# Characteristics of Subcooled Liquid Methane During Passage Through a Spray-Bar Joule–Thompson Thermodynamic Vent System

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L. J. Hastings[a], L. G. Bolshinskiy[b], A. Hedayat[c], and A. Schnell[c]

*a) Alpha Technology, Inc., Huntsville, Alabama 35801*

*b) The University of Alabama in Huntsville, Jacobs Engineering MSFC Group, NASA Marshall Space Flight Center, Huntsville, Alabama 35812*

*c) NASA Marshall Space Flight Center, Huntsville, Alabama 35812*

## Abstract

NASA's Marshall Space Flight Center (MSFC) conducted liquid methane (LCH4) testing in November 2006 using the multipurpose hydrogen test bed (MHTB) outfitted with a spray-bar thermodynamic vent system (TVS). The basic objective was to identify any unusual or unique thermodynamic characteristics associated with subcooled LCH4 that should be considered in the design of space-based TVSs. Thirteen days of testing were performed with total tank heat loads ranging from 720 W to 420 W at a fill level of approximately 90%. During an updated evaluation of the data, it was noted that as the fluid passed through the Joule–Thompson expansion, thermodynamic conditions consistent with the pervasive presence of metastability were indicated. This paper describes the observed thermodynamic conditions that correspond with metastability and effects on TVS performance.

## I. Introduction

Maintaining propellant tank pressure control while minimizing propellant loss is a significant challenge associated with the storage of cryogens in the near zero-gravity environment of space. Thermodynamic vent systems (TVS) are frequently considered as a concept for addressing this issue. A TVS typically includes a Joule–Thompson (J-T) expansion device, a two-phase heat exchanger, and a mixing pump to destratify and extract thermal energy from the tank contents without significant liquid losses. Analytical modeling of such systems is difficult due to the complex combination of microgravity heat transfer and the thermodynamic and fluid mechanic phenomena involved.

Therefore, the primary objective of the original program was to address TVS performance with subcooled liquid methane (LCH4) pressurized with gaseous helium (GHe). Specific goals associated with this primary objective were as follows:

- Evaluate/define a control algorithm for controlling tank pressure and liquid saturation condition.

- Anchor TVS analytical modeling.
- Define operational challenges unique to LCH4.

However, in the process of addressing these goals, challenges unique to LCH4 fluid properties have been encountered. Therefore, the primary purpose of this paper is to address findings relative to that challenge. Information regarding the test facilities and other program objectives is provided only to assist in understanding the use of LCH4 as an in-space propellant. The test facilities, multipurpose hydrogen test bed (MHTB), and spray-bar TVS are described in detail in references 1 and 2, and are therefore only briefly described herein.

## II. Test Hardware

The major test article elements consisted of the test tank and its supporting equipment, including an environmental shroud, the cryogenic insulation subsystem, and the test article instrumentation.

The MHTB 5083 aluminum tank is cylindrical in shape with a height of 3.05 m (10 ft), a diameter of 3.05 m (10 ft), and 2:1 elliptical domes. It has an internal volume of 18.09 $m^3$ (639 $ft^3$) and a surface area of 35.74 $m^2$ (379 $ft^2$), with a resultant surface-area-to-volume ratio of 1.92 1/m (0.58 1/ft) that is reasonably representative of full-scale vehicle tanks.

Testing was performed at the MSFC East test area thermal vacuum facility, Test Stand 300. The vacuum chamber is cylindrical in shape and has usable internal dimensions of 5.5 m (18 ft) in diameter and 7.9 m (26 ft) in height. The facility systems in combination with the test article shroud enable the simulation of orbit environmental conditions by providing vacuum levels of 10–8 torr and a temperature range of 80–320 K (140–576 °R).

Although the MHTB spray-bar TVS design (fig. 1) was optimized for LH2, the "already existing" test hardware offered a low-cost, near-term means for evaluating TVS operations with LCH4 propellant. However, it eventually became obvious that the spray-bar system had operated in a highly degraded mode throughout the test program. The testing conducted and pertinent test results, based on the instrumentation shown in fig. 1, are presented next.

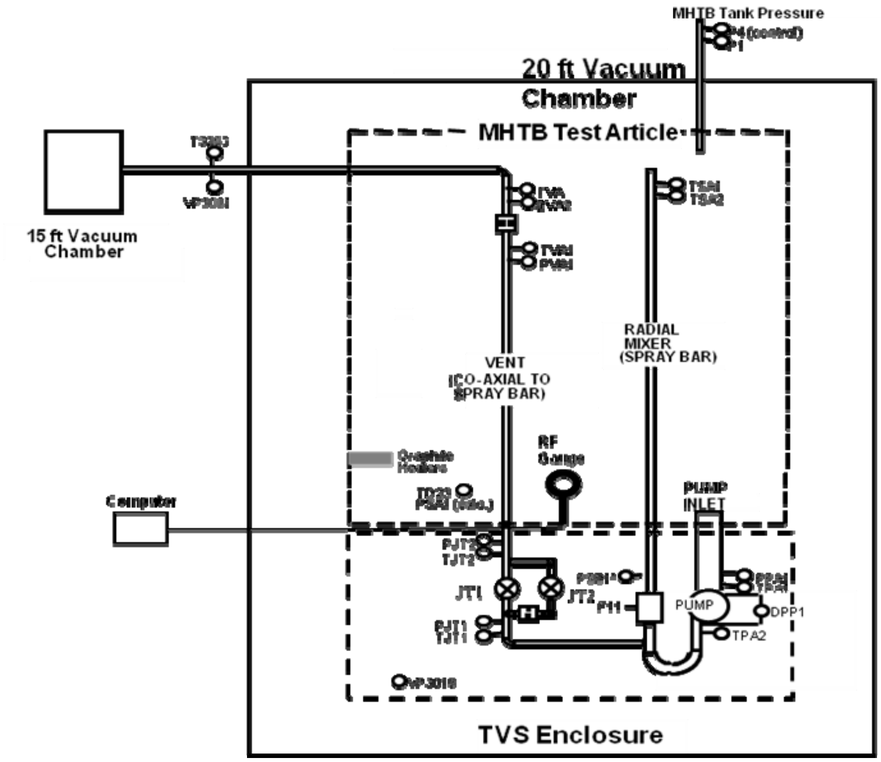


Figure 1. Spray-bar TVS instrumentation.

## III. Propellant Conditioning and TVS Testing

The TVS testing with subcooled liquid methane was conducted in phases as various techniques were attempted to achieve the expected level of performance from the spray-bar system. The objectives, test conditions, hardware adjustments, and the test results associated with each of six test steps or phases are described next.

### *Phase I: Propellant Saturation Pressure Reduction*

The LCH4 saturation conditions were reduced for two reasons: 1) to simulate densified methane in-space storage conditions, and 2) to maximize the difference between the GHe partial pressure and the methane partial or vapor pressure to thereby simulate in-flight storage conditions as closely as possible. Starting with a 90% tank fill level, the pump and J-T2 remained on to reduce the liquid saturation pressure. As shown in fig. 2, after 14 h and 40 min, the liquid saturation pressure was reduced from 110 kPa (16 psia) to 54.3 kPa (7.9 psia).

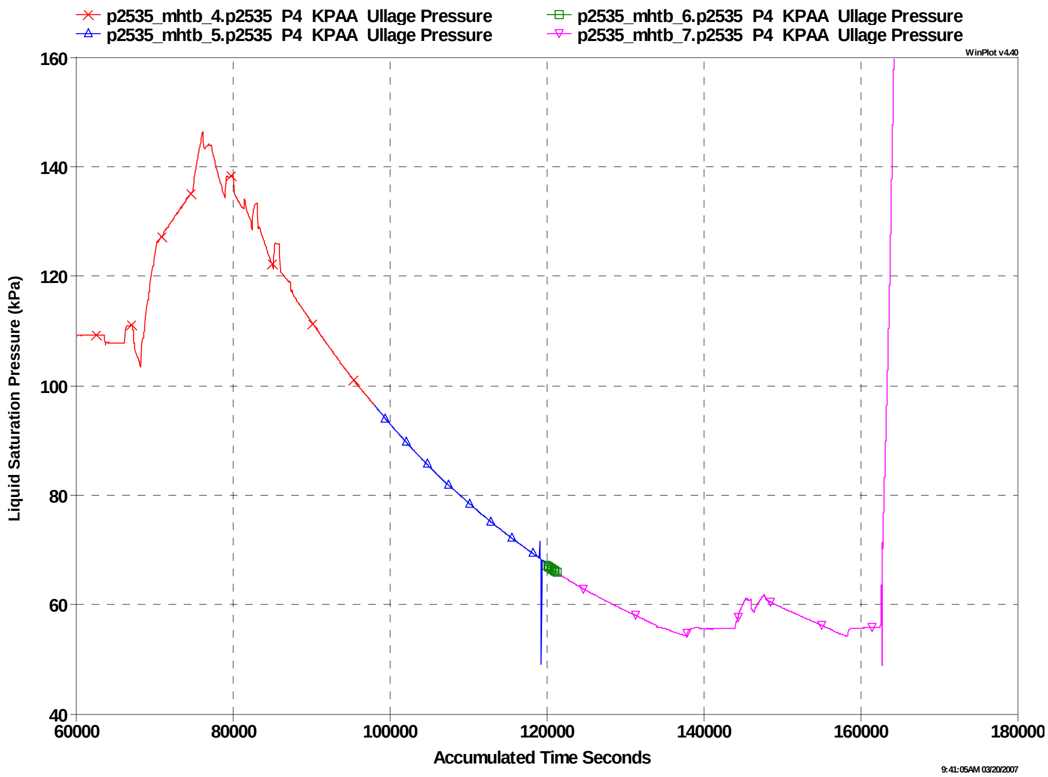


Figure 2. Liquid methane saturation pressure reduction: Phase I testing.

*Phase II: Tank Lockup/Self-Pressurization*

With the tank locked up, two heaters at 300 W each, and the mixer on continuously, the measured temperature rise rates for the tank contents and wall are presented in fig. 3. The tank contents and wall structure temperatures increased at a constant rate of $1.8 \times 10^{-5}$ K/s throughout the self-pressurization period, which resulted in average temperature increases of $2.38 \times 10^{-5}$ K/s and $1.83 \times 10^{-5}$ K/s for the ullage and liquid, respectively. Because the liquid temperatures were higher than the tank wall temperatures, it was evident that not all of the heater power remained in the liquid. Thermal modeling indicated energy additions of 0.251 W (less than 1%) by the TVS operation, 438.5 W (60.9%) into the liquid, and 281 W (39%) to the tank structure for a gross energy input of 720 W.

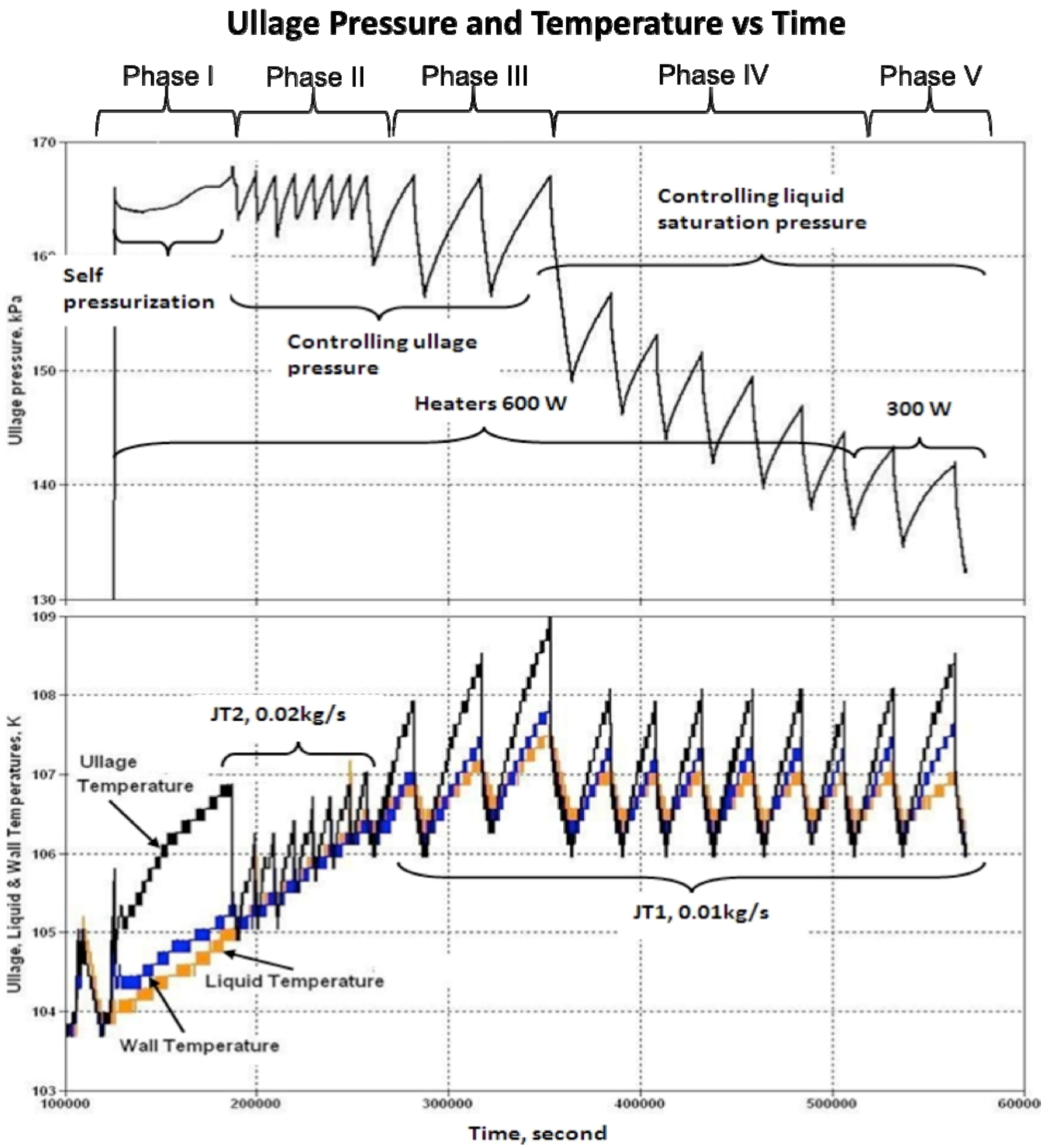


Figure 3. Methane TVS test sequence: Phases II – V.

After tank topping to 90% was complete, with the pump and J-T valve still operating and the liquid saturated at 53.4 kPa (7.9 psia), GHe was injected into the ullage until the pressure reached 166 kPa (24 psia) [GCH4 and GHe partial pressures were 56 kPa (8 psia) and 110 kPa (16 psia), respectively], the value selected for the ullage pressure control band minimum ($P_{min}$).

Then the pump and J-T valve were turned off, and the ullage pressure was allowed to rise to 172.4 kPa (25 psia), the pressure control band control band maximum ($P_{max}$). Therefore, the initial conditions established for beginning the TVS testing (Phase III) were as follows:

- Ullage pressure of 166 kPa (24 psia), the control band minimum set point.
- Two graphite heaters adjusted to 300 W each for a gross heat input from all sources of 720 W.
- J-T2, the larger valve with a flow rate of 0.02 kg/s, equals 72 kg/h.

*Phase III: TVS Keyed to Ullage Pressure Control (J-T2), Heat Input = 600 W*

Seven mixing/vent cycles occurred with the ullage pressure held within a ±3.45 kPa (±0.5 psia) control band for about 17 h. The TVS maintained the tank ullage pressure within the prescribed control band, but the liquid saturation pressure continued to rise throughout operation. This result was unexpected because, during previous MHTB tests with LH2 and LN2, with and without GHe in the ullage, the same spray-bar TVS controlled the ullage pressure while maintaining the liquid saturation pressure at a constant value.[2, 3, 4] However, an evaluation of the methane test data revealed several significant factors which are discussed in the section entitles Data Evaluation.

*Phase IV: Extended Vent Cycles with Reduced Flow Rate (J-T1), Heater Input = 600 W*

J-T1 was then used to determine if tank pressure could be controlled using a lower flow rate J-T valve, to reduce total propellant loss. J-T1 was successful in reducing the ullage pressure and was used for the remainder of the test. On the ninth vent cycle, J-T1 remained open until the liquid saturation pressure was reduced to its original value, just after the previous vent cycle, which resulted in an ullage pressure decrease of ≈10.3 kPa. The ullage pressure was allowed to rise to 10.3 kPa after the vent cycle was complete, and during this time, the liquid saturation pressure rose to a new maximum level. The conditions of the ninth TVS cycle were repeated during the tenth cycle to observe a trend. The liquid saturation continued to rise in a saw-tooth fashion. Because of the unexpected performance of the TVS, during cycle 11 the test team elected to continue testing at 90% fill instead of proceeding to the 50% level. This decision was made for two reasons: 1) the 90% fill case is the most difficult case to match analytically, and 2) the team preferred to have extensive data at one test condition rather than sparse data at multiple test conditions.

*Phase V: TVS Keyed to Saturation Pressure Control (J-T1), Heater Input = 300 W*

During cycles 12–17, the TVS was controlled to liquid saturation pressure. The intent of this mode of operation was to keep the liquid temperature under control, thus demonstrating the capability of providing a desired inlet temperature to an engine. The ullage pressure decreased in a saw-tooth fashion with each cycle.

*Phase VI: TVS Keyed to Saturation Pressure Control, Heater Input = 300 W*

The graphite heater power was reduced during TVS cycles 18–23 to determine if the ullage pressure cycles would reach a steady-state band. However, the ullage pressure cycles continued to drop until the conclusion of the test.

## IV. Data Evaluation

*Saturation Reduction*

Examination of the J-T2 thermodynamic characteristics begins to reveal why there was limited energy removal. In fig. 4, the liquid saturation reduction data are plotted in terms of liquid temperatures upstream and downstream of the J-T valve as opposed to the bulk liquid saturation pressure presented in fig.1. The data revealed that there was no temperature drop across the J-T valve, but instead there was a temperature rise of about 0.25 K. The pressure drop across the J-T was very slight, less than 0.2 kPa (0.03 psia). Based on J-T testing of subcooled methane by Jurns, it is apparent the testing was conducted with the subcooled methane in a "metastable" state. [5] The J-T expansion coefficient was negative; that is, the change in temperature or delta temperature was negative relative to the positive change in pressure or delta pressure.

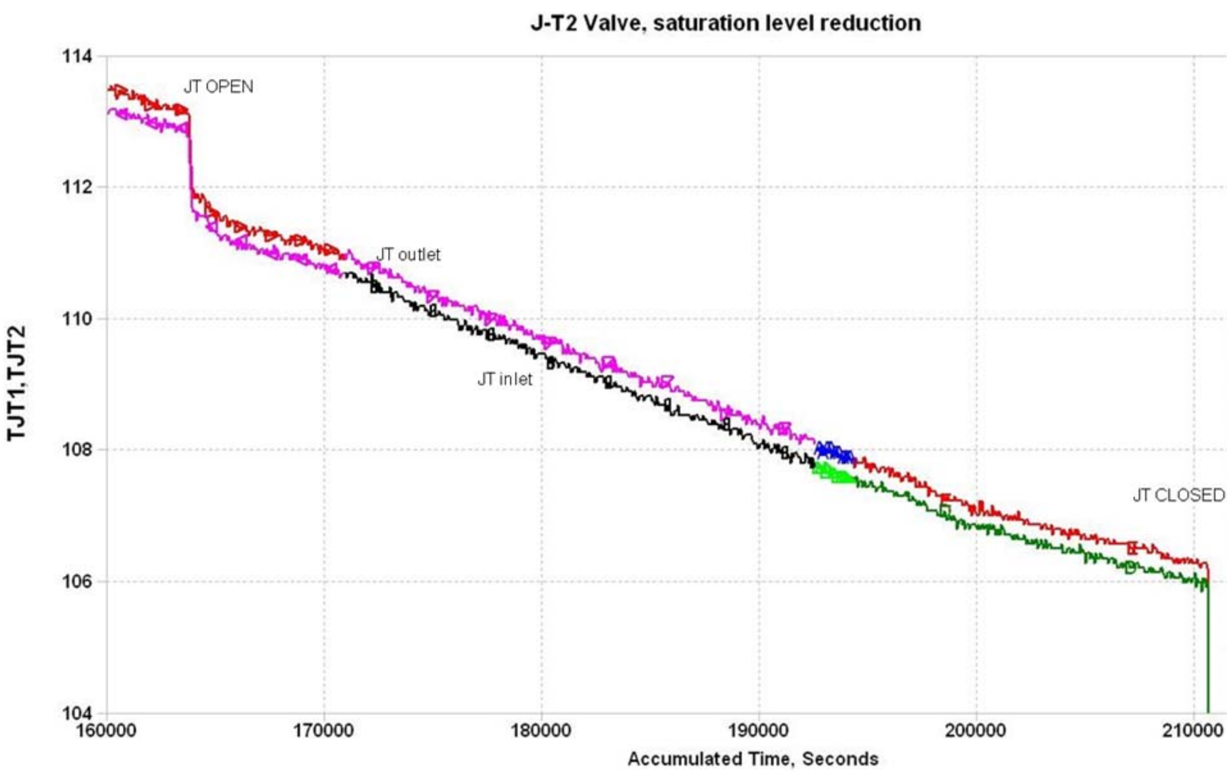


Figure 4. Liquid methane saturation temperature reduction: Phase I testing.

However, the process was successful in reducing the bulk liquid saturation level because the liquid upstream and downstream of the J-T valve were always subcooled relative to the bulk liquid and ullage saturation condition. Further, the ullage volume increased by about 2.5 $m^3$

(34%) based on a 1,053-kg propellant loss during the 14.7-h test period and with an average density of 427 kg/$m^3$. Assuming a constant average temperature, the pressure reduction would be about 34% or 35 kPa (5 psi), which is almost 70% of the total reduction of 56 kPa (8 psi). However, the primary issue or cause for concern was that of operating within the metastable regime of methane. The characteristics and implications of metastable conditions during TVS operations are discussed in the following sections.

## V. Metastable Conditions

A common example of metastable conditions is demonstrated in the laboratory by gradually heating a glass tube of liquid, such as water, above its saturation level or super-heating the liquid without boiling or two-phase conditions. Similarly, as shown in fig. 5, super-heated conditions can be created by reducing pressure until the saturation line is crossed without boiling. In either case, the superheated liquid is in an unstable or metastable state, and the onset of boiling or two-phase liquid can erupt violently.

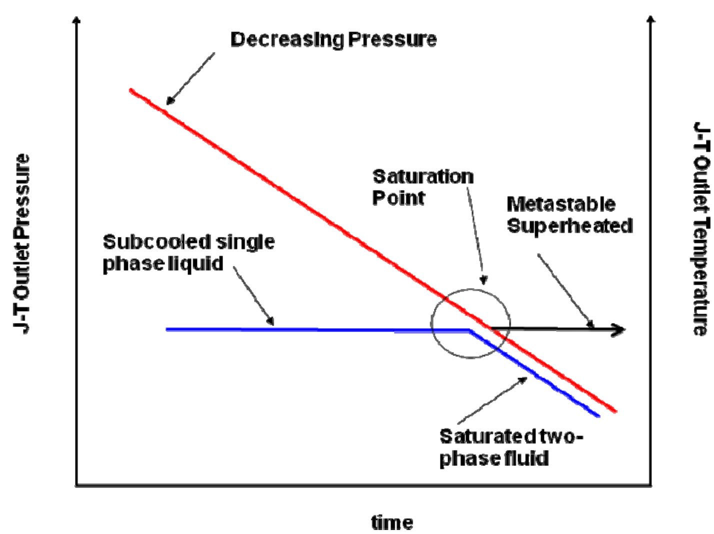


Figure 5. Recognizing presence of metastable liquid.

The same process can be visualized with a “pressure-specific volume” diagram for a pure fluid, as shown in fig. 6. Again, pressure is reduced until the saturation line is crossed and the liquid becomes superheated. However, the lower stability limit can be estimated using techniques described in Jurns.[5]

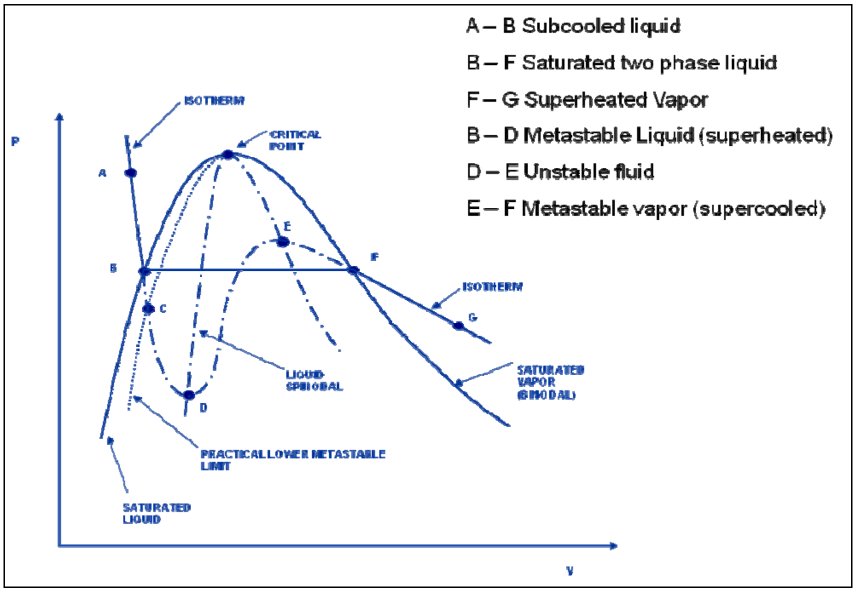


Figure 6. Schematic depicting saturation line and practical lower metastable limit.

*Self-Pressurization and TVS Operation with J-T2*

As mentioned earlier, once the metastable condition was identified, the TVS operation was better understood. Referring to fig. 3, it was noted that the temperature rise rate of the tank and its contents actually increased after the TVS operation with J-T2 began, whereas the TVS should have removed, rather than added, energy.

A closer look at the pressure and temperature data upstream and downstream of J-T2 (fig. 7) indicates that there was virtually no temperature change across the valve even though a pressure reduction of about 20 to 10 kPa (3 to1.5 psi) occurred. Basically, saturated liquid existed on both sides of the valve. Referring to fig. 7, it becomes clear that the metastable conditions prevented any energy reduction within the tank contents. Therefore, although the ullage temperature and pressure was reduced during each mixer operation (by the relatively cool liquid at the J-T valve entrance), thermal energy was being added instead of reduced. Consequently, the tank contents saturation level increased with each cycle.

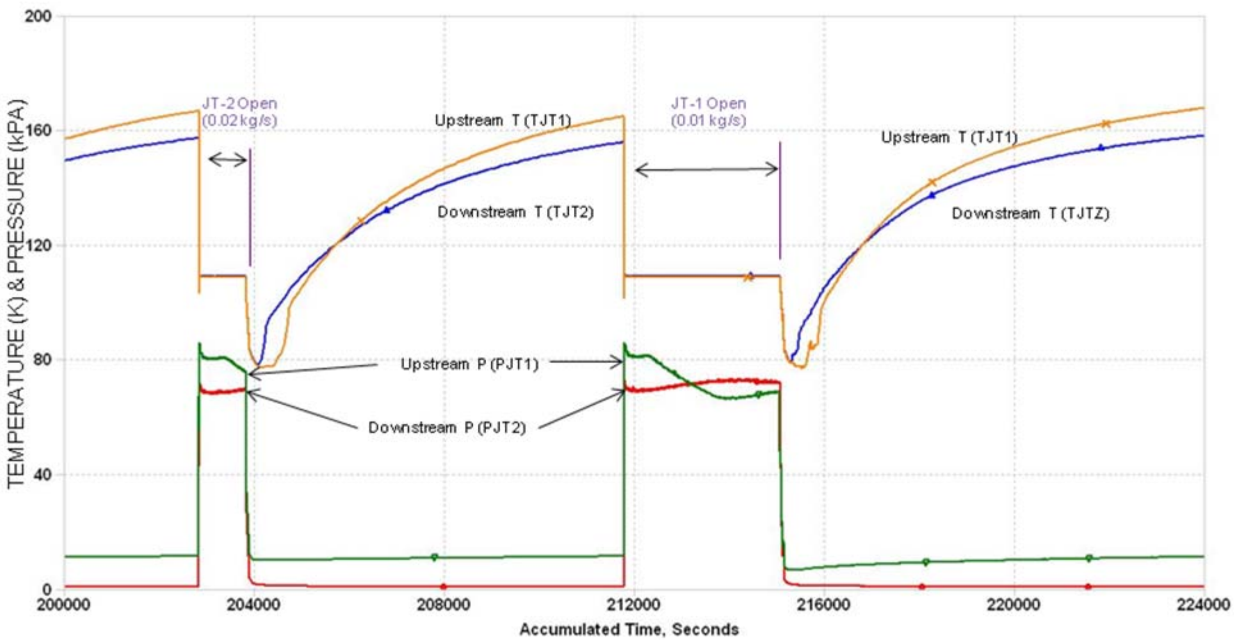


Figure 7. Pressure and temperature upstream and downstream of J-T1 and J-T2, Heater Input = 600 W

*TVS Operation with J-T1*

The lack of success in Phase III motivated Phase IV testing with J-T1 at a predicted flow rate of 0.01 kg/s, that is, one-half that with J-T2. Although the ullage pressure was reduced on a cycle-by-cycle basis, the bulk liquid saturation level increased with each of the first 11cycles. Therefore, Phase V testing was based on controlling liquid saturation temperature instead of ullage pressure; however, the ullage pressure decreased with each vent cycle. Finally, the Phase V testing was repeated in Phase VI with 300 W heater input, a 50% heater power reduction; however, the ullage pressure decrease continued. Examination of thermodynamic conditions on each side of the J-T valve indicates why liquid saturation temperature and ullage pressure could not be controlled simultaneously. As seen in the Phase V testing (fig. 7), there was a slight temperature rise, as opposed to a drop, across the J-T. And the $\Delta P$ was positive but became slightly negative about halfway through the cycle. An expanded version of J-T1 inlet and outlet temperatures for the 300 W heater output conditions (see fig. 8) indicate a slight temperature rise across the J-T valve. The temperature rise across the JT valve is a definite indicator of a metastable condition. Further, the vent flow could not have existed after the downstream pressure exceeded the upstream pressure. Therefore, without a doubt, the TVS performance was severely compromised by the metastable characteristics.

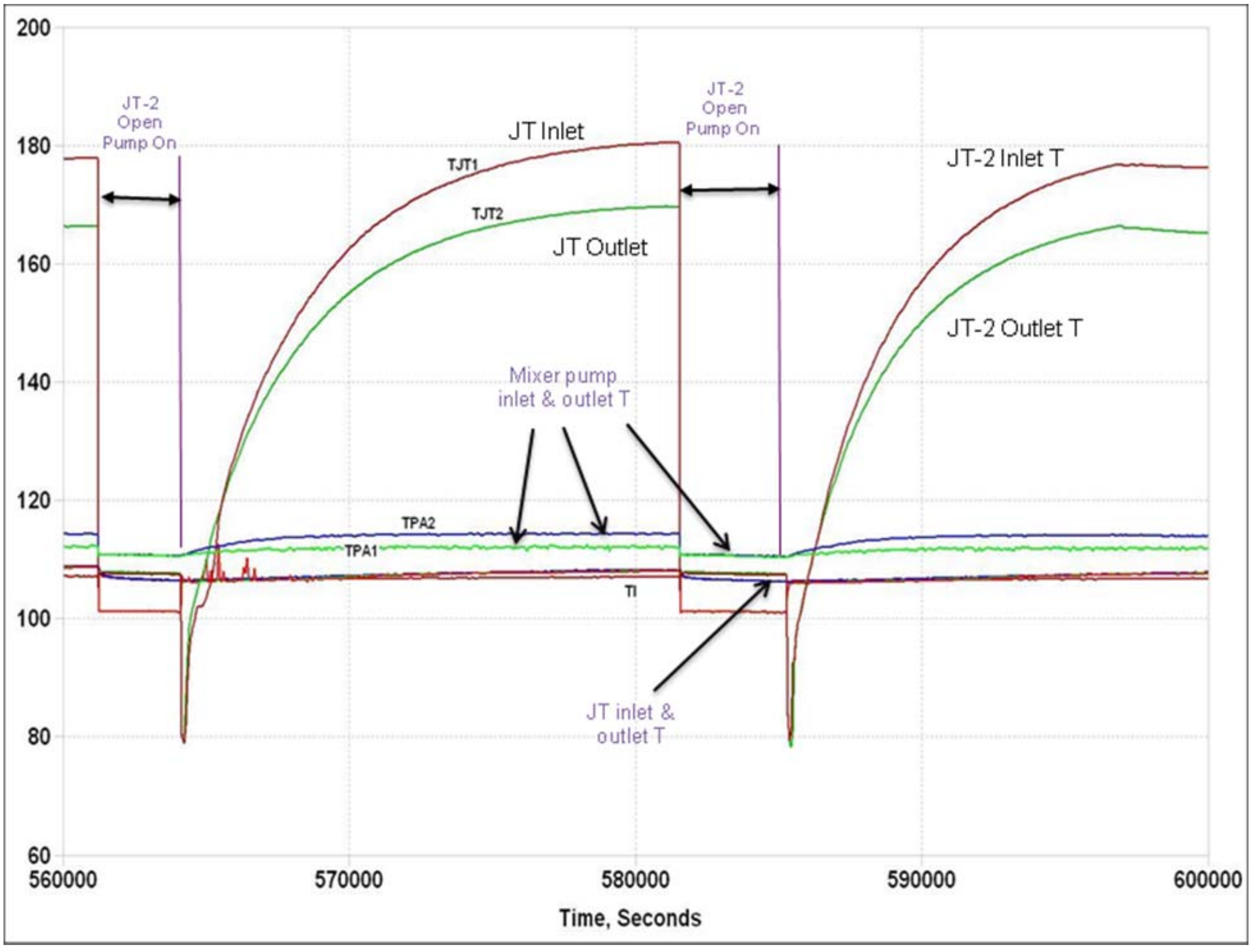


Figure 8. TVS temperatures with J-T1, Heater Input 2 = 300 W

Furthermore, regarding the "valve open" conditions measured at the J-T valve entrance and exit, it was noted that neither the temperature profile nor the magnitude varied with test condition or valve size. The same observation held regarding inlet pressures, except that the profile had longer to evolve with the smaller valve. Next it was noted that "valve open" conditions upstream and downstream of the backpressure control orifice were, for all practical purposes, also were unaffected by the J-T used or by the tank heater load variation of 600 W or 300 W. This was a substantial conclusion. Once the commonality of temperatures for a given position was established, it became convenient to group all the data for a particular measurement position onto a single graph. For example, as shown in fig. 9, the saturation temperature corresponding to the "valve open" measured pressure at a valve entrance was constant at 108 K, which closely matched the measured temperature, thereby indicating a saturated liquid condition throughout the testing. Similarly, at the position immediately downstream of the J-T valve (fig. 10), the measured temperatures also indicated the presence of a saturated liquid.

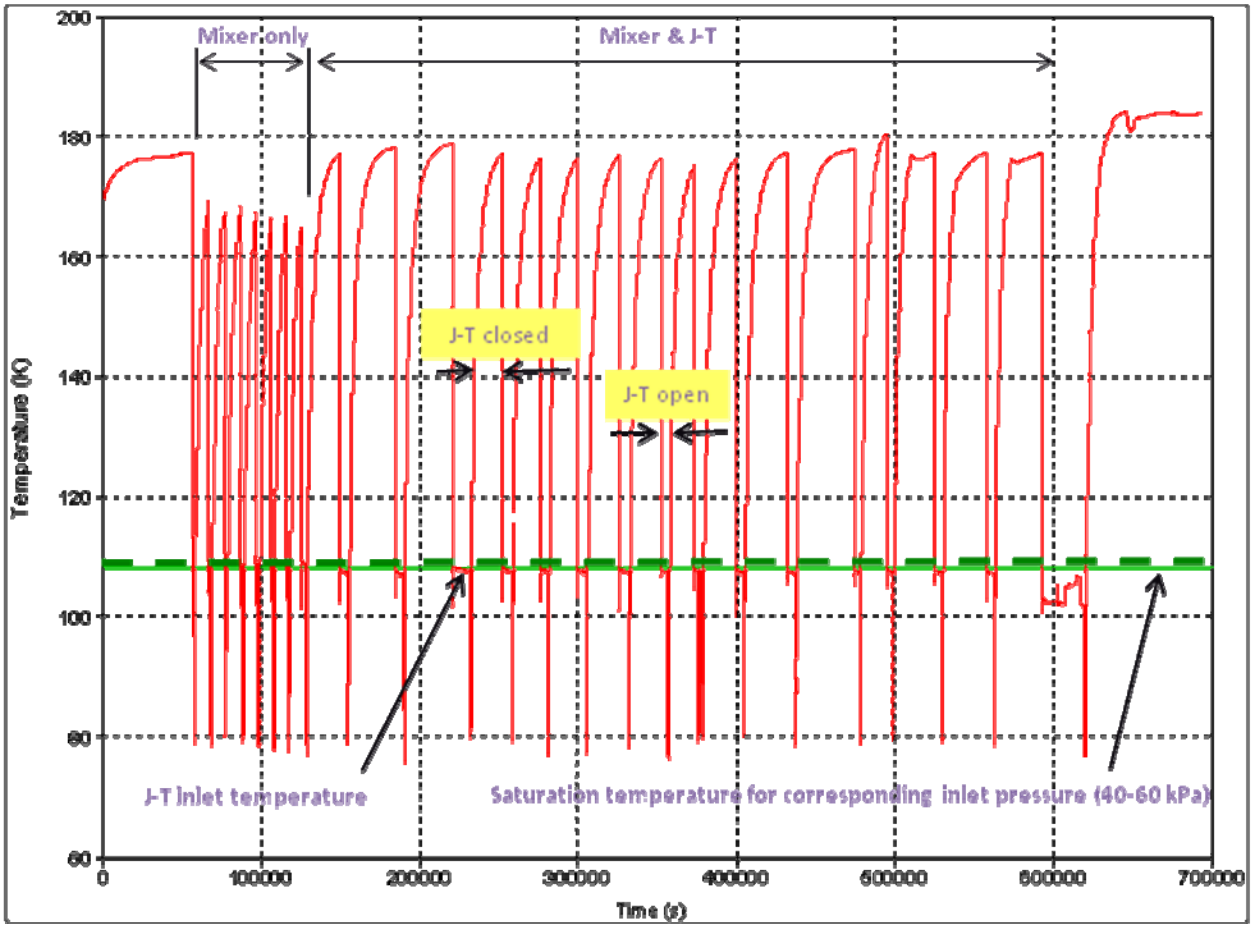


Figure 9. Comparison of J-T inlet temperature with saturation temperatures corresponding to measured inlet pressure. Conclusion: saturated fluid at J-T entrance.

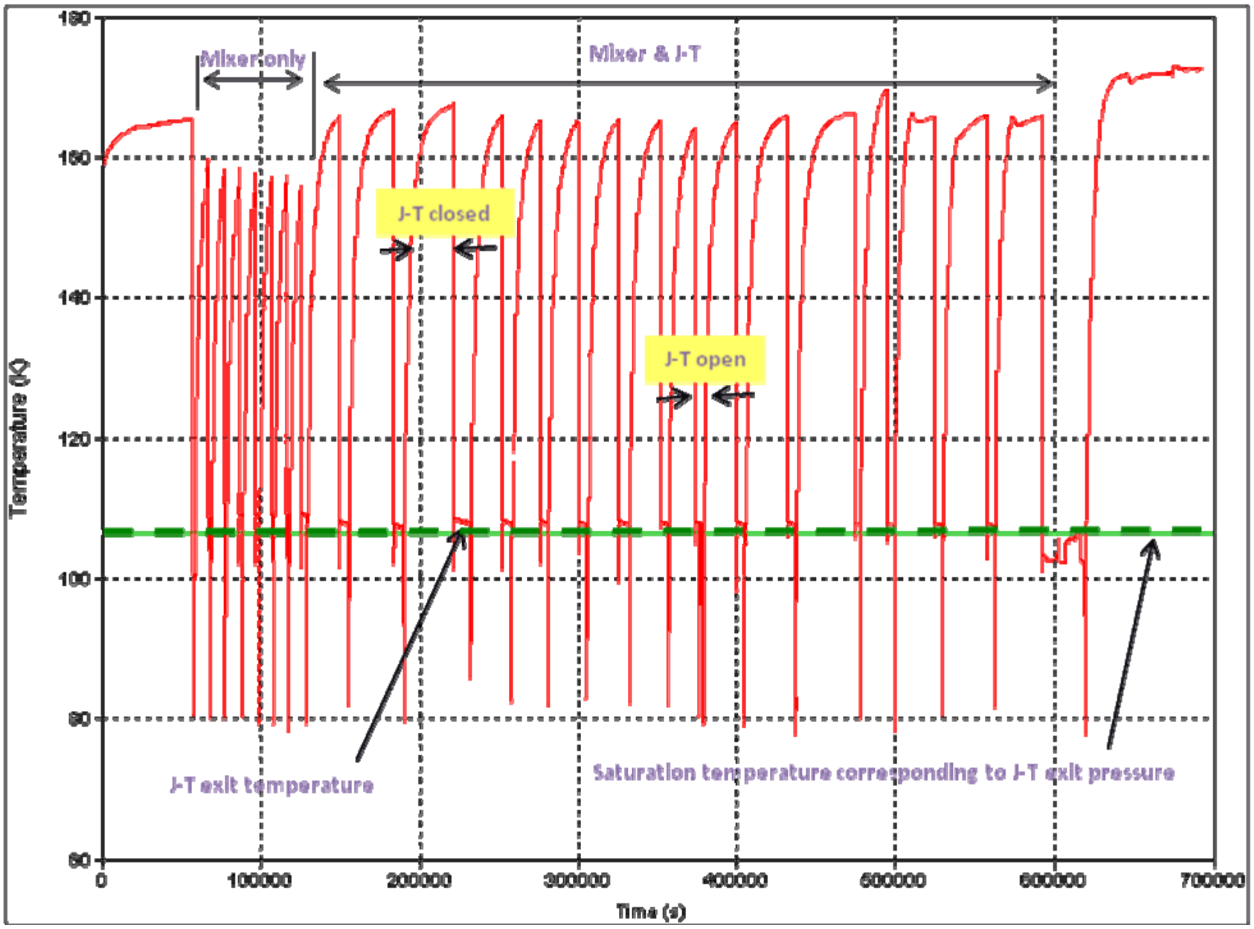


Figure 10 Comparison of J-T exit temperature (TJT2) with saturation temperature corresponding to exit pressure (PJT2). Conclusion: fluid at J-T exit slightly above saturation.

The pressures and temperatures measured upstream and downstream of the back-pressure orifice, which was positioned in the vent line external to the test article but within the vacuum chamber as shown in fig. 1, are presented in figs. 11 and 12, respectively. The temperatures measured during the vent periods on both sides of the orifice were consistently lower than the saturation temperature corresponding to measured pressures, indicating the presence of subcooled liquid throughout the testing. Additionally, the orifice inlet temperatures were about 2 K lower than at the spray-bar entrance. If the TVS had been operating in a normal manner the vented fluid temperatures would have increased, rather than decreased, as it passed through the spray-bar heat exchanger. Finally, another indication of liquid being vented was the sudden pressure spikes that occurred whenever the diffusion pumps were overwhelmed by liquid being vented into the 15-ft chamber. However, since the vent-side liquid was cooler than the bulk liquid circulated through the spray side of the TVS and the longer vent duration, some bulk liquid cooling with the smaller JT valve was obtained.

Figure 11. Comparison of venting orifice inlet temperature (TVA1) with saturation temperature corresponding to inlet pressure (PVA1). Conclusion: subcooled liquid at spray-bar exit/back-pressure orifice entrance.

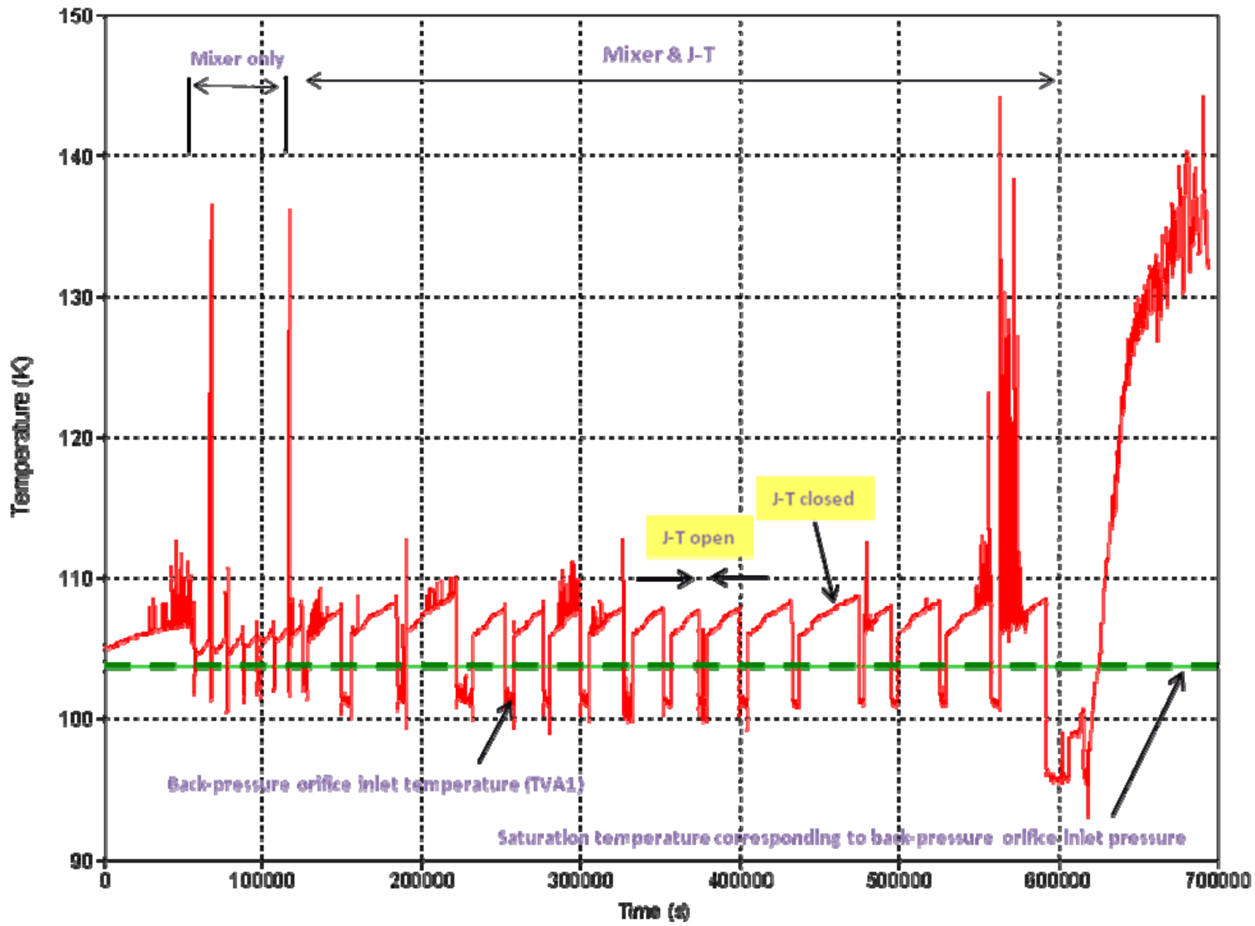


Figure 12. Comparison of venting orifice exit temperature (TVA2) with saturation temperature corresponding to exit pressure (PVA2). Conclusion: subcooled liquid at back-pressure orifice exit/15-ft vacuum chamber entrance.

Therefore, even though the data evaluation is incomplete, the major finding is evident. Without a doubt, the TVS performance was severely compromised throughout the test program by the presence of metastable conditions. This finding and other conclusions are discussed in the next section.

## VI. Summary and Conclusions

MSFC conducted liquid methane testing in November 2006 using the multipurpose hydrogen test bed outfitted with a spray-bar TVS. The basic objective was to identify any unusual or unique thermodynamic characteristics associated with subcooled LCH4 that should be considered in the design of space-based TVSs. Thirteen days of testing were performed with total tank heat loads ranging from 720 W to 420 W at a fill level of approximately 90%. During an updated evaluation of the data, it was noted that as the fluid passed through the J–T expansion, thermodynamic conditions consistent with the pervasive presence of metastability were indicated. Specific observations and implications of metastable methane on TVS performance and recommendations are discussed below.

1. Spray-bar TVS seriously compromised by metastable methane

The J-T cooling with either of two valves, one with a predicted flow rate of 0.02 kg/s and another rated at 0.01 kg/s, was seriously compromised. In both cases the downstream temperature was higher than the upstream or inlet temperature, even though the downstream pressure was lower. In other words the J-T expansion coefficient was negative (negative ΔT over positive ΔP), a characteristic of metastability. Additionally, it was noted that subcooled liquid at 102 K was consistently present at the upstream side of the back-pressure orifice. Therefore, Some cooling was obtained with the smaller valve, apparently because the liquid within the vent side of the spray bar was cooler than the bulk liquid and the longer vent duration allowed some energy exchange with the bulk liquid.

2. TVS applications to reduced gravity methane storage constrained.

Although testing was conducted with a spray bar TVS, it is believed that the metastable condition is primarily a function of degree of subcooling and or helium pressurization above the saturation level. Until further testing demonstrates other-wise, it is recommended that it be assumed that the metastable methane conditions observed herein are also applicable to other TVS concepts. Therefore, usefulness of concepts involving TVS's in combination with densified methane (below normal boiling point) to achieve long-term in-space storage are likely to either be seriously compromised or not viable. Similarly, the application of TVS's to concepts with high partial pressure helium will be constrained (since liquid below the liquid-vapor interface behaves as though it was subcooled). Therefore, in future applications of J-T cooling to methane storage, assurance must be provided that metastable effects have either been mitigated or circumvented. A strong bench test program is recommended for any and all TVS applications to space-based liquid methane storage.

3. Propellant settling to accommodate reduced gravity venting more likely

In view of the above, propellant settling to support venting during reduced gravity methane storage is now more probable.

4. Thermal modeling required to support use of heaters to expedite ground-based pressure control testing

Ground-based testing of pressure control concepts for reduced gravity storage of high density cryogens (such as liquid methane, oxygen, and nitrogen) often necessitate heaters to expedite pressure control cycle rates. However experience with the subject methane testing demonstrated the need for thermal modeling sufficient to determine the energy distribution to the tank contents vs the tank walls and other heat leak sources. Furthermore, it is recommended future testing include at least a partial test cycle with the actual anticipated heat load.

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