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INVESTIGATIONS INTO TANK VENTING FOR PROPELLANT RESUPPLY

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Abstract

Models and simulations have been developed and applied to the evaluation of propellant tank ullage venting, which is integral to one approach for propellant resupply. The analytical effort was instrumental in identifying issues associated with resupply objectives, and it was used to help develop an operational procedure to accomplish the desired propellant transfer for a particular storable bipropellant system. Work on the project was not completed, and several topics have been identified as requiring further study; these include the potential for liquid entrainment during the low-g venting, and thermal/freezing effects in the vent line and orifice. Verification of the feasibility of this propellant venting and resupply approach still requires additional analyses as well as testing to investigate the fluid and thermodynamic phenomena involved.

Nomenclature

A	= surface or flow area
C_d	= discharge coefficient
c_p, c_v	= specific heat at constant pressure, volume
D	= diameter
F	= force
Gr	= Grashof number
h	= specific enthalpy
h_c	= convective heat transfer coefficient
k	= thermal conductivity
M	= molecular weight
m	= mass
Nu	= Nusselt number
P	= pressure
Pr	= Prandtl number
$\dot{Q}$	= heat transfer rate
R	= gas constant
T	= temperature
u	= specific internal energy
V	= gas volume, velocity
Y, y	= weight fraction, mole fraction
γ	= specific heat ratio
μ	= absolute viscosity
ρ	= density
$\dot{\omega}$	= flow rate

Subscripts

g	= pressurant gas
v	= propellant vapor

Introduction

The resupply of propellant on-orbit has been recognized as an important technology objective for some time, and it has been studied for application to the space station and other spacecraft.[1,2] The complexities associated with resupply have also been noted, including difficulties of zero-g fluid management and the avoidance of overboard contamination. The design and development of the now-terminated International Space Station Propulsion Module (ISSPM) entailed the requirement for frequent resupply of monomethyl hydrazine (MMH) and nitrogen tetroxide (NTO) from the Space Shuttle Orbiter during the 12-year design life of the ISSPM.

Some of the resupply methods previously studied are shown in Table 1, along with important characteristics of each one. Upon consideration of the ISSPM propulsion system type (pressure regulated) and the desire to minimize Orbiter modifications for propellant transfer, the Ullage Venting concept was selected. The method chosen was to vent the propellant tanks to a prescribed pressure to allow for resupply of propellant, which then recompressed the existing ullage. Although this paper will deal only with the complexities associated with tank venting, the overall propellant resupply topic involves variables such as station configuration, solar cycles, propellant remaining, and planned reboost durations. In addition, there are fluid and thermodynamic issues associated with the transfer of fluid into the propellant tanks.

Table 1 On-Orbit Propellant Resupply Methods

Resupply Method	Characteristics
Ullage Recompression	• Incoming liquid compresses existing tank ullage • Operationally simple • No overboard venting • Applicable to blowdown systems • Compressive heating affects transfer rate and duration
Ullage Venting	• Tank pressure vented to allow liquid refill • Applicable to pressure regulated systems • Requires liquid/gas separation • Need to preclude overboard liquid venting and contamination • Need to preclude freezing during venting • Compressive heating affects transfer rate and duration
Ullage Exchange	• Incoming liquid displaces ullage gas to supply tank/source • Closed loop, constant pressure pumping • Applicable to presure regulated systems • May need to drain back to establish ullage volume • Fluid management issues in supply system
Drain/Vent	• Drain all tank propellant back to supply system • Vent remaining liquid/gas overboard to vacuum • Applicable to complex surface tension designs • Need to preclude freezing during venting

The OMS tanks baselined for the ISSPM use surface tension propellant management which allows for liquid reorientation throughout the tank, and a major issue concerned the ability to vent the tanks without releasing propellant to the environment around the station and Orbiter. A plan was developed to vent the tanks during reboost engine firings so that the acceleration would provide liquid settling during the venting process; the reboost firings, which are required periodically for drag makeup, would be supplied by other propellant tanks in the ISSPM.

The amount of tank venting required is driven by the amount of propellant to be transferred into the ISSPM, which in turn is a function of various mission parameters. The maximum resupply requirement of 9000 lbm represented the worst case in terms of the degree of venting and pressure decay in the propellant tanks. In order to accommodate the large resupply quantities, ullage venting to low pressures was required, and the resulting low temperatures created concerns over freezing in the vent line. This potential for freezing and disruption of the venting timelines had to be addressed in the strategy for tank venting.

Analytical Modeling

Analytical models were developed to simulate the venting process for both fuel and oxidizer tanks. The models incorporate expressions for sonic venting of a gas mixture (especially important for the oxidizer tank with its high NTO vapor concentration), and include thermodynamics and heat transfer methodology which have been validated on previous spacecraft applications.[3]

The schematic in Fig. 1 is a representation of the venting geometry and configuration, and indicates the physical processes included in the simulation model.

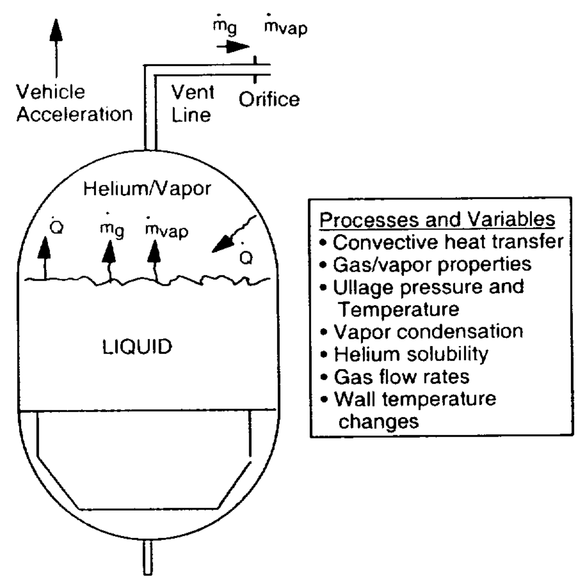

Fig. 1 Tank Venting Representation

The expression for sonic flow of a gas mixture is used, where gas properties are averaged to account for the mixture of helium pressurant and propellant vapor, as indicated below:

$$\dot{\omega} = C_d AP\sqrt{\frac{\gamma}{RT}\left(\frac{2}{\gamma+1}\right)^{\frac{\gamma+1}{\gamma-1}}} \tag{1}$$

The average gas properties for the mixture are determined as follows:

$$R = R_v Y_v + R_g Y_g \tag{2}$$

$$\bar{\gamma} = \frac{\bar{c}_p}{\bar{c}_v} \tag{3}$$

$$\bar{c}_p = c_{pv} Y_v + c_{pg} Y_g \tag{4}$$

$$\bar{c}_v = c_{vv} Y_v + c_{vg} Y_g \tag{5}$$

The individual flow rates for helium and vapor are then expressed as:

$$\dot{\omega}_g = Y_g \dot{\omega} \tag{6}$$

$$\dot{\omega}_v = Y_v \dot{\omega} \tag{7}$$

One factor which changes the content of the ullage is vapor condensation, and this is taken into account in the calculation of overall ullage gas properties and flow rate. The approach is to allow condensation during the venting process when the vapor pressure is above the saturated value for the current ullage gas temperature. Another option in the model is the calculation of saturated gas in the propellant as the pressure decreases during the venting. Although this can add helium to the ullage, most of the liberated helium should stay suspended in the liquid due to the low acceleration.

The models involve thermodynamics and heat transfer, and the analytical tasks include 1) selecting methods which provide adequate accuracy, 2) identifying and describing all the relevant physical processes, and 3) avoiding excessive complexity. A good understanding of the physical processes is important; for example, it would not be sensible to over-complicate a model by including detailed analytical models of processes which are relatively insignificant to the overall results, and which are overwhelmed by system uncertainties in other areas. The treatment of the physical processes can be illustrated by expressing the first law of thermodynamics for the tank ullage control volume.

$$\frac{d}{dt}\left(m_g u_g + m_v u_v\right) = \dot{Q} - \dot{m}_g h_g - \dot{m}_v h_v \tag{8}$$

On the right side of the equation , the terms in order represent heat transfer to the ullage, the energy of exiting pressurant gas, and the energy of exiting vapor. The heat transfer term includes convective heat transfer from the tank wall and propellant surface as well as heat released due to vapor condensation.

After appropriate manipulation and substitution, the expression can be written for temperature change.

$$\dot{T} = \frac{\dot{Q} - \dot{m}_g\left(h_g - c_{vg}T\right) - \dot{m}_v\left(h_v - c_{vv}T\right)}{m_g c_{vg} + m_v c_{vv}} \tag{9}$$

It is important to establish realistic predictions for the ullage gas temperature, since one of the critical concerns is the potential for vapor freezing and flow restriction during venting. Therefore, a major constraint in the analysis is the avoidance of vapor freezing while venting to the desired pressure within the time available during reboost firings. The propellant temperature is assumed to be constant, while the tank wall temperature is a function of the material properties and heat transfer. The new tank pressure at each time interval is calculated after accounting for ullage mass and temperature changes.

The selection of the appropriate heat transfer mechanism is critical to internal thermodynamic modeling, and it was initially assumed that free convection would be the dominant mode based on the low acceleration environment during the reboost firing. Free convection dominates over forced convection if the Grashof number is larger than the square of the Reynolds number[4], and especially if the ratio of the two values is greater than 10. This relationship was evaluated for all the simulation cases, with the result that the ratio of interest is greater than 100 for most of the venting period. Therefore, the selection of free convection appears valid.

Convective heat transfer can be expressed as:

$$\dot{Q} = h_c A(\Delta T) \tag{10}$$

where ΔT applies to the temperature difference between wall and gas or between liquid and gas. Modeling is based on free convection inside spherical cavities[4] with the following relationships:

$$h_c = \frac{kNu}{D} \tag{11}$$

where:

$$Nu = 5.90 \ for \ Gr\Pr < 10^4$$

$$Nu = 0.59(Gr\Pr)^{0.250} \ for \ 10^4 < Gr\Pr < 10^9$$

$$Nu = 0.13(Gr\Pr)^{0.333} \ for \ 10^9 < Gr\Pr < 10^{12}$$

The heat transfer coefficient is influenced by a number of parameters, including vehicle acceleration and gas properties. The change in the temperature of the wall exposed to the ullage is calculated using the convective heat transfer in conjunction with wall heat capacity.

Bipropellant systems introduce additional variables involving the oxidizer, which in this case is nitrogen tetroxide. The relatively high vapor pressure means that vapor properties must be included in the oxidizer tank model. In the calculation of ullage gas properties, the incorporation of vapor effects includes the following expressions[5] for viscosity and thermal conductivity:

$$\mu = \frac{\mu_v y_v M_v^{0.5} + \mu_g y_g M_g^{0.5}}{y_v M_v^{0.5} + y_g M_g^{0.5}} \tag{12}$$

$$k = k_v y_v + k_g y_g \tag{13}$$

Simulations were written to model the venting of both fuel and oxidizer tanks. Flexibility was provided in the subroutines so that the analysis could either include or ignore the effects of vapor condensation, helium desaturation/outgassing, and heat transfer. Inputs included tank volumes and properties, initial conditions, orifice size, vehicle acceleration, and desired final pressure.

Analysis Results

Some interesting findings resulted from the analytical effort. First, for a given vent orifice size, venting to a given pressure takes significantly longer for the NTO tank due to the large vapor mass mixed with the helium pressurant; this effect is illustrated in Fig. 2, which shows a difference of over 700 sec in the time required to achieve the desired tank pressure. The fuel and oxidizer vent simulations were run with a common vent orifice diameter of 2.98 mm, and this example represents the maximum requirement (in terms of tank pressure decay) for ullage venting.

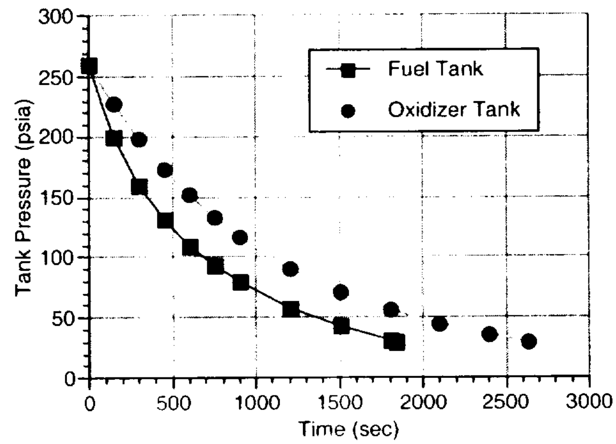

Fig. 2 Fuel and Oxidizer Venting Comparison

The ullage mass distribution during the venting process is shown in Fig. 3, and for the oxidizer tank the initial vapor mass is 60% of the total gas mass in the ullage. The mass differential diminishes as the venting proceeds. Helium constitutes nearly the entire ullage mass for the fuel tank, and is shown for reference on the plot.

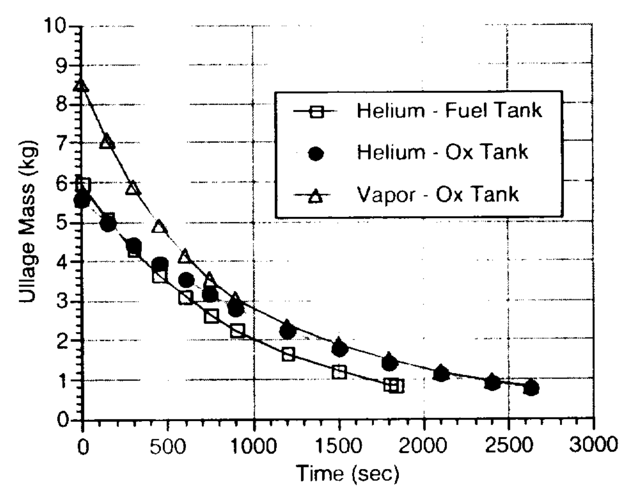

Fig. 3 Ullage Mass Distribution

It is desirable to avoid freezing temperatures in order to minimize the potential for venting disruption. The fuel tank has advantages in that the amount of vapor is very small, and the freezing point for MMH is much lower than for the NTO. It is possible to drop below the fuel freezing point if the venting is conducted very rapidly; however, the vent orifice can be sized to complete the desired venting within the timeframe allowed. Fig. 4 illustrates the ullage temperature profile for the fuel tank resulting from venting of the tank initially at 260 psia to a final pressure of 30 psia. The smaller orifice extends the venting duration significantly, but provides a comfortable margin above the freezing point. The resulting time required for the venting, about 1800 sec, fits within the allowable time for a reboost burn. Therefore, propellant settling can be maintained for the entire venting duration.

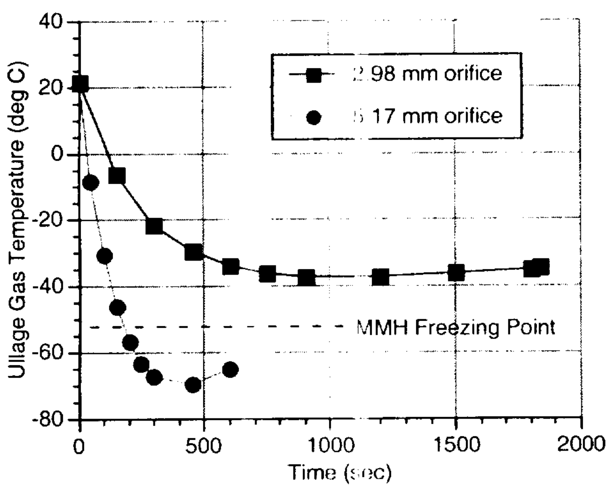

Fig. 4 Fuel Tank Venting Characteristics

The problem is considerably more difficult for the oxidizer tank, primarily due to the higher freezing point and much larger vapor mass. Fig. 5 shows a comparison of fuel and oxidizer tank venting from 260 to 30 psia using the same size orifice. The fuel ullage stays above its freezing point, but the oxidizer does not, even though the ullage temperature is higher in the oxidizer tank. The inclusion of oxidizer vapor condensation is favorable, but the temperature still drops below freezing at a time well short of the required venting time. The adiabatic trend for the oxidizer tank is shown for reference. It is seen that vapor condensation results in a significantly higher ullage temperature early in the venting, and Fig. 6 shows the contribution of the various heat transfer mechanisms. Vapor condensation actually dominates the cumulative heat transfer to the ullage in the early phases, significantly affecting the rate of temperature decrease; however, after about 1000 sec, condensation ceases and convective heat transfer from the wall and liquid surfaces plays the greater role.

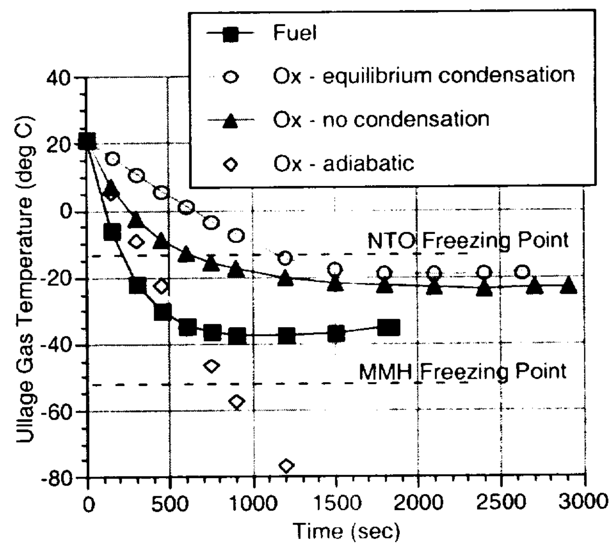

Fig. 5 Ullage Gas Temperature During Venting

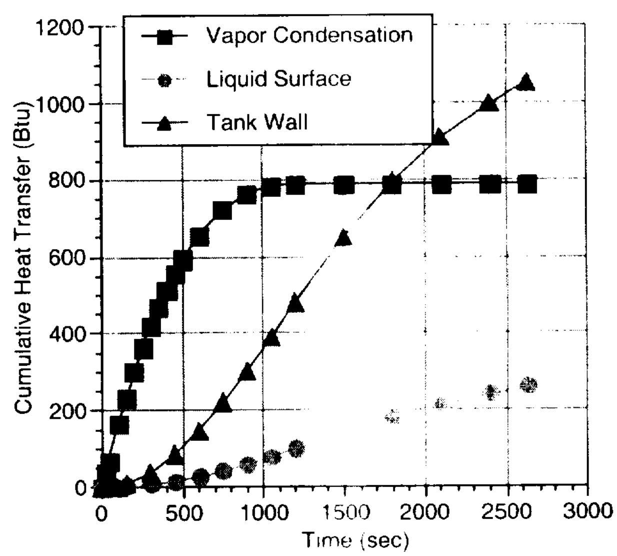

Fig. 6 Heat Transfer to Ullage During Venting

An obvious approach to the oxidizer freezing concern would be to consider smaller vent orifices to extend the venting time and allow heat transfer to result in higher ullage temperatures. Fig. 7 shows the result of simulations to investigate the relationship between orifice size and temperature for a case where it is required to vent the tank from 260 to 30 psia. It is possible to avoid freezing using a very small orifice, but the resulting venting durations are extremely long. For the ISSPM application, these times are well beyond the desired durations for a reboost burn.

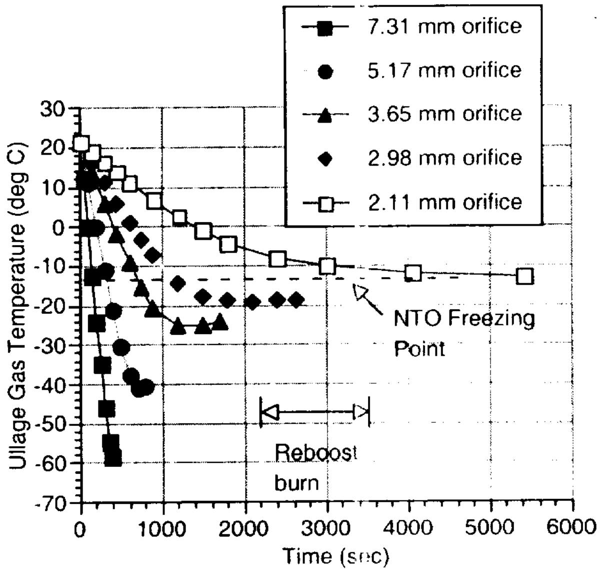

Fig. 7 Effect of Vent Orifice Size on Ullage

A strategy was developed to split the reboost activity into multiple burns, thereby allowing for ullage gas warmup prior to the next burn/vent cycle. A simulation of this approach is shown in Fig. 8, illustrating an initial tank blowdown to about 110 psia, followed by a termination of venting to allow for ullage warmup. A second burn/vent cycle is then initiated to take the tank down to the desired pressure. Although the plot shows a full warmup to equilibrium temperature between cycles, the actual case may be something inbetween depending upon the time between burns. Another assumption in the analysis is that vapor pressure returns to the initial value, and this equilibrium may not be fully achieved in the time available. With assurance of adequate time between vent cycles, this approach is shown to be effective in achieving the low pressures required to accept the propellant transfer, while avoiding freezing conditions in the oxidizer tank.

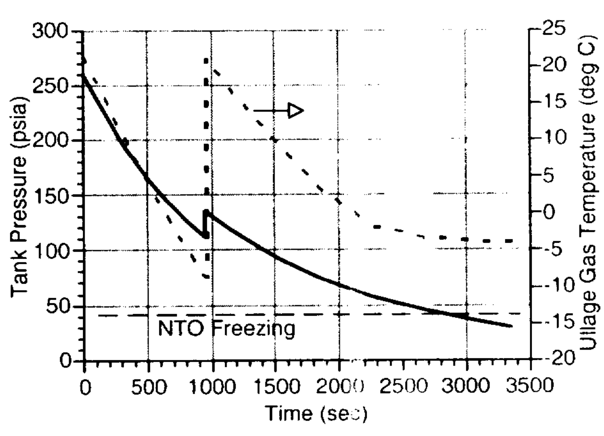

Fig. 8 Use of Burn/Vent Cycles for Ullage Warmup

While this approach appeared to be acceptable for the ISSPM, the requirement to tailor the reboost activity does impact the operational timelines; acceptability for other applications would have to be assessed.

Pressurant solubility was also evaluated in the analysis, but had only a minor effect on tank pressure and venting times. For the example of extensive oxidizer tank venting from 260 to 30 psia, the effect on ullage temperature was less than 0.5°C. Acceleration is another variable which affects heat transfer, and the increased heat transfer associated with doubling the acceleration for the same venting case raised the minimum ullage temperature by only about 2°C.

Discussion of Technical Issues

Perhaps the most critical concern is the avoidance of liquid expulsion during the venting process. This was especially important for the ISSPM application since the timelines called for periods of simultaneous venting of fuel and oxidizer tanks. While liquid settling is achieved by initiating the venting subsequent to a prescribed time after start of a reboost burn, the accelerations are very small (less than 0.001g), and there are still concerns regarding achievement of a stable interface and the possibility of liquid entrainment. For example, a liquid droplet will move toward the vent port if drag forces resulting from the exiting gas exceed the force due to acceleration. The drag force was first calculated using the conventional velocity squared relationship:

$$F = \tfrac{1}{2} C_d A \rho V^2 \qquad (14)$$

The conclusion is that only microscopic droplets could be transported in the flow. However, considering that the Reynolds number for a droplet is very low in the cylindrical portion of the tank (on the order of 1), it was deemed more appropriate to employ Stokes flow for drag on a slowly moving sphere:[6]

$$F = 3\pi\mu V D \qquad (15)$$

where V is the gas velocity in the ullage and D is the droplet diameter.

As before, the drag force was compared to the force due to acceleration for various droplet sizes. The conclusion again is that droplets would have to be very small (< 1 mm diameter) to allow for transport in the ullage toward the vent port. There would be a greater possibility of entrainment for small condensation droplets or for droplets existing closer to the vent outlet where the gas velocity is higher. Therefore, if the propellant is initially settled, the potential for liquid entrainment during venting appears low.

Another phenomenon affecting the potential for liquid entrainment during venting is the desaturation and outgassing of helium during the venting process. Fig. 9 illustrates the effective increase in liquid volume due to bubble formation (the "soda pop" effect) in the liquid mass; the low acceleration will prevent most of the evolved helium from reaching the ullage volume during the venting operation. It should be noted that while the figure shows uniformity for the bubbles, most of the actual helium bubble nucleation sites will likely be on internal structural components and tank walls.

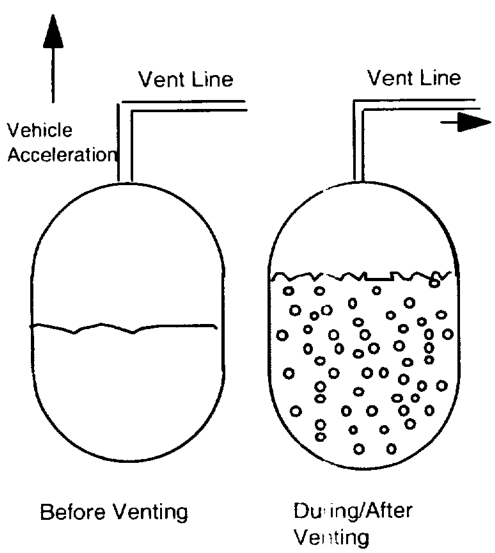

Fig. 9 Desaturation Effects During Ullage Venting

The combination of liquid movement closer to the vent port plus a possible increase in turbulence at the surface must be considered. For example, extensive venting of a fully saturated propellant tank with a relatively low initial ullage volume could result in enough outgassing for the "foamy" propellant mass to entirely fill the tank volume. Although it is unlikely that a propellant resupply would be required or conducted for this condition, it does illustrate that this desaturation phenomenon should be considered in the evaluation of tank venting. Of course, propellant/pressurant combinations with high solubility values would exhibit greater susceptibility to this phenomenon.

The resupply mass which can be received by the propellant tank is influenced by the tank pressure subsequent to the venting operation. The determination of post-vent target pressure is not completely straightforward, and is influenced by vapor pressure and solubility phenomena. For example, at the end of a vent cycle the tank pressure will increase due to 1) re-establishment of equilibrium vapor pressure, and 2) evolution of helium gas from the supersaturated condition existing at the end of venting. The amount of gas evolved is dependent on the propellant mass and the pressure decay due to venting, meaning that the effect is greater when a tank at low ullage volume undergoes significant venting. These effects, which are especially important for the oxidizer tank, are taken into account in the determination of the desired post-vent tank pressure.

Other issues requiring further study include uncertainties in NTO vapor properties and uncertainties in the heat transfer model fidelity at the acceleration levels of less than 0.001g. The latter factor is an issue since the spacecraft data base used for model validation does not extend below about 0.01g. A final concern relates to potential thermal/freezing effects in the vent line and orifice, and it is possible that active heating will be required. Thermal analyses for the vent line and orifice were not completed.

Conclusions

The analytical effort was instrumental in identifying issues associated with ISSPM resupply objectives, and it was used to help develop an operational procedure to accomplish the desired propellant transfer. Several topics have been identified as requiring further study; these include the potential for liquid entrainment during the low-g venting, effects of liquid surface turbulence due to desaturation, uncertainties in NTO vapor properties, and thermal/freezing effects in the vent line and orifice. Also, since the acceleration level of less than 0.001 g is low relative to the spacecraft data base used for model validation, there is some uncertainty in the fidelity of the heat transfer models. Verification of the feasibility of this propellant venting and resupply approach still requires additional analyses as well as testing to investigate the fluid and thermodynamic phenomena involved. Although some of the timelines and procedures are specific to ISSPM and the propellants used, many of the findings and issues should be relevant for future applications involving tank venting.

Acknowledgments

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