

Thermodynamic Vent System Performance Testing with Subcooled Liquid Methane and Gaseous Helium Pressurant

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Due to its high specific impulse and favorable thermal properties for storage, liquid methane (LCH_4) is being considered as a candidate propellant for exploration architectures. In order to gain an understanding of any unique considerations involving micro-gravity pressure control with LCH_4 , testing was conducted at the Marshall Space Flight Center using the Multipurpose Hydrogen Test Bed (MHTB) to evaluate the performance of a spray-bar thermodynamic vent system (TVS) with subcooled LCH_4 and gaseous helium (GHe) pressurant. Thirteen days of testing were performed in November 2006, with total tank heat leak conditions of about 715 W and 420 W at a fill level of approximately 90%. The TVS system was used to subcool the LCH_4 to a liquid saturation pressure of approximately 55.2 kPa before the tank was pressurized with GHe to a total pressure of 165.5 kPa. A total of 23 TVS cycles were completed. The TVS successfully controlled the ullage pressure within a prescribed control band but did not maintain a stable liquid saturation pressure. This was likely due to a TVS design not optimized for this particular propellant and test conditions, and possibly due to a large artificially induced heat input directly into the liquid. The capability to reduce liquid saturation pressure as well as maintain it within a prescribed control band, demonstrated that the TVS could be used to seek and maintain a desired liquid inlet temperature for an engine (at a cost of propellant lost through the TVS vent). One special test was conducted at the conclusion of the planned test activities. Reduction of the tank ullage pressure by opening the Joule-Thomson valve (JT) without operating the pump was attempted. The JT remained open for over 9300 seconds, resulting in an ullage pressure reduction of 30 kPa. The special test demonstrated the feasibility of using the JT valve for limited ullage pressure reduction in the event of a pump failure.

KEYWORDS: cryogenic, test, thermodynamic, vent, methane, helium

INTRODUCTION

Cryogenic propellants offer exploration architectures both non-toxicity and higher performance compared to storable propellant options. Methane in particular has generated considerable interest due to its favorable thermal properties which make it easier to store compared to liquid hydrogen. MSFC, in cooperation with its partners at other NASA centers, continues to implement advanced technology development efforts, both in ground testing and analysis, in order to increase the technology readiness level (TRL) of CFM concepts. Propellant tank pressure control is a technology challenge which must be addressed before cryogenic propellants can be used for longer duration space missions, including lunar missions. The state of the art for upper stage tank pressure control is to settle the propellant and vent the tank ullage until the pressure reaches the desired operating pressure. Auxiliary systems for propellant settling incur weight penalties in the form of propellant and hardware. The use of GHe poses another challenge as it affects the performance of the TVS by changing the duration and number of cycles, as observed in previous MSFC testing with liquid hydrogen (LH₂) and liquid nitrogen (LN₂) [1,2]. GHe pressurant is frequently considered to enable orbital and lunar surface engine starts and to pressurize the tank during engine burns. Thus, the effects of GHe pressurant on TVS operation in LCH₄ must be considered.

This paper focused on LCH₄ testing, with a pressurant GHe, which took place in November 2006. The test program was funded under the Propulsion and Cryogenic Advanced Development (PCAD) project. The purpose of the test program was to quickly gain some "first look" test data for TVS performance with LCH₄. Therefore, the primary objectives of the test were: 1. Demonstrate the operation of a spray-bar TVS in LCH₄ with a GHe pressurant, 2. Gather data for analytical models, and 3. Operate a radio frequency (RF) mass gauge as a piggy back experiment. (Results from the RF gauging portion of the test were not explored in this paper.) As part of the first objective, the team chose to operate the test with subcooled LCH₄ relative to ambient conditions. The purpose of this test condition was to demonstrate TVS operation with a large difference between liquid saturation pressure and the total tank ullage pressure, representative of a propellant tank pressurized in preparation for an engine firing.

TEST SETUP

The multipurpose hydrogen test bed (MHTB) aluminum tank was cylindrical with 2:1 elliptical domes, a total length of 3.05 m, and a diameter of 3.05 m. It had an internal volume of 18.09 m³ and a surface area of 34.75 m² with a resultant surface area to volume ratio of 1.92 m⁻¹. The tank was equipped with internal graphite heaters, which were used during this test to increase heat input to the tank in order to shorten the TVS cycle duration, enabling the test team to gain more TVS cycles in the limited amount of test time. An environmental shroud was used to impose a uniform boundary temperature of 305 K on the tank insulation surface. The shroud was 4.57 m high with a diameter of 3.56 m.

The test article instrumentation consisted primarily of thermocouples and silicon diodes to measure insulation, fluid, and tank wall temperatures. The tank interior was equipped with two silicon diode rakes for measuring liquid and ullage temperatures. The TVS system was instrumented with pressure and temperature measurements on the pump, spray-bar, and along the vent line. More detail on the instrumentation was provided by Hastings, et alii [3].

Testing was performed at the MSFC East Test Area thermal vacuum facility, Test Stand 300 (TS300). The facility systems, in conjunction with the MHTB shroud, enabled the simulation of orbital thermal conditions. Since minimizing ambient heat leak was not considered critical for the successful operation of this test, the vacuum chamber LN₂ cold walls were not operated. A valuable facility capability during the boiloff heat leak

measurement portion of the test was the test article back pressure control system used to maintain steady-state MHTB ullage pressure. The system was composed of several flow control valves, in parallel, located in the MHTB vent line. Each valve was regulated through a closed loop control system. This control system changed the valve positions based on a comparison between the measured MHTB ullage pressure and the desired set point. More detail on the test facility was provided by Hastings et alii [3].

The test article was the same spray-bar thermodynamic vent system (TVS) previously tested at MSFC. This hardware was selected as the test article for two reasons: 1. it had track record of highly successful tests in LH₂ and LN₂ which demonstrated the robustness of the design, and, 2. to avoid the cost and a year or more of procurement time required to obtain a new TVS, which would have significantly delayed the procurement of the "first look" TVS data with LCH₄. The spray-bar TVS concept, developed by Boeing [5], consisted of a recirculation pump, JT device, concentric tube heat exchanger and spray-bar assembly. Since the presence of a non-condensable gas physically limits how much the ullage pressure can be reduced in a given TVS cycle, efficient mixing and cooling of both the liquid and ullage was especially critical. Since it mixes and destratifies the entire tank contents, regardless of liquid level and location, the spray-bar TVS was especially suited for operation with a non-condensable pressurant such as GHe. The configuration of two JT valves installed in parallel for a previous TVS test remained for this test. However, JT#2, the larger of the two valves was a new pneumatic valve installed after the failure of the valve used as JT#2 for the previous two test series. Both JT valves were successfully used during this test series. FIGURE 1 illustrated a schematic of the spray-bar TVS. A more detailed description of the spray-bar TVS, the advantages of this concept, as well as details on how it operated, were included in the references [3, 5].

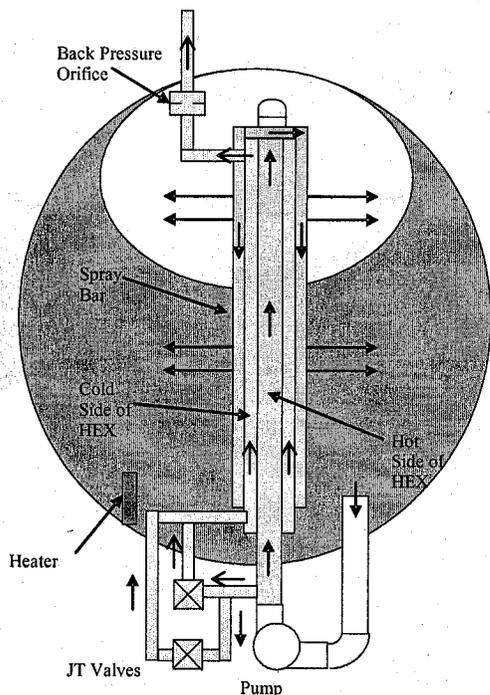


FIGURE 1. Spray-Bar TVS Concept

TEST PROCEDURES

Boiloff Testing

In order to assess the performance of the TVS and later model the system analytically, the heat leak into the tank through the insulation and the penetrations, had to be known. The heat leak from all ambient sources was measured during a boiloff test. The tank ullage pressure was held at a nearly constant value ± 0.0069 kPa by the facility back pressure control system. The boil-off flow rate was measured with a flow meter. Once the boil-off flow rate reached steady state, it, along with other test article data was recorded and used to calculate the heat transfer into the tank. The boiloff test was conducted at approximately 37% fill level with an ambient heat leak of 120 W and a total heat leak of 420 W with the heaters turned on.

Tank Propellant Subcooling

The tank was initially filled to 37% with saturated propellant in order to conduct the boiloff test described above. In order to achieve the objective of maintaining a large difference between the ullage pressure and liquid saturation pressure, the tank propellant was subcooled. The test team attempted to resume fill with liquid subcooled through an external heat exchanger attached to the propellant fill line. The recirculation pump and JT#2 were operated in order to augment the subcooling of the incoming propellant. Although the external heat exchanger functioned properly, lowering the liquid supply temperature, the propellant entering the tank was not adequately subcooled since the propellant temperature had risen significantly during storage inside the supply trailer for 3 days during the boiloff test. After the tank reached 90% fill, the pump and JT#2 remained on in order to subcool the propellant as much as possible. After 14 hours, 40 minutes, the pump/JT#2 had lowered the liquid saturation pressure to 54.3 kPa. This was the longest continuous operation of any TVS configuration in MSFC testing history. This operation was significant in that it demonstrated that a TVS can be used to lower the liquid saturation pressure to a target value, at the cost of propellant lost through the TVS. After the propellant was subcooled by the TVS, the tank was topped to 90%, resulting in a liquid saturation pressure of approximately 56 kPa.

TVS Testing

The tests with subcooled LCH_4 and a GHe pressurant in the ullage were conducted at approximately the 90% fill level. After tank topping was complete, with the pump still operating, GHe was injected into the ullage until the pressure reached 166 kPa, the value selected for P_{\min} of the TVS ullage pressure control band. The pump and JT were turned off and the ullage pressure was allowed to rise to 172.4 kPa, the value selected for P_{\max} of the ullage pressure control band. The graphite heaters were adjusted to an input of approximately 600 W (total heat leak from all sources was 720 W) since the pressure rise was too slow with a heater input of 300 W.

FIGURES 2 and 3 illustrated the ullage pressure and liquid saturation pressure throughout the TVS test. FIGURES 4 and 5 illustrated the liquid and ullage temperatures during TVS operation. Seven cycles with the pump and JT#2 were conducted at a 3.4 kPa control band. The TVS system maintained the ullage pressure within the control band. However, the liquid saturation pressure continued to rise, instead of remaining level as observed in all other MSFC TVS tests with the same TVS hardware [1, 2, 4]. The team theorized that the TVS vent cycle was not long enough to sufficiently cool the liquid. Thus, on the 8th vent cycle, the TVS was allowed to operate over a 6.9 kPa control band. The saturation pressure remained nearly flat during the vent portion of the cycle, but rose during the subsequent 6.9 kPa ullage pressure

rise. TVS vent line temperatures indicated that superheated gas was not exiting the vent line, and that liquid was pooling in the vent line after JT#2 closed. JT#1 was then used in order to determine if tank pressure could be controlled using a lower flow rate JT valve, reducing total propellant loss. JT#1 was successful in reducing the ullage pressure, and thus was used for the remainder of the test. On the 9th vent cycle, JT#1 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 10.3 kPa after the vent cycle was complete, and during this ullage pressure rise, the liquid saturation pressure rose to a new maximum level. The conditions of the 9th TVS cycle were repeated during the 10th cycle in order to observe a trend. The liquid saturation continued to rise in a saw tooth fashion. During cycles 12 through 17, the TVS controlled to liquid saturation pressure. This 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 dropped in a saw tooth fashion with each cycle. The graphite heater power was reduced during TVS cycles 18 through 23 in order 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.

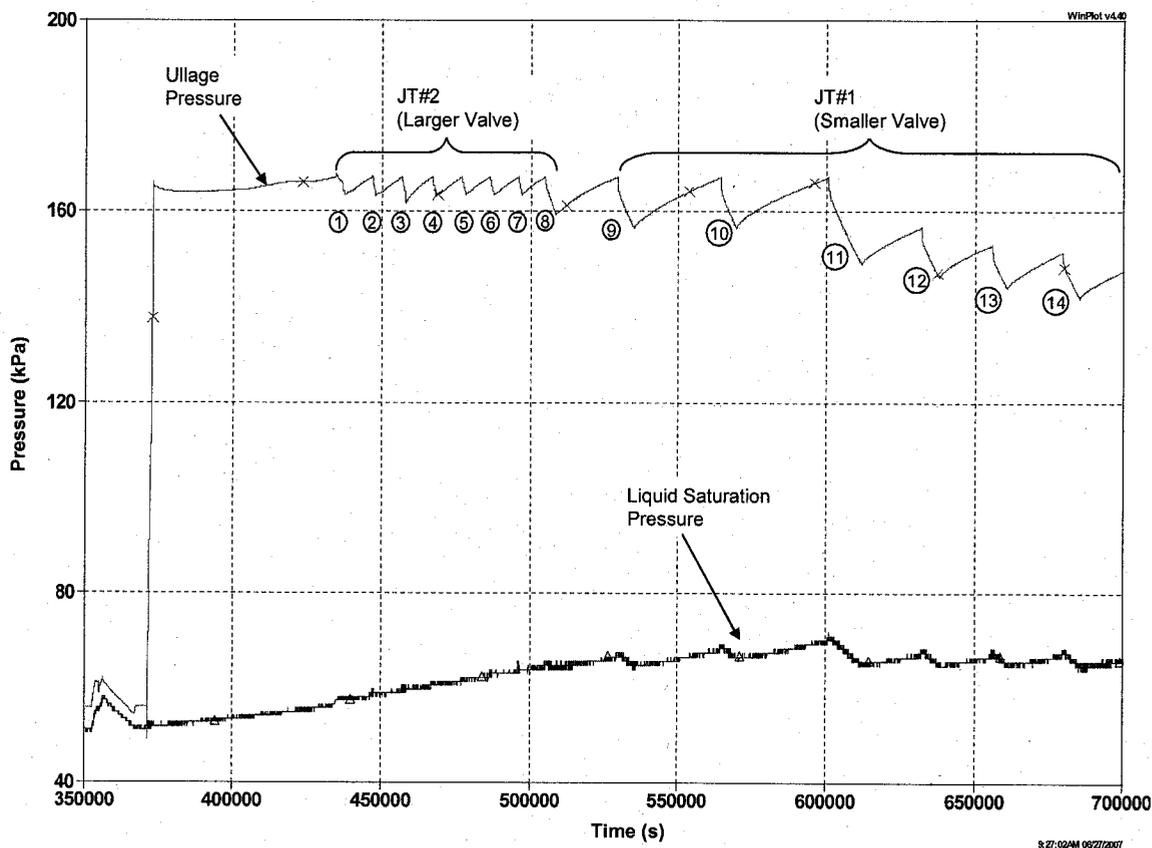


FIGURE 2. Ullage and Liquid Saturation Pressures for Cycles 1 - 14, 90% Fill

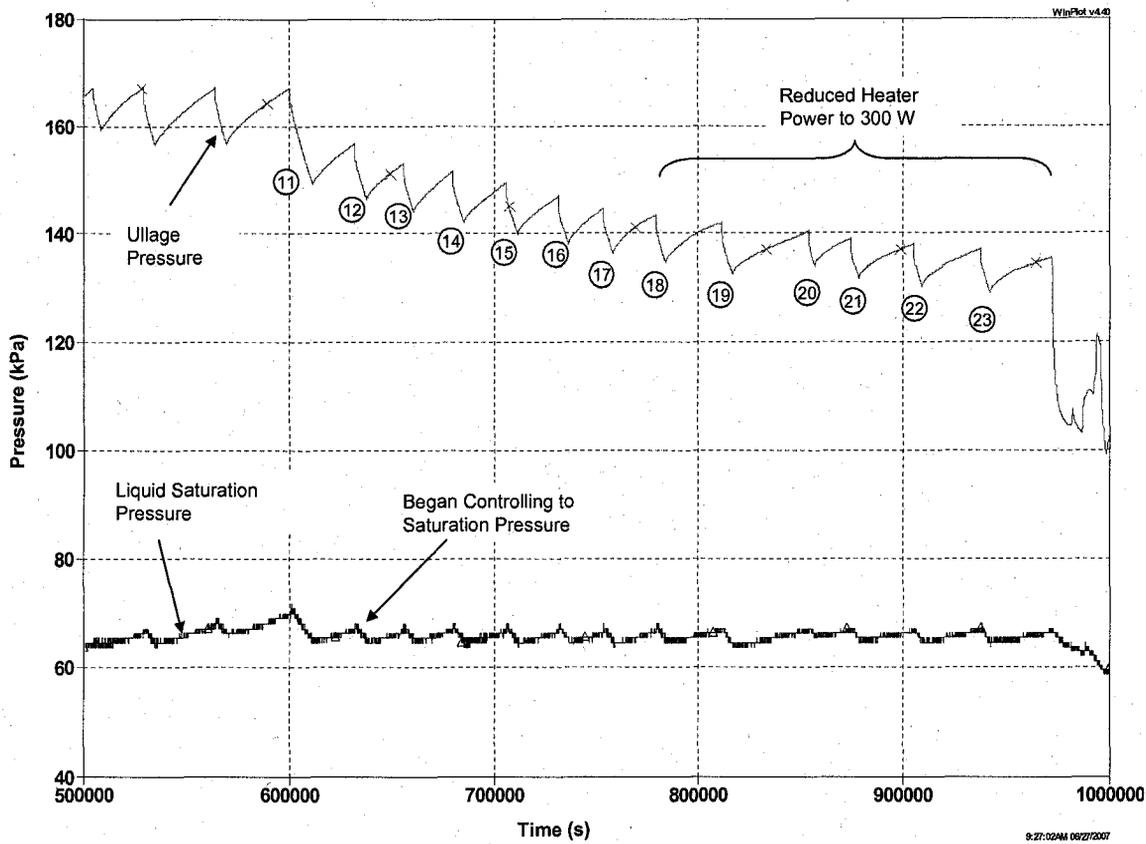


FIGURE 3. Ullage and Liquid Saturation Pressures for Cycles 11 - 23, 90% Fill

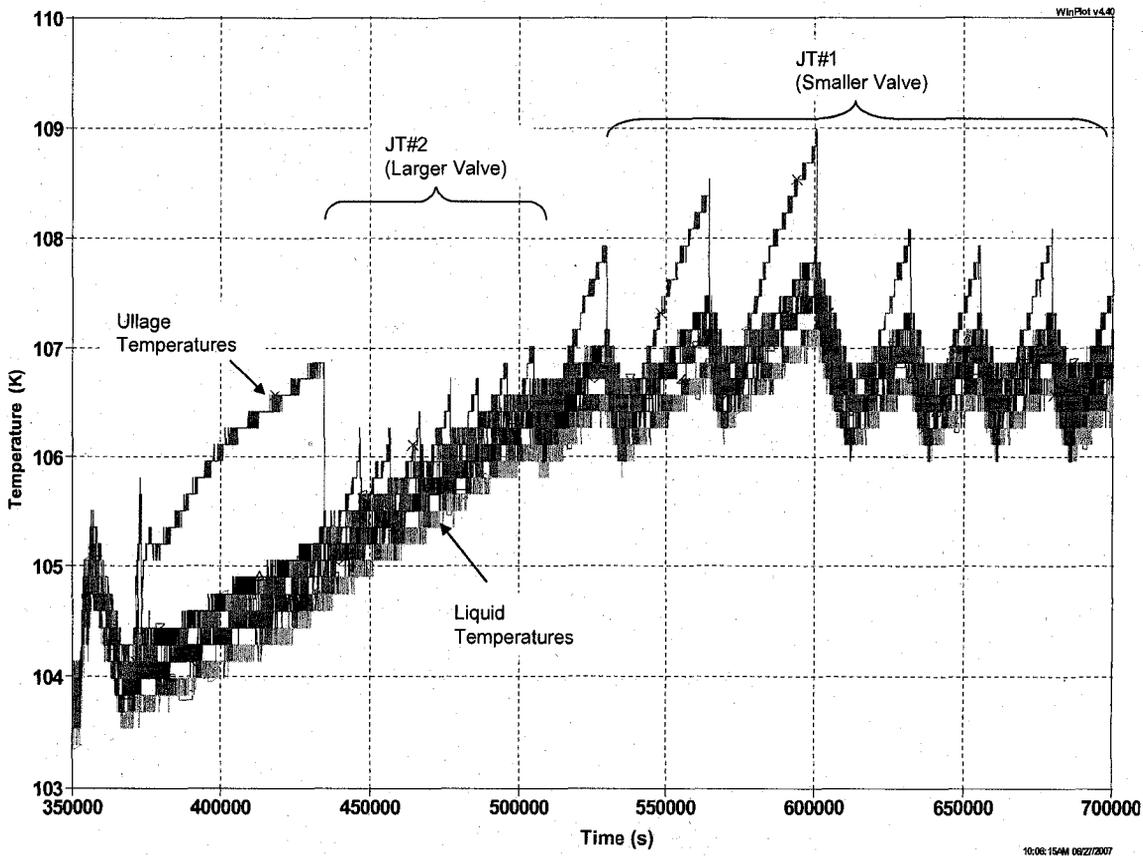


FIGURE 4. Ullage and Liquid Temperatures for Cycles 1 - 14, 90% Fill

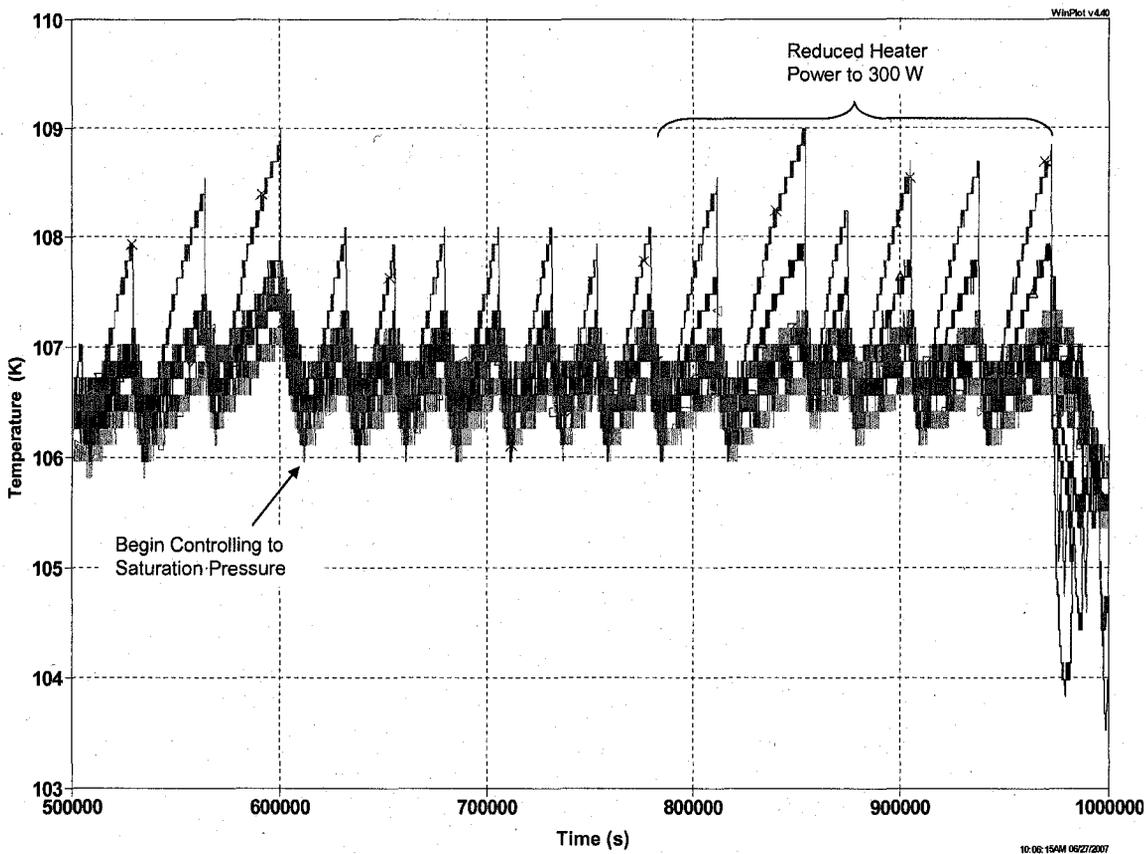


FIGURE 5. Ullage and Liquid Temperatures, Cycles 11 - 23, 90% Fill

Special JT Valve Test

Special tests were not generally planned in advance, and typically conducted with whatever propellant remained in the tank. They explored off-nominal conditions with little or no opportunity for test repeats. If the test data revealed any significant phenomena, the test conditions might be explored at length in a subsequent test program. The special test for this test program focused on observing whether or not the TVS could reduce the tank pressure in a tank with a higher fill level without the recirculation pump or with the pump at lower speeds. A similar special test had been conducted with LH₂ in a previous test program, but at a much lower fill level [2].

RESULTS AND DISCUSSION

The ambient heat leak, measured during the boiloff test conducted at the 37% fill level, was approximately 120 W. The ambient heat leak was likely elevated since the vacuum chamber cold walls and the tank leg heat guards were not activated for this test series. Minimizing ambient heat leak was not considered to be critical for the successful operation of this test series. The total heat leak with the heaters set to 300 W was approximately 420 W.

The main objective of this test program was to evaluate the pressure control performance of a TVS in a subcooled LCH₄ tank pressurized with GHe. 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 since, 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 [1, 2, 4]. The test data revealed that a spray-bar TVS concept, which is designed to reach both the ullage and liquid regardless of position within the tank, physically couples the two together, presenting a challenge with regard to design. A given spray-bar design which effectively cools the ullage may not remove enough heat energy from the liquid. The test results indicated that this particular TVS did not remove enough heat energy from the liquid within the amount of time required to reduce the ullage pressure from P_{max} to P_{min}. Thus it did not keep the liquid saturation pressure from rising given the conditions in this particular test. This spray-bar TVS design was the product of the careful optimization of several variables including propellant properties, heat exchanger configuration and dimensions, pump speed, and the size of the JT device. Since the vent flow from the TVS was not completely vaporized during the operation of JT#2, it is possible that heat exchanger portion of the design played a role in the TVS performance during this test. The artificial heat input of 600 W from the heaters directly into the liquid could have played a role as well since the spray-bar was originally designed to remove 55 W with a margin of over 15 times that value with saturated LH₂ in the MHTB [5]. All of these potential factors in the TVS performance during this test must be explored further through analysis and extensive test data evaluation. It is possible that analysis and test data evaluation may reveal other factors that drove the performance of the TVS during this test. When the TVS mode of operation was changed from controlling to the ullage pressure to controlling to the liquid saturation pressure, in an attempt to remove adequate heat energy from the liquid, the ullage pressure decreased with each cycle. This decrease occurred because the ullage was cooled for a significantly longer duration compared to operation of the TVS controlling to ullage pressure, since the JT valve remained open longer in order to remove all of the heat input to the liquid during the pressure rise part of the cycle.

During the special test, JT#1 was held open for over 9300 seconds without the pump operating. The ullage pressure decreased 30 kPa during that interval. The slope of the ullage pressure decreased significantly as the ullage temperature approached liquid temperature. It was concluded that JT operation without a recirculation pump may be a potential back up operational mode for tanks with high fill levels.

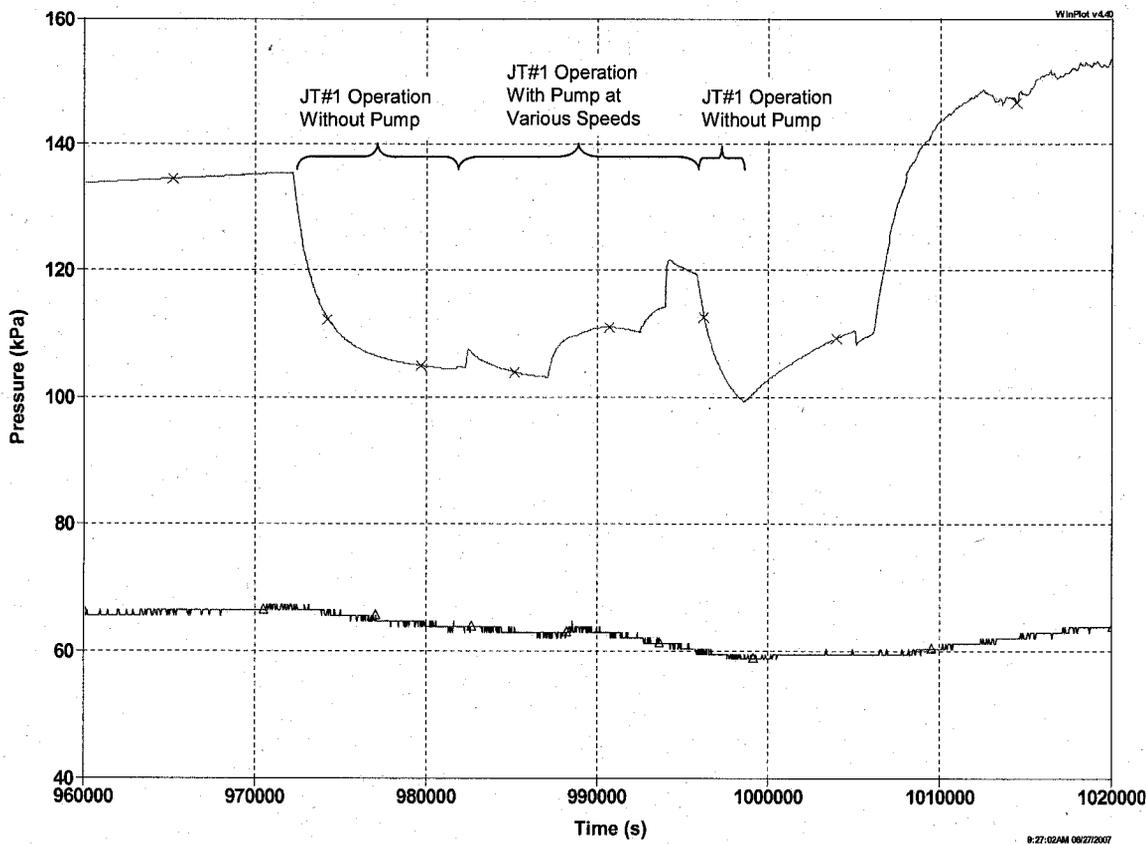


FIGURE 6. Ullage and Liquid Saturation Pressures During Special JT Test

SUMMARY

Testing with subcooled LCH_4 presented a challenge to the MSFC test team that had not been encountered before. The spray-bar TVS did not perform in a manner similar to past tests of the same hardware in the MHTB, with LH_2 and LN_2 . Typically, the use of this particular spray-bar to maintain the ullage pressure within a 6.9 kPa control band resulted in a stable liquid saturation pressure, not a liquid saturation pressure increase as observed during this test series. This particular TVS maintained control of the ullage pressure but did not hold the liquid saturation pressure at a constant level, possibly due to the design, which was optimized for a different propellant and different operating conditions. A large artificial heat input directly into the liquid may have played a role as well. However, the TVS did successfully demonstrate the ability to maintain the liquid saturation pressure (id est liquid temperature) within a control band despite a possible lack of optimization in its thermal design. The TVS also demonstrated the capabilities of operating for a long duration and reducing the liquid saturation pressure to a desired target. These results were significant since the TVS demonstrated the capability to provide the required inlet temperature to an engine. During the special test, tank pressure control was achieved without the pump, using the JT alone, in a tank with a high fill level. This demonstrated the possibility of added operational flexibility, and possible back-up operational mode for the spray-bar TVS system.

This test series provides valuable insight into factors that must be considered when designing and optimizing a spray-bar. The design aspect of the spray bar which allows it to reach both the liquid and ullage regardless of position, also couples the ullage and liquid together such that performance in each zone must be carefully examined during design and optimization. All TVS concepts have advantages and disadvantages. A design team

considering a TVS will need to consider many factors when selecting a concept. The data from this test will continue to be analyzed and used to update analytical models of TVS systems which will ultimately benefit teams who select a TVS for propellant tank pressure control.

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