ZERO GRAVITY CRYOGENIC VENT SYSTEM CONCEPTS FOR UPPER STAGES

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ABSTRACT

The capability to vent in zero gravity without resettling is a technology need that involves practically all uses of sub-critical cryogenics in space, and would extend cryogenic orbital transfer vehicle capabilities. However, the lack of definition regarding liquid/ullage orientation coupled with the somewhat random nature of the thermal stratification and resulting pressure rise rates, lead to significant technical challenges. Typically a zero gravity vent concept, termed a thermodynamic vent system (TVS), consists of a tank mixer to destratify the propellant, combined with a Joule-Thomson (J-T) valve to extract thermal energy from the propellant. Marshall Space Flight Center's (MSFC's) Multipurpose Hydrogen Test Bed (MHTB) was used to test both spray-bar and axial jet TVS concepts. The axial jet system consists of a recirculation pump heat exchanger unit. The spray-bar system consists of a recirculation pump, a parallel flow concentric tube heat exchanger, and a spray-bar positioned close to the longitudinal axis of the tank. The operation of both concepts is similar. In the mixing mode, the recirculation pump withdraws liquid from the tank and sprays it into the tank liquid, ullage, and exposed tank surfaces. When energy extraction is required, a small portion of the recirculated liquid is passed sequentially through the J-T expansion valve, the heat exchanger, and is vented overboard. The vented vapor cools the circulated bulk fluid, thereby removing thermal energy and reducing tank pressure. The pump operates alone, cycling on and off, to destratify the tank liquid and ullage until the liquid vapor pressure reaches the lower set point. At that point, the J-T valve begins to cycle on and off with the pump. Thus, for short duration missions, only the mixer may operate, thus minimizing or even eliminating boil-off losses.

TVS performance testing demonstrated that the spray-bar was effective in providing tank pressure control within a 6.89 kPa (1psi) band for fill levels of 90%, 50%, and 25%. Complete destratification of the liquid and ullage was achieved at these fill levels. The axial jet was effective in providing tank pressure control within the same pressure control band at the 90% fill level. However, at the 50% level, the system reached a point at which it was unable to extract enough energy to keep up with the heat leak into the tank. Due to a hardware problem, the recirculation pump operated well below the axial jet design flow rate. Therefore, it is likely that the performance of the axial jet would have improved had the pump operated at the proper flow rate. A CFD model is being used to determine if the desired axial jet performance would be achieved if a higher pump flow rate were available. Testing conducted thus far has demonstrated that both TVS concepts can be effective in destratifying a propellant tank, rejecting stored heat energy, and thus, controlling tank pressure.

NOMENCLATURE

CdA	equivalent flow area
h_{fg}	heat of vaporization
h	enthalpy
$Lohm$	viscojet flow resistance
$\dot{m}$	mass flow rate
P	pressure
$\dot{Q}$	heat leak rate
S	specific gravity at viscojet inlet
T	temperature
t	time
U	internal energy
X	viscojet exit quality
ΔP	pressure drop across viscojet

INTRODUCTION

The development of high-energy cryogenic upper stages is essential for the efficient delivery of large payloads to various destinations envisioned in near term chemical propulsion programs. Also, many advanced propulsion systems, including solar thermal and nuclear fission, use hydrogen as a working fluid. Some of these systems are intended for long duration missions. A key technology challenge for all of these applications is cryogenic fluid management (CFM) advanced development, specifically, the long term storage of cryogens in space. In response to this challenge, MSFC has initiated an advanced

development/technology program to broaden the CFM experience/data base. Due to the cost of, and limited opportunities for, orbital experiments, ground testing is being employed to the fullest extent possible. Therefore, a major objective of the MSFC program has been to perform ground based advanced development testing on CFM systems for space transportation applications.

A significant challenge associated with long term storage of cryogens in space is maintaining propellant tank pressure control while minimizing propellant boiloff loss. Auxiliary thrusters are traditionally used to settle the propellants in order to accomplish tank venting. Such systems incur increasing weight penalties associated with the propellant and hardware required to perform the settling burns. In addition, tank venting may become necessary at an inopportune time in the mission timeline. The thermodynamic vent system (TVS) concept enables tank pressure control through venting without resettling. A TVS typically includes a Joule-Thompson expansion device, two-phase heat exchanger, and a mixing pump to destratify and extract thermal energy from the tank contents without significant liquid losses.

However, TVS implementation has been constrained by the lack of opportunities for on-orbit experience, mainly due to funding constraints. Analytical modeling of such systems is difficult due to the complex combination of micro-gravity heat transfer, thermodynamic, and fluid mechanic phenomena involved, and is further complicated by the lack of on-orbit data to correlate with the models.

SPRAY-BAR CONCEPT

The spray-bar TVS concept, developed by Boeing (Reference 1), was the first TVS concept tested in MSFC's Multipurpose Hydrogen Test Bed (MHTB) (Reference 2). An illustration of spray-bar TVS concept is provided in Figure 1. One advantage of this concept is that the active components (J-T expansion valve, subsystem pump, and isolation valve) are located outside of the tank. Such an approach simplifies component installation and enables modification or changeout of TVS components without entering the tank. Also, this configuration supports feed line and engine thermal conditioning during micro-gravity coast. The second, and perhaps more important advantage, is the longitudinal spray-bar, which is used to achieve both liquid bulk and ullage gas thermal destratification through mixing. Since the liquid bulk and ullage are destratified regardless of position, and the self induced heat transfer mechanisms are based on forced convection, the spray-bar concept lends itself to verification in normal gravity. Therefore, there is the potential for minimizing the dependence on costly micro-gravity experimentation.
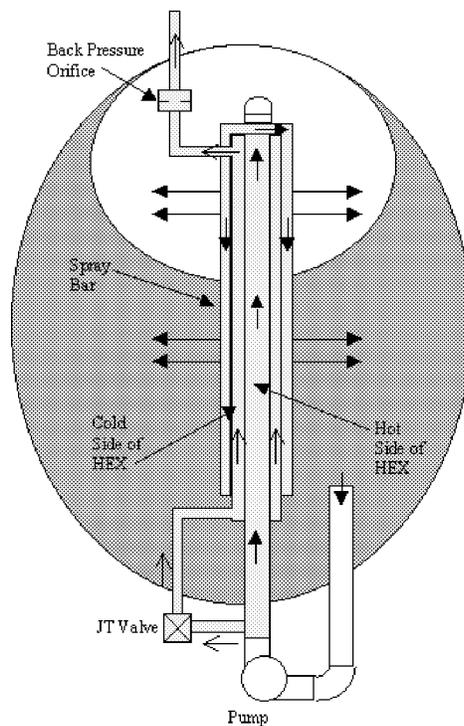
Figure 1: Spray-Bar TVS Concept

In the mixing mode, fluid is withdrawn from the tank by the pump and flows back into the tank through a spray-bar positioned along (or near) the tank longitudinal axis. The fluid is expelled radially back into the tank through the spray-bar, which forces circulation and mixing of the tank contents regardless of liquid and ullage position, assuring destratification and minimum pressure rise rate. For missions lasting from a few days to weeks, depending on the insulation performance, tank mixing may be sufficient to control the tank pressure with no propellant loss. When pressure control can no longer be achieved with mixing alone, a portion of the circulated liquid is passed through the J-T valve, where it is expanded to a lower temperature and pressure, passed through the heat exchanger element of the spray-bar, and finally is vented to space. Therefore, the vented fluid removes thermal energy from, and thus cools, the bulk fluid circulated through the mixing element of the spray-bar.

In an orbital propellant transfer scenario the spray-bar concept can be used to assist tank refill. By filling through the spray-bar/heat exchanger, the in-flowing fluid can be cooled and used to mix the tank contents, thus resulting in a "no-vent fill" process with minimal propellant losses. Additionally, if capillary liquid acquisition devices (LAD) are used for micro-gravity propellant expulsion, the liquid within the LAD can be conditioned by the spray-bar TVS. By withdrawing liquid from the capillary liquid acquisition device,

cooling it through the J-T device, and returning it to the LAD, thermal conditioning of the LAD liquid is achieved. Thus heat entrapment within the LAD can be minimized or perhaps eliminated.

AXIAL JET CONCEPT

The axial jet TVS system, provided by the Glenn Research Center, was the second TVS concept tested in the MHTB. A schematic of the axial jet concept is included in Figure 2. The advantage of this concept is simplicity. For the most part, the hardware does not require precise and complicated design and fabrication, as with the spray-bar concept.
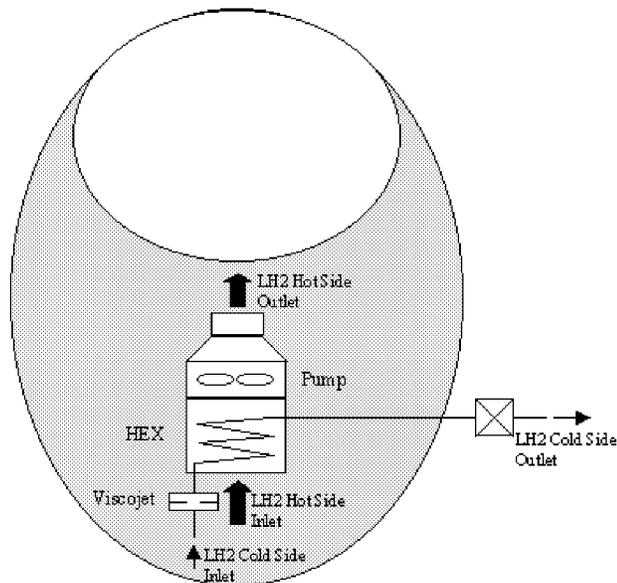

Figure 2: Axial Jet TVS Concept

The operation of the axial jet concept is very similar to that of the spray bar concept. The main differences are the configuration of the heat exchanger and the way the cooled bulk liquid is returned to the tank (axially versus radially). As with the spray-bar concept, the axial jet TVS can be used to condition the propellant within the LAD. Such a configuration, with an axial jet TVS, was recently tested in Boeing's Solar Thermal Upper Stage Test Demonstrator (STUSTD) ground test at MSFC (Reference 3). During the testing, the axial jet TVS was able to subcool the liquid within the LAD. A similar configuration is proposed to fly aboard the Solar Orbit Transfer Vehicle (SOTV).

TEST SET UP

The major test article elements consist of the test tank and environmental shroud with supporting equipment, cryogenic insulation subsystem, and test article instrumentation. The technical description of each of these elements is presented in the following sections.

TEST TANK AND SUPPORTING EQUIPMENT

The MHTB aluminum tank is cylindrical with a height of 3.05 m, a diameter of 3.05 m and 2:1 elliptical domes as shown in Figure 3. It has an internal volume of 18.09 m^3 and a surface area of 34.75 m^2. The tank is ASME pressure vessel coded for a maximum operating pressure of 344 kPa and was designed to accommodate various CFM concepts. The low heat leak composite legs and other tank penetrations are equipped with LH_2 heat guards so that more accurate measurement of the tank insulation performance can be made.
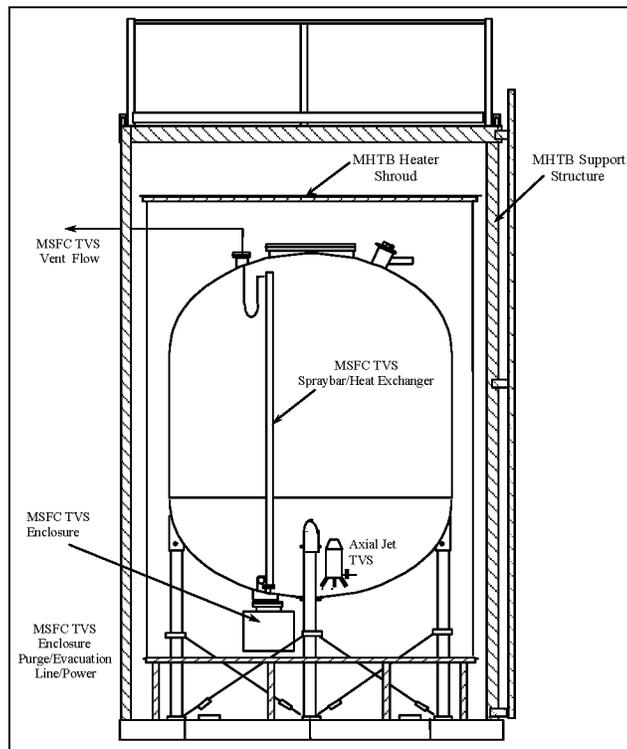

Figure 3: MHTB Tank and Support Equipment

The tank is enclosed within an environmental shroud which contains a ground hold conditioning purge, (similar to a payload bay) and imposes a range of uniform temperatures on the insulation external surfaces during orbit hold simulations. The shroud is 4.57 m high with a diameter of 3.56 m, and contains a purge ring for distributing dry nitrogen.

CRYOGENIC INSULATION SUB-SYSTEM

The MHTB insulation consists of a "spray-on" foam/multilayer combination. The foam element enables the use of a payload bay type purge during ground hold periods and the 45 layer multilayer insulation (MLI) provides thermal protection while at vacuum conditions in orbit. As reported in Reference 4, which describes the insulation performance in more detail, the combined effects of the MLI variable density, large vent hole pattern, and installation technique yield substantial performance improvements. However, in this application, the insulation system is compromised by the TVS hardware installation and taken "as is" as part of the MHTB tank configuration.

INSTRUMENTATION

The tank instrumentation consists primarily of thermocouple and silicon diodes to measure insulation, fluid, and tank wall temperatures. The MLI interstitial pressure is measured at the SOFI/MLI interface using a thin walled probe that penetrates the MLI. The probe is also equipped with a port for both dew point and gas species sampling. Two of the four composite legs, the vent, fill/drain, pressurization, pressure sensor probe, and manhole pump-out penetrations are instrumented to determine the solid conduction component of heat leak. The tank is internally equipped with two silicon diode rakes, which provide temperature gradient measurements within both ullage and liquid. The TVS systems are instrumented with pressure and temperature measurements throughout, in order to determine the pump flow rate, gas state in the vent lines, and vent gas mass flow rate. These measured values are used to quantify the performance of the two TVS concepts.

TEST FACILITY

Testing was performed at the MSFC East Test Area thermal vacuum facility, Test Stand 300. The cylindrical vacuum chamber has usable internal diameter of 5.5 meters and height of 7.9 meters. The chamber pumping train consists of a single stage gaseous nitrogen (GN_2) ejector, three mechanical roughing pumps with blowers, and two 1.2 meter diameter oil diffusion pumps. Liquid nitrogen cold walls surround the usable chamber volume providing cryopumping and thermal conditioning. The facility and test article shroud systems in combination enabled simulation of orbital conditions (vacuum levels as low as 10^{-8} torr and insulation surface temperatures ranging from 80 to 300 K).

A key facility capability was the test article pressure control subsystem used to maintain the steady-state tank ullage pressure necessary during the boiloff tests, which are described in the next section. The subsystem was composed of several flow control valves (located in the MHTB vent line), each of which

was regulated through a closed loop control system. This control system adjusted the valve positions based on a comparison between the measured tank ullage pressure and a desired set point.

TEST PROCEDURES

Two types of tests were performed with the TVS system in the MHTB. The first type was referred to as the boiloff test, and the second was the TVS performance test. A more detailed description of each type of test is provided in the following subsections.

BOILOFF TESTING

Boiloff testing was conducted to determine the ambient heat leak into the MHTB tank and to set up consistent initial conditions for each of the TVS tests. The first test series was conducted with the vacuum chamber LN_2 cold walls operating to produce a minimum heat leak condition. The second series was run without the LN_2 cold walls, thereby providing a high ambient heat leak condition. Details relating to the performance of boiloff testing were reported in Reference 4. Maintenance of constant ullage pressure and steady state insulation temperatures was necessary during this test. The boiloff vent flow rate was typically recorded for 6 hours after steady state was achieved.

The ambient heat leak is expressed as an energy balance across the tank boundary where the boiloff heat transfer is equal to the sum of the heat transfer through the insulation, the tank penetrations, and the rate of energy storage, if any, as seen in the following equation:

$$\dot{Q}_{boiloff} = \dot{Q}_{insulation} + \dot{Q}_{penetrations} + \frac{\Delta U_{system}}{\Delta t}.$$

The terms $\dot{Q}_{boiloff}$ and $\dot{Q}_{penetrations}$, are defined using the test data. Specific calculation of these parameters can be found in Reference 4. The thermal storage term $\Delta U_{system} / \Delta t$ represents the energy flow into or out of the test tank wall, insulation, and fluid mass. It is driven by the fluid saturation temperature, which varies as ullage pressure varies. Since the ullage pressure is held within a tight control band (+/- 0.0069 kPa), this term is considered negligible. The $\dot{Q}_{insulation}$ term can then determined using the defined quantities listed above.

TVS PERFORMANCE TESTING

The spray-bar was evaluated at 90%, 50%, and 25% fill levels in the first test series. In the second series, both the spray-bar and axial jet concepts were tested at 90% and 50% fill levels, but with an elevated heat leak condition. The ambient heat leak was elevated during Series 2 due to the axial jet TVS hardware addition, and because the facility cold walls were not operated.

For each fill level, after boiloff testing was complete, the tank was locked up and allowed to self pressurize until the ullage pressure (P4) reached the maximum tank pressure set point of 138 kPa. Upon reaching this pressure, the recirculation pump was turned on, and mixing continued until the ullage pressure reached 131 kPa, the tank minimum set point. Upon reaching the minimum set point, the pump was turned off and the tank would self pressurize for the next cycle. This automated operation continued until the tank liquid saturation pressure (PSA1) reached the lower pressure set point. At this point, the J-T device was used to extract heat energy from the liquid whenever the pump operated. Both TVS system concepts operated in this manner until the tests concluded. This TVS control logic is illustrated in Figure 4.
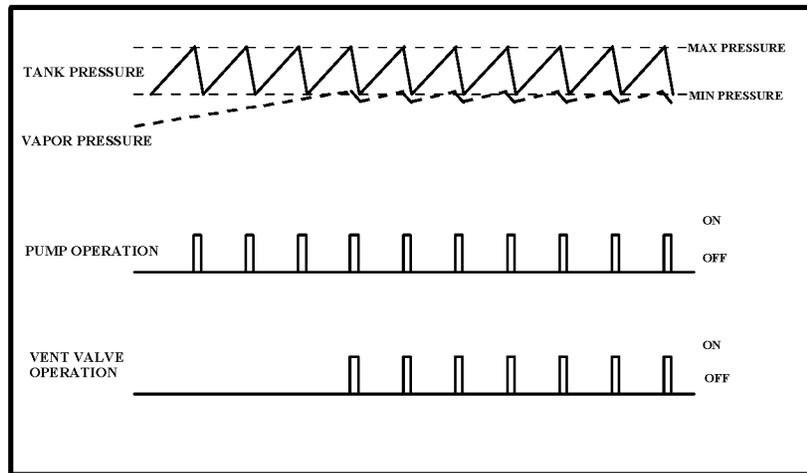

Figure 4: TVS Control Logic Illustration

RESULTS AND DISCUSSION

The baseline heat leak, mixing or destratification performance, and thermal energy removal, for both TVS concepts, are discussed in the following sections.

TANK HEAT LEAK

The results from the boiloff tests, presented in Table 1, indicated that the ambient heat leak for Series 1 was less than half that of Series 2. The heat leak for Series 2 was greater due to additional heat leak through the axial jet TVS hardware (not present during series 1), and because the vacuum chamber cold walls were not operating. As one would expect, the heat leak magnitude had a significant influence on the vent cycle operation, which was discussed in some detail, for the spray-bar configuration, in Reference 5.

Table 1: Ambient Heat Leak Data From Boiloff Tests

Fill Level (%)	Ambient Heat Leak, Test Series 1, (Watt)	Ambient Heat Leak, Test Series 2, (Watt)
90	20.2	54.1
50	18.7	51.0
25	18.8	----

PROPELLANT TANK DESTRATIFICATION

Spray-Bar

The test data confirmed that the spray-bar was effective in destratifying the tank ullage and liquid, as can be seen from the plot of the silicon diode rake temperatures in Figure 5. The percentages listed with each silicon diode designation represent the liquid fill level. During tank lock-up, the ullage became significantly stratified. When the spray-bar was activated, the ullage rapidly destratified, regardless of fill level. For the 50% fill level in Series 1, the tank destratified such that the liquid and gas temperatures were within 0.4 K of each other. These results were significant since they represented the worst case gravity environment of 1-g. In micro-gravity, the spray-bar would be even more effective in mixing the tank contents, since there would be no significant gravitational force to pull the sprayed fluid out of the ullage. The spray-bar was also effective in chilling down warm tank walls regardless of propellant position, which would be beneficial in tank fill operations. For example, during the 50% fill test illustrated in Figure 5, the tank dome cooled approximately 2 K during spray-bar operation.
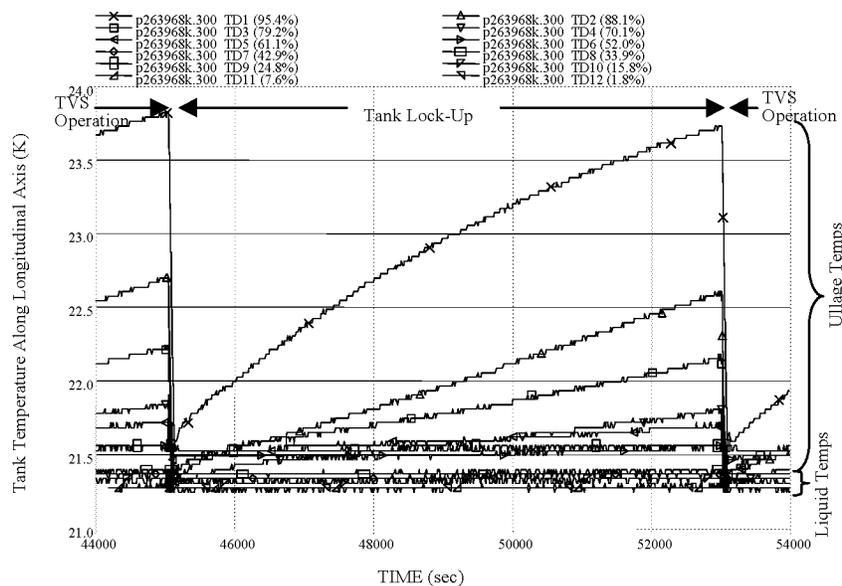
Figure 5: Plot Illustrating Tank Stratification/Destratification for the Spray-Bar, 50% Fill, Series 1

Axial Jet

The axial jet did not appear to destratify the ullage as can be seen by the plots in Figures 6 and 7. However, there was not a significant rise in temperature during the tank lock-up between TVS cycles. One explanation for the lack of destratification was that the liquid jet did not penetrate the liquid/ullage interface, and thus was unable to cool the ullage. However, due to a hardware problem, the axial jet recirculation pump operated at approximately 38 lpm, one third of its rated flow rate of 114 lpm. A CFD model of the axial jet was constructed in order to investigate whether or not, the higher flow rate would have significantly improved the axial jet performance. Preliminary results from that model are discussed later in this paper.

One observation that was counter-intuitive, was the tank lock-up time between TVS cycles, for the axial jet versus the spray-bar. The tank lock-up time for the axial jet was expected to be less than for the spray-bar since it was not as effective in cooling the ullage as the spray-bar. It was expected that the warm, stratified ullage would lead to a pressure rise rate much greater than for the cool, destratified ullage created by the spray-bar. However, the tank lock-up times for the axial jet were actually longer for both fill levels tested in Series 2. Some potential causes for this phenomenon have been identified, and are being investigated. Potential causes include: larger ullage volume (lower fill level) during axial jet tests, evaporation of liquid deposited on tank surfaces by the spray bar, and less efficient destratification of the tank liquid by the spray-

bar compared to the axial jet. CFD models planned for both TVS concepts will clarify this phenomenon, and the results of these analyses will be published at a later date.
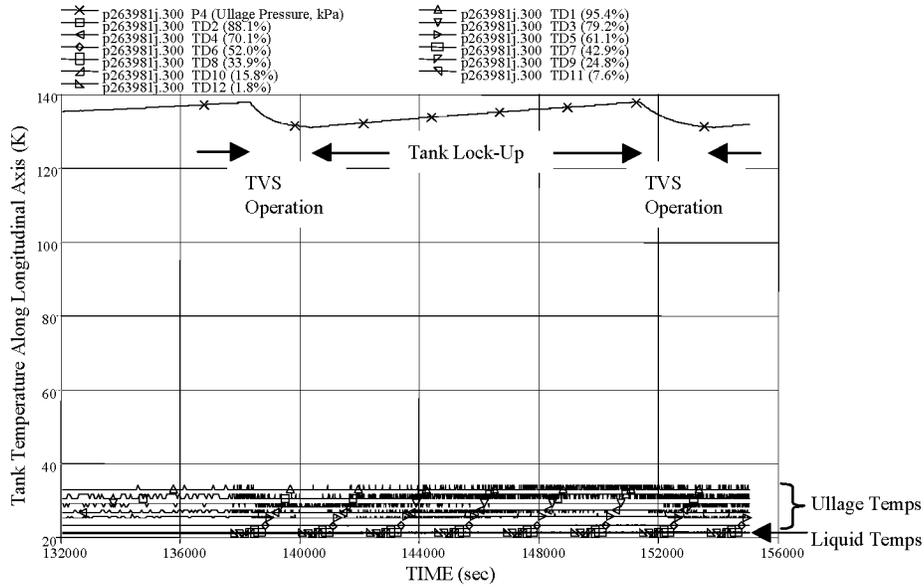

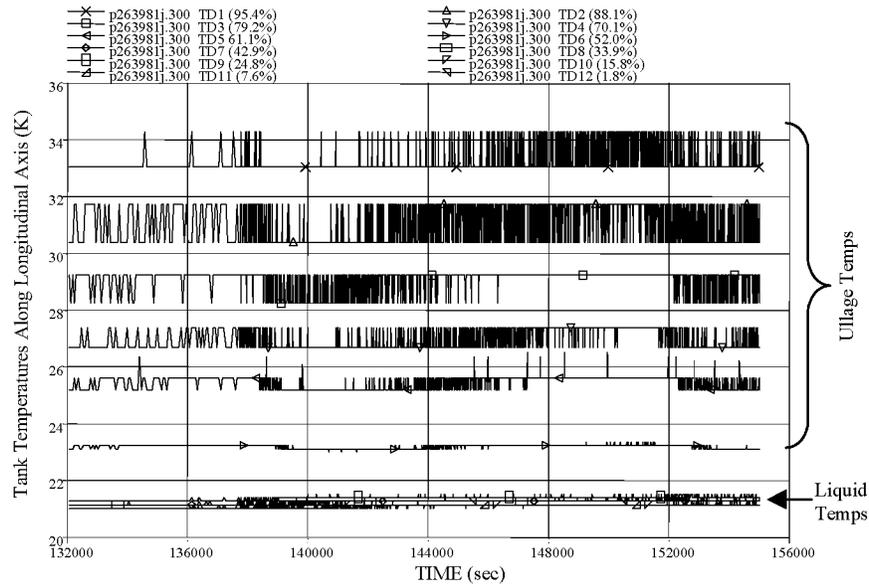Figure 6: Plot of Tank Stratification for Axial Jet, 50% Fill, Series 2

Figure 7: Enlarged Plot of Tank Temperatures in Figure 6

HEAT ENERGY EXTRACTION

The most important measure of TVS performance is its ability to extract thermal energy from the tank propellant. Once the propellant has reached the saturation temperature at tank operating pressure, the TVS system must be able to extract enough energy to offset the ambient heat leak into the tank and maintain tank pressure control. The heat extracted by the vent flow is calculated by the following equations:

$$\dot{Q}_{vent} = \dot{m}_{vent}(h_{out} - h_{in})$$

$$\dot{Q}_{ave} = \dot{Q}_{vent}\left(\frac{t_{open}}{t_{total}}\right)$$

Given the duty cycle (valve open time divided by the sum of valve open plus valve closed time) for a particular test, the value of vent heat extraction is averaged ($\dot{Q}_{ave}$) over a selected interval, during steady state operation, of each test in order to yield valid comparisons of TVS performance from test to test.

Table 2: Calculated Heat Extraction and Mass Flow Rates for Both TVS Concepts

Test Series	Mixer Type	Fill Level (%)	$\dot{Q}_{vent}$ (Watt)	$\dot{Q}_{ave}$ (Watt)	$\dot{m}_{vent}$ (kg/s)
1	Spray Bar	90	1444	15.9	0.0034
1	Spray Bar	50	1486	16.3	0.0035
1	Spray Bar	25	1507	17.5	0.0036
2	Spray Bar	90	**	**	**
2	Spray Bar	50	2108	40.6	0.0048
2	Axial Jet	90	215.8	109.3	0.000485
2	Axial Jet	50	223.4	77.3	0.000499

** Hardware problem, not enough J-T cycles to calculate heat extracted.

Spray-Bar

The vent mass flow rate for the spray-bar TVS is calculated using the compressible flow equation for a gas through a sonic orifice shown in the following equation:

$$\dot{m}_{vent} = \frac{0.14(CdA)P}{\sqrt{T}} \ .$$

The assumption that gas was flowing through the orifice was verified with the test data, which indicated that the heat exchanger completely vaporized the two-phase mixture exiting the J-T valve.

Table 2 summarizes the average heat extraction rates for all of the spray-bar tests conducted, both in 1996 and 1998. When comparing $\dot{Q}_{ave}$ values to the ambient heat leak values for the same test, in all cases, the $\dot{Q}_{ave}$ value is lower than the corresponding ambient heat leak value. The maximum difference, 21%, occurred in test Series 1 at the 90% fill level. In reality, the thermal energy removed by the TVS equaled the ambient heat leak into the tank. Otherwise, the tank pressure would not have remained within the prescribed pressure control band and the liquid saturation pressure would have continued to rise.

Potential sources for the difference between the heat extraction rate and the ambient heat leak were investigated. One source considered, but ruled out, was instrumentation uncertainties. The error in measured quantities would had to have been much larger than the instrumentation uncertainties to yield the additional enthalpy necessary to raise the heat extraction rate to the ambient heat leak value. The small magnitude of the vent mass flow rate and its calculation sensitivities made it the most likely candidate to account for any difference between the ambient heat leak and the TVS heat extraction calculation.

Axial Jet

The vent flow rate for the axial jet was calculated using an the following equation for the mass flow rate through the viscojet:

$$\dot{m}_{vent} = 0.9(\frac{10000}{Lohm})(\Delta P * S)^{1/2}(1 - X) \ .$$

Further detail on this flow rate equation is supplied in Reference 6. The comparison of the heat extraction calculations for the axial jet in Table 2, to the ambient heat leak values in Table 1, reveals a 102% difference for the 90% fill case, and a 52% difference for the 50% fill case. These differences are even greater than those observed for the spray-bar configuration. As with the spray-bar tests, the most likely candidate for these differences lies again in the vent mass flow rate calculation. The equation was originally formulated for a liquid or two phase mixture flowing through the viscojet. Temperature and pressure data at

the viscojet exit indicated that the state was a gas, the quality of which is X=1. Since at X=1, the vent flow rate becomes zero, the (1-X) term was discarded and the vent flow rate was calculated based on a liquid state. This would lead to a much larger calculation for mass flow rate, and thus a greater heat extraction rate. As with the spray-bar cases, the heat extraction calculation is irrelevant if the TVS is able to maintain the propellant tank pressure within the subscribed control band. One can conclude that the TVS is able to remove heat energy at a rate equal to the ambient heat leak. Such was the case for the axial jet at the 90% fill level. However, at the 50% fill level, the TVS was unable to remove enough heat energy to maintain the tank ullage pressure within the control band. As the TVS continued to operate, tank ullage pressure continued to increase.

CFD MODELING

Since the axial jet concept, due to a hardware problem, ran at less than its designed capacity, any comparison of the test data alone is incomplete. In order to gain a more valid comparison of the two concepts, a CFD model of the axial jet configuration was assembled. The tool used was CFX-4, a CFD code distributed by AEA Technology, Inc. In addition to the fluid dynamics modeling, CFX is capable of modeling ambient heat leak into, as well as heat and mass transfer within, a system.

Two CFX cases were modeled, at the 50% fill level, with pump flow rates of 114 lpm (30 gpm) and 38 lpm (10 gpm). Ambient heat leak and mass transfer within the tank were not taken into account. The initial temperature conditions for each case were identical and based on actual test data. Temperature contours from the two cases were included in Figures 8 and 9. The preliminary results show that the liquid jet barely penetrated the liquid/ullage interface for the 38 lpm case, as seen in Figure 8. The temperature contour indicated a stratified ullage, which is unaffected by the jet. This was confirmed by the ullage temperature data, which remained stratified and almost constant, as shown in Figure 7. For the case run at the rated flow rate of 114 lpm, the liquid jet penetrated the liquid/ullage interface and hit the tank dome, as shown in Figure 9. The temperature contour indicated that some ullage cooling took place, although the very top of the ullage was still quite warm. Therefore, it is reasonable to assume that the axial jet performance would have been improved had the mixer been able to run at the rated flow rate. However, the performance cannot be quantified at this time since the CFD case modeled the fluid dynamics only. Results with ambient heat transfer and mass transfer effects will be published at a later date.
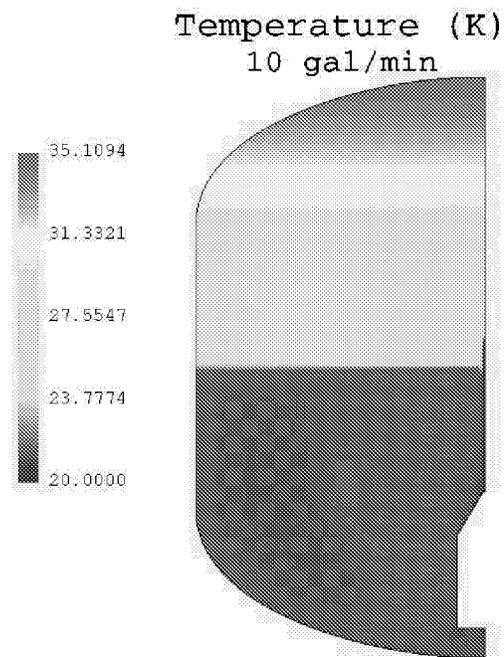
Temperature (K)
10 gal/min

35.1094

31.3321

27.5547

23.7774

20.0000

Figure 8: Temperature Contour in Tank, Axial Jet, 50% Fill, 10 gpm

Temperature (K)
30 gal/min

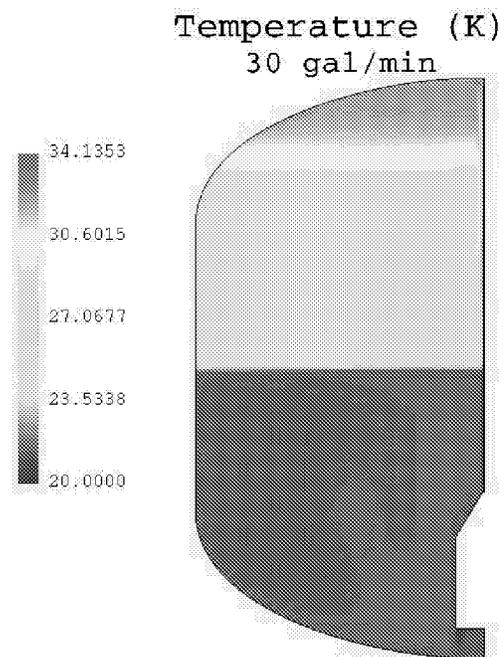34.1353

30.6015

27.0677

23.5338

20.0000

Figure 9: Temperature Contour in Tank, Axial Jet, 50% Fill, 30 gpm

CONCLUSIONS

The test data dramatically illustrate that the spray-bar TVS configuration was very effective in destratifying, and removing heat energy from, the propellant tank contents. This was evidenced by the fact that the spray-bar maintained ullage pressure within the prescribed control band, for all fill levels and heat leak values tested. The axial jet was ineffective in destratifying the tank ullage, and failed to maintain the tank ullage pressure within the control band for the 50% fill case. Preliminary CFD models indicated that the hardware problem limiting the mixer flow rate to almost 1/3 of its rated value, was a factor in the reduced performance of the axial jet. Had the mixer liquid jet penetrated the ullage, some destratification would have taken place. Unfortunately, that amount of destratification is difficult to quantify at this time. However, future CFD modeling with heat and mass transfer should provide some insight into whether or not the axial jet would have performed nominally at the rated mixer flow rate.

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