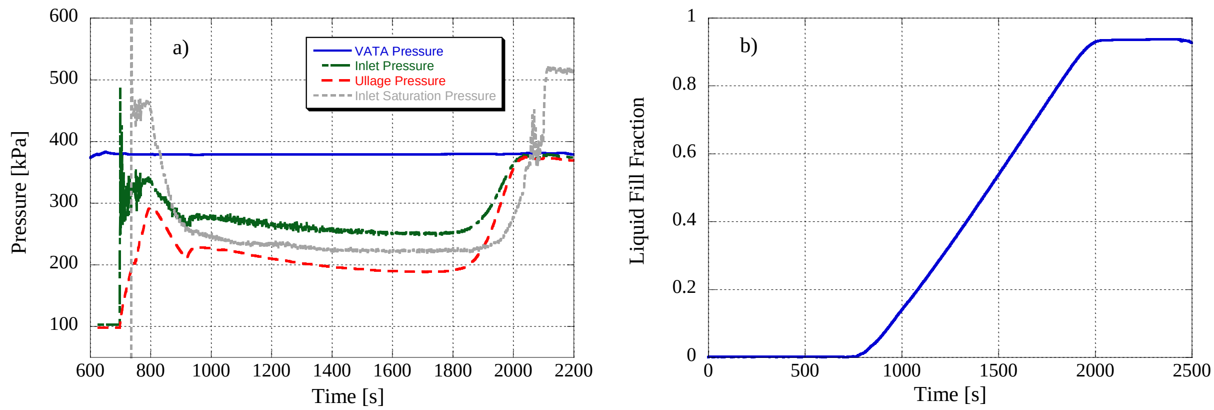


Figure 7: a) Pressure Traces and b) Fill Level versus Time for Test 2, 20180401

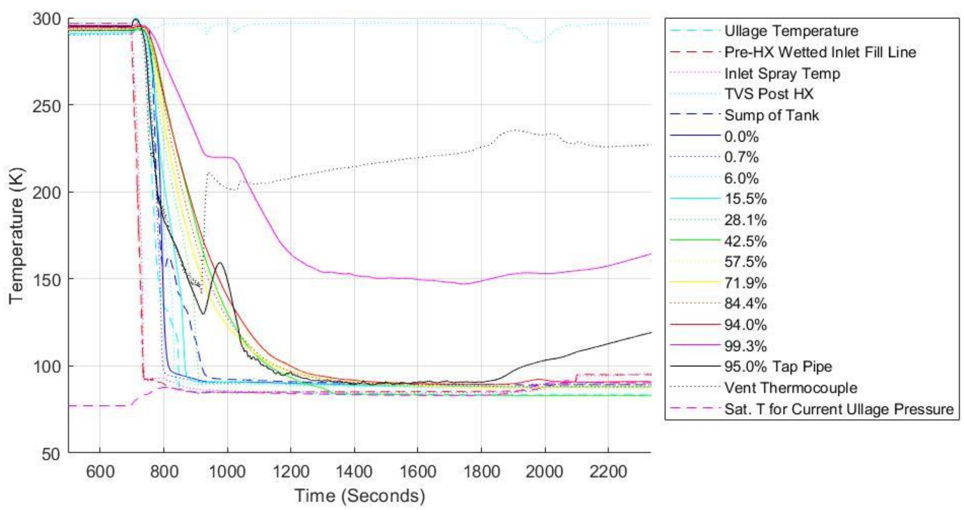


Figure 8: Various Tank Temperatures versus Time for Test 2, 20180401

Similar behavior is shown for Test 3 in Figures 9a, 9b, and 10 for the pressure, fill level, and tank wall temperatures for Test 20180402, respectively. Here, the target temperature to initiate a NVF was 148K, and results again show a successful fill. Figure 9a shows that the transfer stalls when the supply and receiver tank pressures equilibrated, causing a longer total chill and fill duration, but the amount of total LN_2 consumed between Tests 2 and 3 are approximately the same. The VC/NVF experiments achieve the second highest final fill levels of the three methods tested. Vented chill/NVF may not be possible in low-g unless settling was an option.

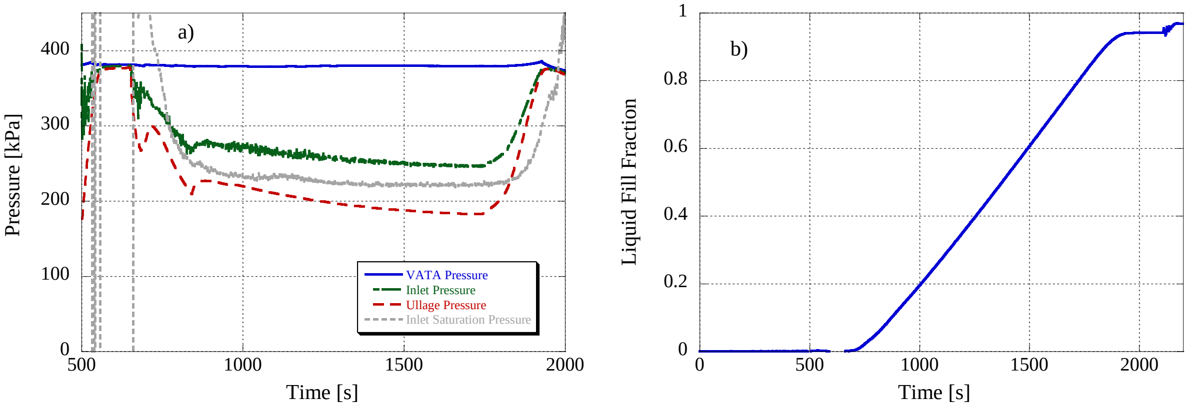


Figure 9: a) Pressure Traces and b) Fill Level versus Time for Test 3, 20180402

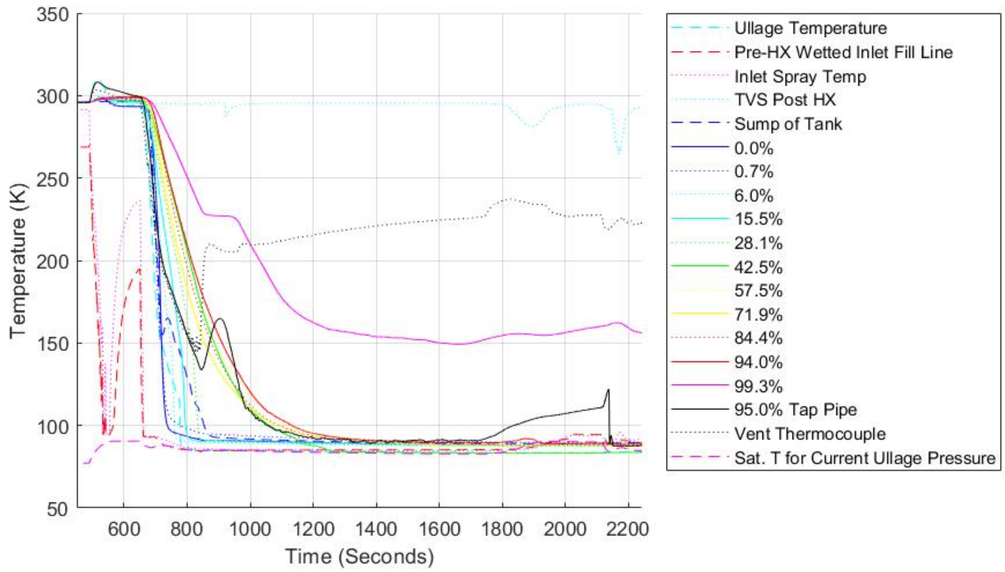


Figure 10: Various Tank Temperatures versus Time for Test 3, 20180402

5.3 Tests 4-7, Attempted No-Vent Transfers

Tests 4-7 were transfers attempted using the TVS. Figures 11a, b and 12 plot the pressure, fill level, and temperatures as a function of time, respectively, for test 20180403. Figure 13 plots relevant TVS and injector performance. A NVT is initiated after single phase liquid is entering the tank, and the TVS is engaged at 92s near the start of flow as indicated in the sharp drop in pressure at the TVS exhaust as well as the location downstream of the vacuum valve (both shown in Figure 4) and by the response in the flow meter. The major aspect to note in Figure 11a is the transfer actually stalls around 900s as the supply and receiver tank pressures equilibrate due to excessive boil-off during tank chilldown. However, the flow through the TVS continues (because there is always a pressure drop and thus flow rate in the TVS line), and at around 1400s, the pressure in CRYOTE drops below the inlet/supply tank pressure, and the flow into the receiver tank resumes, with the pressure continuing to drop from that point forward. The classic “rollover” in pressure is visible around 1400s. Between 750s and 1600 seconds, the injector itself is chilling down as indicated in Figure 13 for the pre-injector temperature and spray temperature (temperature of fluid being injected into tank) chilling down to below 100K. Around 1100s, single phase liquid is injected into the tank. Figure 12 shows most of the tank thermal energy is removed by 1800s as indicated by the wall temperatures bottoming out. At 2300s, the TVS is cycled off, indicated by the sharp rise in pressure in the TVS vent line, and the fill is successful around 2700s.

The fact that the transfer could recover without having to cycle off the supply valve or without having to vent the receiver tank is quite remarkable. The implication is that if the TVS remains on to cool the incoming flow and the injector itself, that the pressure in the receiver tank may eventually fall below the supply pressure and the flow can recommence without any user in the loop operating the supply and receiver tank valves. If the TVS was not being utilized, the warm tank would continue to warm the ullage, and the pressure would continue to rise until the gas temperature reached equilibrium with the tank. Direct evidence of this occurring can be seen in Test 8. Meanwhile, as in the VC/NVF tests, the inlet state during fill stays in a subcooled state, but there is flashing evident due to the low ullage pressure. Once again, the low ullage pressure is direct evidence of a net positive mass condensation rate across the receiver tank liquid/vapor interface; this is corroborated by the warm ullage temperature throughout fill due to reasons cited earlier.

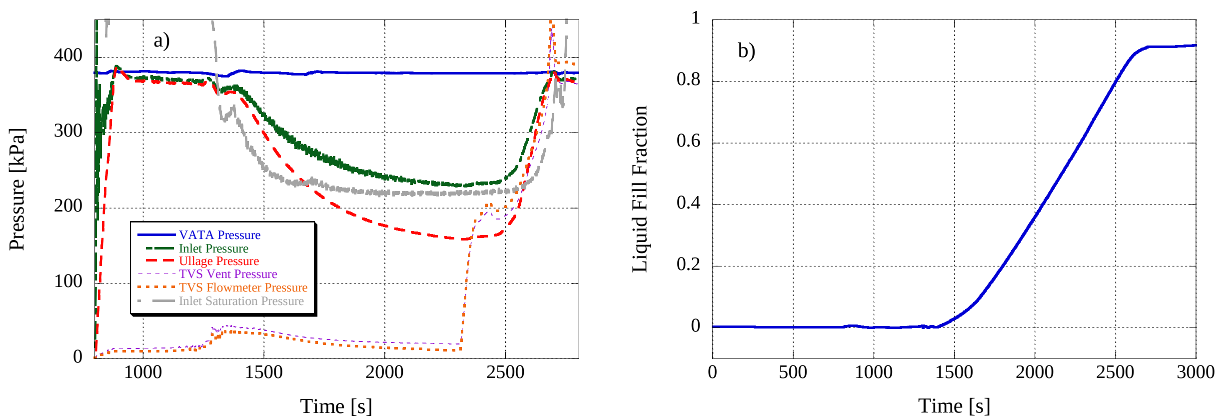


Figure 11: a) Pressure Traces and b) Fill Level versus Time for Test 4, 20180403

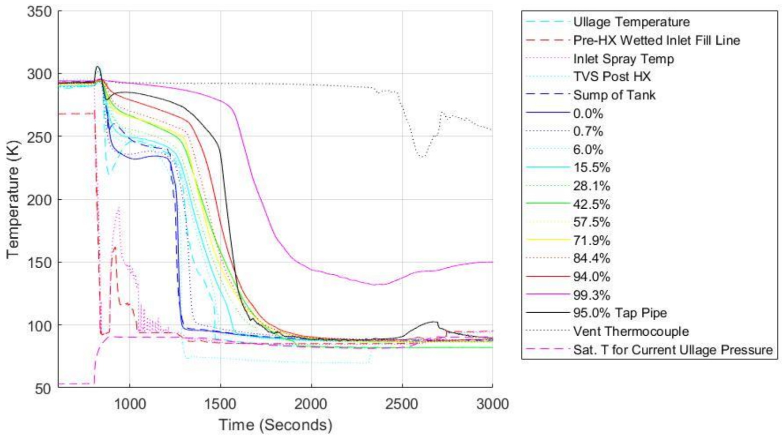


Figure 12: Various Tank Temperatures versus Time for Test 4, 20180403

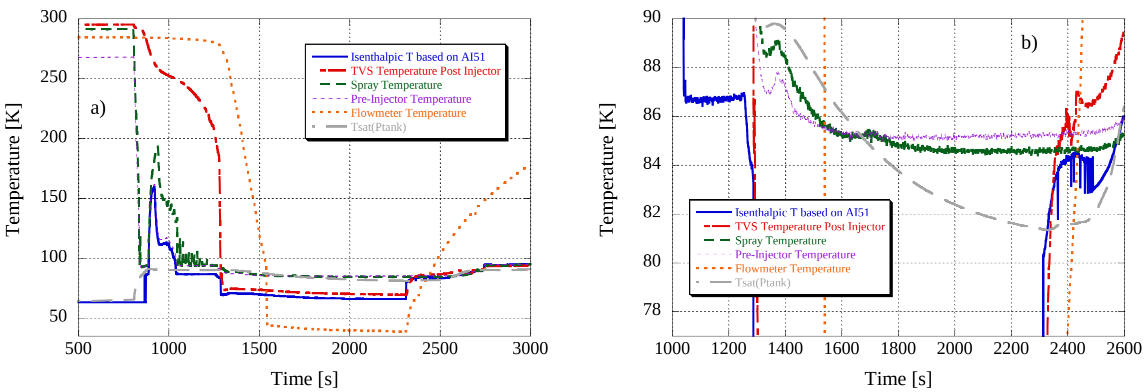


Figure 13: TVS Injector Temperatures versus Time for Test 4, 20180403

Figure 13 shows that once the TVS is engaged, the isenthalpic fluid temperature in the line just before the vacuum valve drops immediately and remains well below the normal boiling point of the fluid, indicating the flashing and expansion across the JT orifice. The difference in temperature pre- and post- injector is evidence of the TVS fluid absorbing heat. Meanwhile, the TVS line temperature downstream of the vacuum valve ("Flowmeter Temperature") starts at ambient as expected. Once the pressure rolls over, both the pre-injector temperature and spray temperature drop rapidly as the injector body and ullage both chill down. Around 1100 seconds, single phase liquid is injected into the tank; around 1300 seconds, the entire TVS injector is chilled down because the TVS post injector temperature bottoms out near 80K. Shortly thereafter, the temperature downstream of the TVS vacuum valve actually drops below all the other temperatures. Based on the measured pressure in the line (~20 kPa) and the measured temperature, there is evidence of two-phase gas/solid flow, because the measured temperature is less than the triple point temperature, yet the measured pressure is higher than the triple point pressure. While there is no flow visualization to confirm this, it is not uncommon in systems with JT orifices for the potential for solid/gas flow to occur. Nonetheless, computed properties like fluid density downstream in the line and mass flow rate were not permissible between 1500-2300s, which makes it impossible to assess TVS energy removed from the injector for Test 4.

Despite all this, Test 4 shows that a NVT is possible at warm initial conditions, that a fill of >90% was achievable, and that the TVS could remove enough thermal energy to prevent venting through the main CRYOTE vent valve.

Another important finding is as follows: In general, it was originally believed that the TVS augmented injector was designed to subcool the liquid being injected into the tank, because the expanded TVS gas and the main injector liquid line have sufficient contact inside the injector. Examination of Figures 4 and 13b show otherwise. The data for Pre-Injector Temperature (before the split in flow between TVS line and main injection line) and the Spray Temperature track nearly identically throughout the whole time that the TVS is engaged. In fact, for most of the time, the spray temperature of liquid going into the receiver tank is actually *warmer* than the upstream temperature before the split-off in the flow; only at 1775s does the spray temperature drop below the inlet temperature indicating heat transfer between the TVS and main injection line. But this cooling is only ~1K, and it occurs late in the transfer. Furthermore, both the inlet temperature and spray temperatures are not cooler than the saturation temperature based on the ullage pressure until after the TVS has removed sufficient energy from the ullage, decreasing the temperature and thus pressure in the ullage as shown by the crossover in Figure 13b around 1750s.

The explanation for the transfer recovering is due to the consistent TVS flow through the metal matrix injector (due to the constant available pressure drop due to the vacuum). Comparing Pre- and Post-TVS injector temperatures clearly show a temperature gradient from the TVS inlet to TVS exit line. In other words, the TVS is actually pulling energy out of the injector metal matrix rather than the incoming liquid spray. Cooling of the metal matrix itself explains why the stalled flow is able to restart just by simply engaging the TVS for sufficient time. The TVS gas removes energy from the metal, which then acts as a “cold finger” for the surrounding warm ullage gas, allowing the local gas to condense, collapsing the pressure, thus allowing flow to restart without ever having to vent through the main receiver tank vent line. Comparing Figures 8, 10, and 12 corroborate this finding because the ullage temperatures are slightly colder for Test 4 where the TVS was engaged versus Tests 2 and 3 where it was not engaged.

Test 5 (20180404) results are plotted in Figures 14 – 16. Table 5 shows that the TVS was turned on at 915s, approximately 5 minutes after the start of NVT. The TVS was then turned off around 1900s. Figure 14a shows that the flow stalls around 1200s and remains stalled until 1800s. Shortly after, the tank pressure drops as near-single phase liquid is injected between 1800-2600s followed by single phase liquid injection from 2600s-3200s. Tank chilldown ends around 2300s shown in Figure 15 except for the upper most ullage temperatures. Figure 14b shows the tank fills linearly in time and a successful NVF occurs at 3268s and a liquid level of 91% with the TVS engaged for half the time as in Test 4.

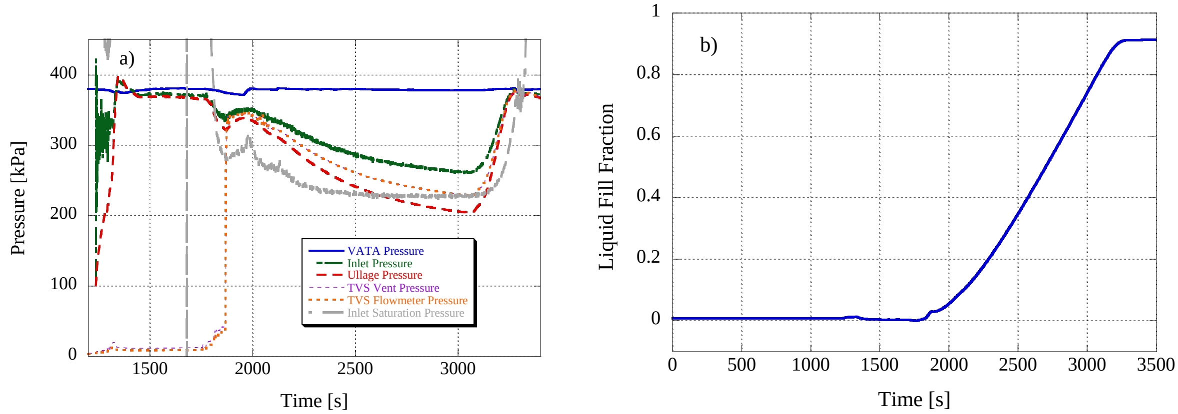


Figure 14: a) Pressure Traces and b) Fill Level versus Time for Test 5, 20180404

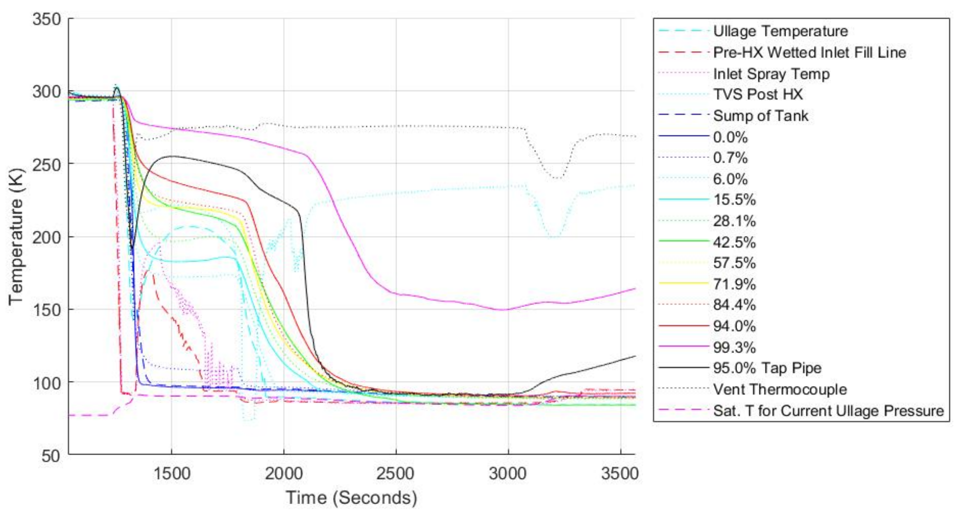


Figure 15: Various Tank Temperatures versus Time for Test 5, 20180404

Figure 16 is a 6-part plot that outlines the TVS performance for Test 5. Within minutes of engaging flow through the TVS line, both the pre-injector temperature and spray temperatures drop down to saturation conditions. Unlike in Test 4 when the temperature downstream of the injector stayed cold long enough to allow the flowmeter temperature to drop below the triple point, in Test 5 the TVS is turned off around 1900s when the tank walls are chilled down, the spray temperature is at saturation again, only ~100s after the flow recovered from the stall. Figure 16c plots the computed density up and downstream of the vacuum valve and shows that the density tracks inversely with the temperatures in Figure 16a. Figure 16d plots the mass flow rate and shows how the flow increases as the TVS line quickly chills down toward the triple line. It is speculated that if the TVS were allowed to run continuously, the line would chill down further, density would increase, and the flow may become two phase again. Cumulative mass consumed by the TVS and the cumulative energy removed from the injector plus main injection stream are plotted in Figures 16e and f, respectively. As shown, 30kJ of energy are removed at the cost of only 0.25 kg of fluid. Test 5 proves that another warm initial temperature NVF was possible with the TVS engaged for less than half the time of Test 4. While not shown in a zoomed-in plot, there is no noticeable cooling of the fluid in the main injection line (~1 K), which only occurs after 1800s.

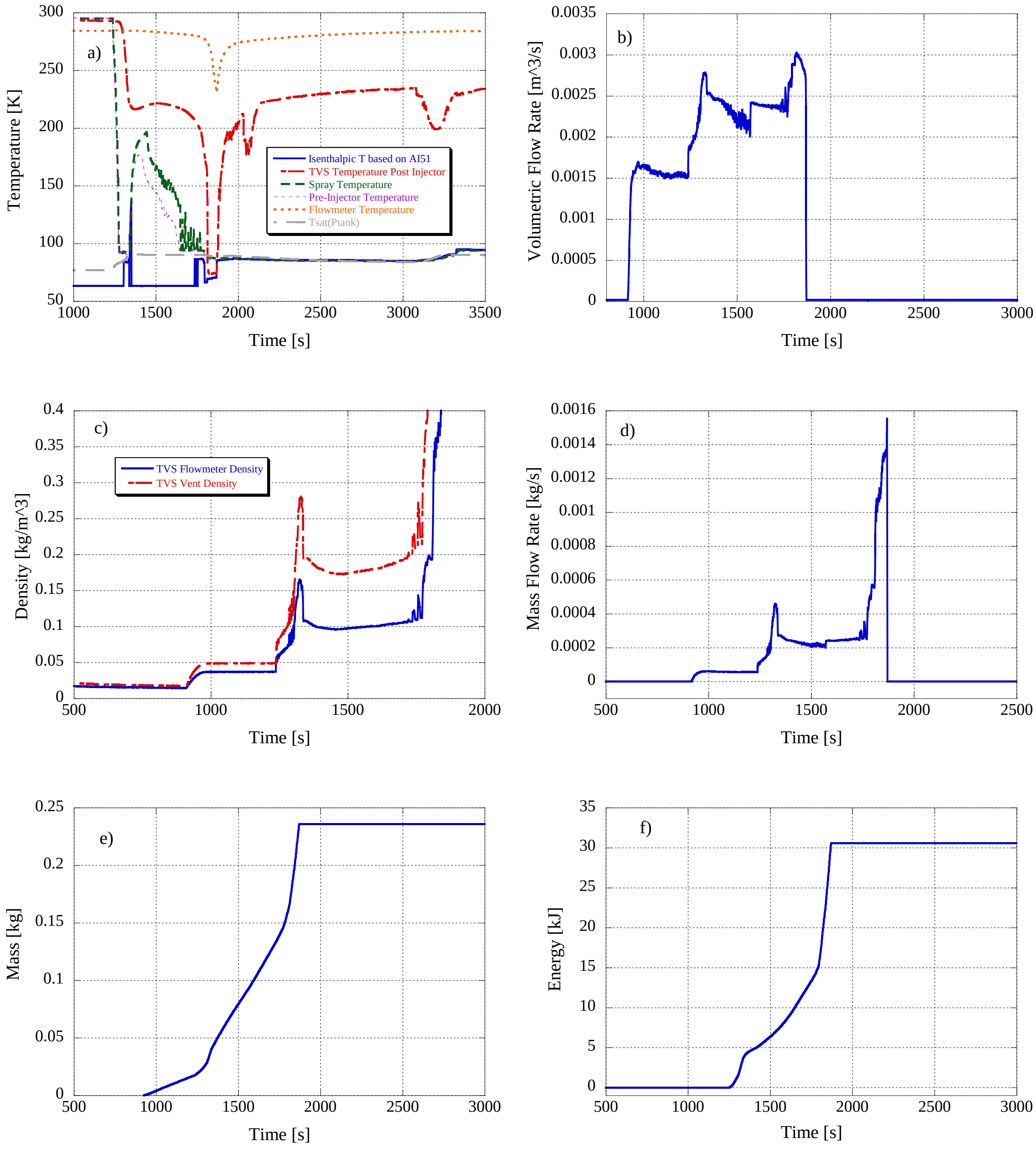


Figure 16: TVS Injector a) Temperatures, b) Volumetric Flow Rate, c) Fluid Density, d) Mass Flow Rate, e) Cumulative Mass Usage, and f) Cumulative Energy Absorbed versus Time for Test 5, 20180404

Figures 17 and 18a-e plot the CRYOTE temperatures, pressures, TVS temperatures, volumetric flow rate, cumulative mass consumed, and cumulative energy absorbed, respectively for Test 6. In this test, the TVS was engaged at 121s and turned off at 1070s in an attempt to save even more mass than Tests 4 and 5. However results in Figures 17 and 18a and b show that the flow stalls twice, once at ~800s and once more at 1200s. Therefore, the TVS had to be turned back on to recommence the stopped flow. The TVS is cycled back on at 1804s, delta P decreases, CRYOTE tank wall temperatures plummet, chilldown ends, and ullage pressure resumes the classic decay between 1800-2800s. The pressure rises as the ullage compresses at 3100s, but by that point the fill is successful at >90%. Figure 18b shows the TVS temperature was cycled off because it fell below the triple point for a short time. Unfortunately the TVS was not on long enough to pull enough thermal energy out of the injector and thus ullage. The volumetric flow rate in Figure 18c shows the fluctuations as the TVS is cycled on, off, and potentially experiences two phase flow. Meanwhile, Figures 18d and e show the start/stop total mass consumed and energy absorbed, nearly the same 30 kJ as the previous test.

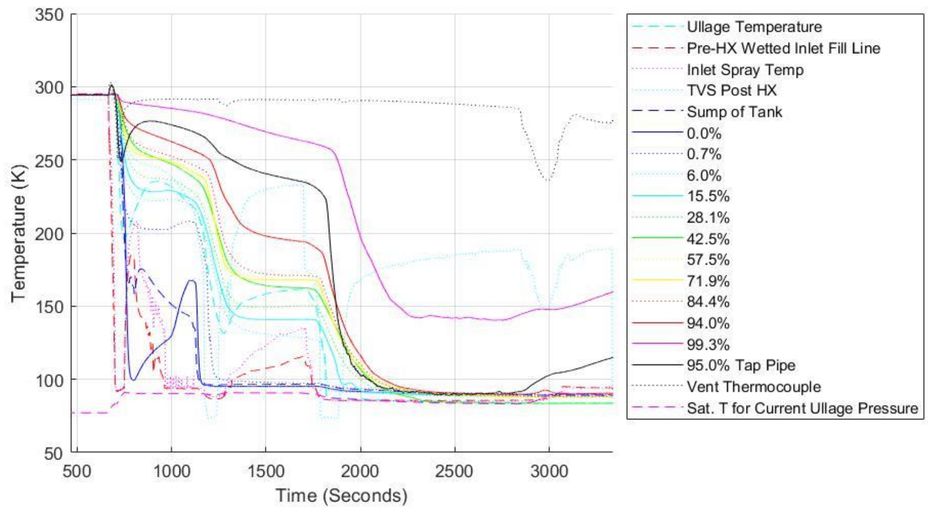
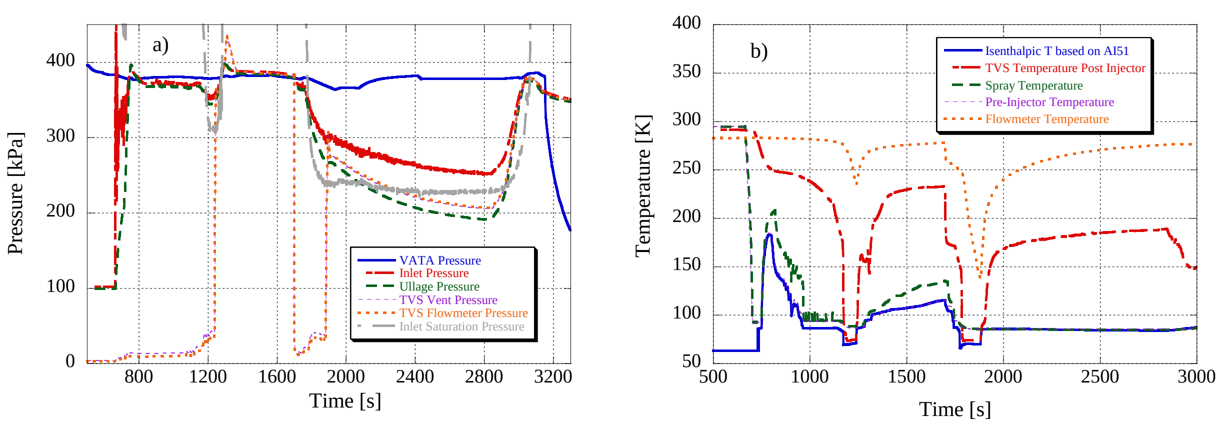


Figure 17: Various Tank Temperatures versus Time for Test 6, 20180405



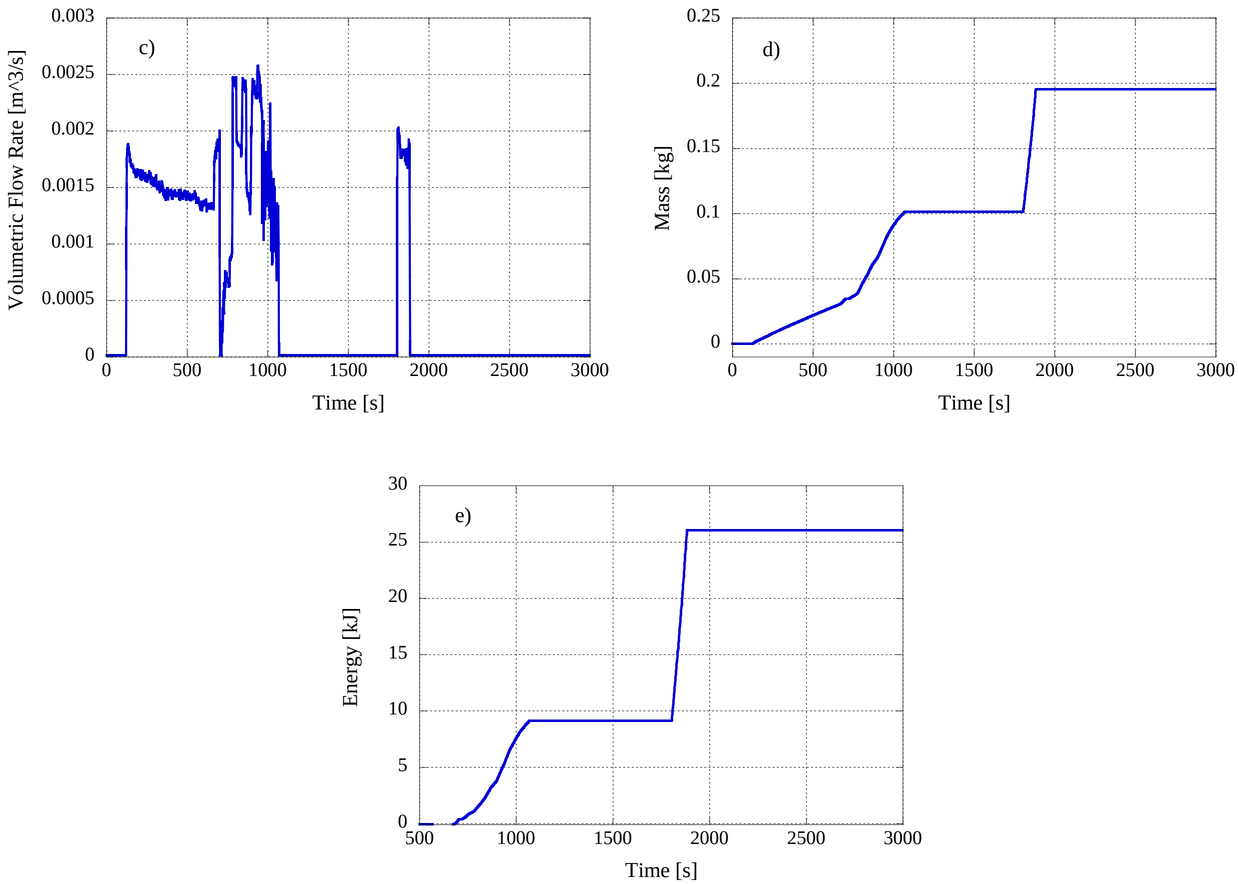


Figure 18: a) Pressure Traces, b) TVS Injector Temperatures, c) Volumetric Flow Rate, d) Cumulative Mass Usage, and e) Cumulative Energy Absorbed versus Time for Test 6, 20180405

Finally, Figures 19 and 20a and b plot CRYOTE wall temperatures, pressure, and TVS temperatures, respectively for Test 7, 20180406. Here the TVS was engaged at 722s and then quickly turned off at 915s in an attempt to transfer with minimal TVS mass usage. The net result however, is that the transfer failed. Examination of Figure 20a shows that the TVS was turned on early with respect to the stalled transfer, and disengaged when the receiver tank pressure began to decay. Figure 20b shows that when the TVS is engaged, both the spray temperature and pre-injector temperatures drop to saturation indicating single phase liquid injection into CRYOTE. Figure 19 shows that while liquid is being injected into the tank at this point, the majority of the thermal energy in the tank walls was not removed. Because of the premature cycling-off of the TVS line, Figure 20b shows an increase in the spray temperature, indicating two phase liquid/gas flow into the tank. Figure 20a shows that the receiver tank pressure never quite recovers and thus the transfer remains stalled.

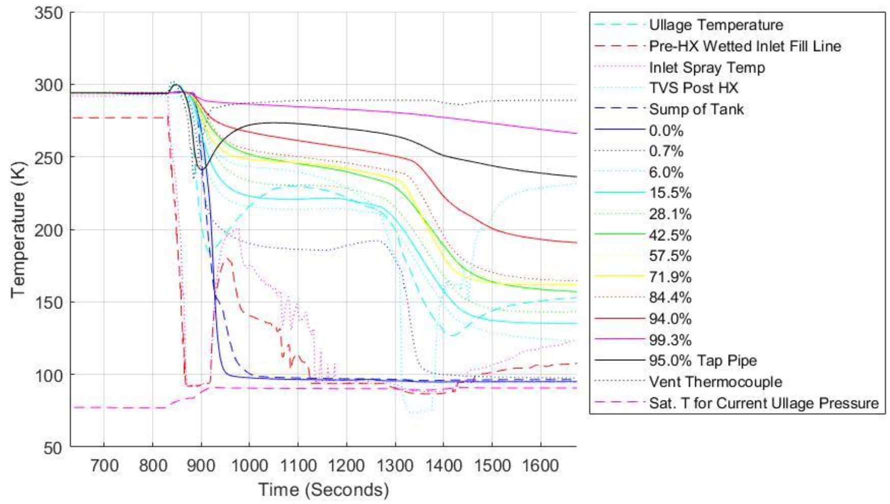


Figure 19: Various Tank Temperatures versus Time for Test 7, 20180406

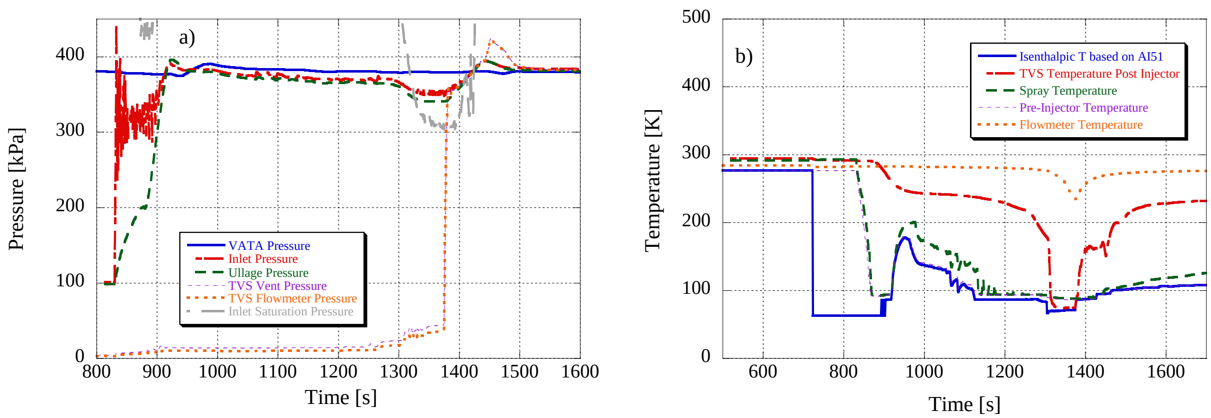


Figure 20: a) Pressure Traces and b) TVS Injector Temperatures versus Time for Test 7, 20180406

6.0 Conclusions

Eight 1-g cryogenic liquid nitrogen transfer tests were conducted on a thin walled titanium tank using a new TVS augmented top spray injector. Three different transfer methods were investigated: a classic charge-hold-vent/no-vent fill, two vented chill/NVF, and four NVFs with the TVS augmented injector. Results show the following trends:

1. For CHV/NVF and VC/NVF, sufficient thermal energy must be removed from the system before closing the main vent valve and initiating a fill, which depends on knowing the system target temperature ahead of time.
2. A non-vented transfer at warm wall temperatures is possible using the TVS augmented injector, as was demonstrated in three of four attempted tests, at the cost of sacrificing a very small amount of propellant.

3. Addition of a TVS augmentation line to a single injector is feasible to both chill down and fill a cryogenic propellant tank without ever having to vent through the receiver tank main vent valve. A TVS augmented injector thus shows promise for simplifying transfer operation and the need to cycle valves or monitor liquid level in the tank.
4. If given enough time and mass, the TVS line can actually restart a stalled flow by opening a new heat transfer path from the cold TVS fluid to the injector metal matrix to allow warm ullage gas to condense, thus collapsing ullage pressure.
5. The effectiveness of the TVS was highest when the injector body was warmest.
6. The TVS heat exchanger does not work as originally intended; the primary cooling benefit is not on cooling the main injection fluid line, but rather the metal matrix of the injector itself.
7. Despite proven feasibility, Test 7 showed that the addition of a TVS heat exchanger to a normal top spray injector does not necessarily guarantee successful fill. The timing and length of TVS engagement is vital to the success of a NVT. The most successful transfers were when the TVS remained on until chilldown of the receiver tank walls was complete.

Nonetheless, the addition of a TVS augmentation is a tantalizing concept at simplifying cryogenic tank-to-tank transfer. What remains to be seen is if a true NVT can be performed at or above ambient warm wall conditions (>300K) as well as how performance of such a concept will change in the microgravity of space.

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