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ANALYSIS OF A SPACE EMERGENCY AMMONIA DUMP USING THE FLOW-NET TWO-PHASE FLOW PROGRAM

J. Navickas
McDonnell Douglas Space Systems Company
Huntington Beach, California

W.C. Rivard
Mechanical Engineering Department
University of Maine

ABSTRACT

Venting of cryogenic and non-cryogenic fluids to a vacuum or a very low pressure will take place in many space-based systems that are currently being designed. This may cause liquid freezing either internally within the flow circuit or on external spacecraft surfaces. Typical ammonia flow circuits were investigated to determine the effect of the geometric configuration and initial temperature, pressure, and void fraction on the freezing characteristics of the system. The analysis was conducted also to investigate the ranges of applicability of the FLOW-NET program. It was shown that a typical system can be vented to very low liquid fractions before freezing occurs. However, very small restrictions in the flow circuit can hasten the inception of freezing. The FLOW-NET program provided solutions over broad ranges of system conditions, such as venting of an ammonia tank, initially completely filled with liquid, through a series of contracting and expanding line cross sections to near-vacuum conditions.

INTRODUCTION

Freezing of either a cryogenic or a non-cryogenic fluid during venting to a low pressure environment is a concern in the design of the space liquid storage systems. There are many situations where such venting may be necessary. For instance, the Space Station ammonia loop may have to be vented during an emergency, liquid delivered to orbit may have to be dumped during a shuttle emergency, or liquid may have to be transferred from a high-pressure supply tank to a tank at a low pressure. During the design phases of such orbital liquid systems the question is often asked whether most of the liquid can be vented prior to freezing, and in which specific locations in the flow circuit can such freezing occur.

The design complexity of the space fluid systems requires that adequate computational tools be available for the analysis of such systems. During the venting process a typical storage system will start out with a storage tank initially at a high pressure and a low void fraction. As liquid flows through the system, it increases in void fraction, decreases in temperature, and can result in a completely evaporated liquid or a single-phase vapor flow at the outlet to space. The analysis of such a system is rather demanding computationally and the methods of analysis are currently under development and have not reached a state of maturity where such problems can be solved routinely. Typical designs considered in the present analysis

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were analyzed both to provide some insights into the freezing problem and to check out the applicability of the FLOW-NET program.

COMPUTATIONAL METHOD

The FLOW-NET program was used to conduct the computations. The initial version of the program, called SOLA-LOOP, was developed at the Los Alamos Scientific Laboratory (ref. 1). The program development continued at Flow Science, Inc. and at the present time the development continues at the University of Maine.

Conservation of mass, energy, and momentum equations solved by the program are given in reference 2. They are repeated here for the sake of completeness.

Conservation of mass

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u A}{A \partial x} = \frac{S_g + S_e}{V}$$

$$\frac{\partial \rho_g'}{\partial t} + \frac{\partial A}{A \partial x} \left(\rho_g' u + \frac{\rho_g' \rho_\ell' u_r}{\rho} \right) = J_e + J_c + \frac{S_g}{V}$$

$$\frac{\partial \rho_i'}{\partial t} + \frac{\partial A}{A \partial x} \left(\rho_i' u + \frac{\rho_i' \rho_\ell' u_r}{\rho} \right) = \frac{S_i}{V}$$

Conservation of momentum

$$\frac{\partial u}{\partial t} + \frac{\partial}{\partial x} \left(\frac{u^2}{2} \right) + \frac{1}{\rho A} \frac{\partial}{\partial x} \left(\frac{A \rho_g' \rho_\ell' u_r^2}{\rho} \right) = - \frac{\partial P}{\rho \partial x} + g_x - \frac{1}{2} (f_w, f_L)\, u \mid u \mid + \dot{u}_p$$

$$\frac{\partial u_r}{\partial t} + \frac{\partial}{\partial x} \underline{\left\{ u_r \left[\frac{u + u_r (\rho_e' - \rho_g')}{2\rho} \right] \right\}} = \left(\frac{1}{\rho_\ell} - \frac{1}{\rho_g} \right) \frac{\partial P}{\partial x} - \frac{K_d \rho u_r}{\rho_g' \rho_\ell'} - \underline{u_r \left(\frac{J_e}{\rho_g'} + \frac{J_c}{\rho_\ell'} \right)}$$

Conservation of energy

$$\frac{\partial}{\partial t} (\rho_g' E_g + \rho_\ell' E_\ell) + \frac{\partial A}{A \partial x} \left\{ u_g [\rho_g' E_g + P \theta] + u_\ell [\rho_\ell' E_\ell + P (1 - \theta)] \right\} = \frac{Q_{in} + S_i H_i + S_v H_v + S_\ell H_\ell}{V}$$

In these equations,

A = cross sectional area
E_g = specific total gas energy
E_ℓ = specific total liquid energy
f_L = area change loss coefficient
f_w = friction loss coefficient
g_x = body acceleration
H_i = noncondensible gas enthalpy
H_ℓ = liquid enthalpy
H_v = vapor enthalpy
J_c = rate of condensation

J_e = rate of evaporation
K_d = liquid-gas momentum exchange coefficient
P = pressure
t = time
S_g = external gas source
S_i = external noncondensible gas source
S_e = external liquid source
S_v = $S_g - S_i$
u = mixture velocity
u_r = relative velocity between liquid and vapor
$\dot{u}_p$ = acceleration due to externally applied force
V = mixture volume
x = distance
θ = void fraction
ρ = mixture density
ρ_g = vapor density
ρ_i = noncondensible gas density

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The equations of motion as presented here are equivalent to those in other two-phase flow programs such as ATHENA (ref. 3), RELAP5 (ref. 4), and TRAC (ref. 5). In these equations K_d is a function that describes the momentum exchange between the liquid and the gas phases. Large differences in liquid-gas velocities are associated with a small value of K_d. Conversely, small differences in liquid-gas velocities are associated with a large value of K_d. Initially the FLOW-NET program was formulated assuming relatively small velocity differences. This permitted the elimination of terms underlined in the momentum equation. These terms have been included in a recent program modification (ref. 6). Although the capability to solve problems with large velocity differences exists, such problems can be solved only when K_d is known, which, in most cases, has to be determined experimentally. Fortunately, there are classes of problems where K_d could be safely assumed to be large. System venting problems considered here can be assumed to have small relative velocities between phases. In such a case, the continuously decreasing system pressure will cause nucleation and continuous vapor generation. Such nucleation usually occurs at solid surfaces, thus breaking up any tendency to separate the phases into a low-velocity liquid phase attached to the solid surfaces and a high-velocity vapor core. This is illustrated in Figure 1.

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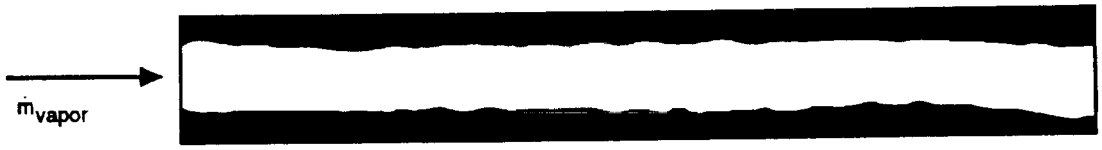
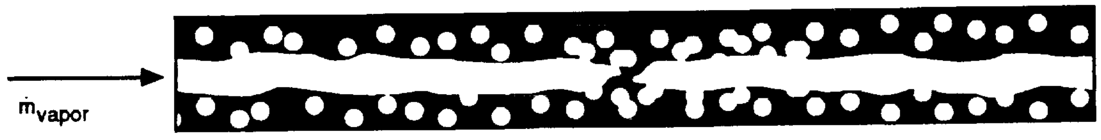


Constant Pressure Flow



Decreasing Pressure Flow

Figure 1. Effect of pressure decrease on flow configuration

NUMERICAL SOLUTIONS

The venting analyses presented in this paper were conducted as part of the Two-Phase Integrated Thermal System (TPITS) shuttle experiment designed to evaluate the Space Station two-phase ammonia thermal control system. Although the analyses were performed to evaluate a specific system, results are applicable to other similar systems and show significant trends and design conditions to be avoided.

Two specific analyses were conducted. In the first one a typical ammonia tank was vented to space. A long-duration run was made to determine the point where freezing is likely to occur. In the second case short runs were conducted to determine the effects of flow restrictions in the vent line and initial tank thermodynamic conditions.

1. Venting of an Ammonia Tank

The computational model considered is shown in Figure 2. The supply tank initial conditions were P = 67.0 psia, T = 35°F. The outside boundary pressure was kept at 31.16 psia for 10 seconds, then allowed to decrease to 1.24 psia in 300 seconds. The pressure was not decreased any further to avoid temperature decrease below freezing, a condition that has no physical meaning, because the program can consider only liquid-vapor mixtures with no solid phase. The saturation temperature corresponding to the 1.24 psia pressure is −100°F, slightly above the −107.86°F freezing temperature.

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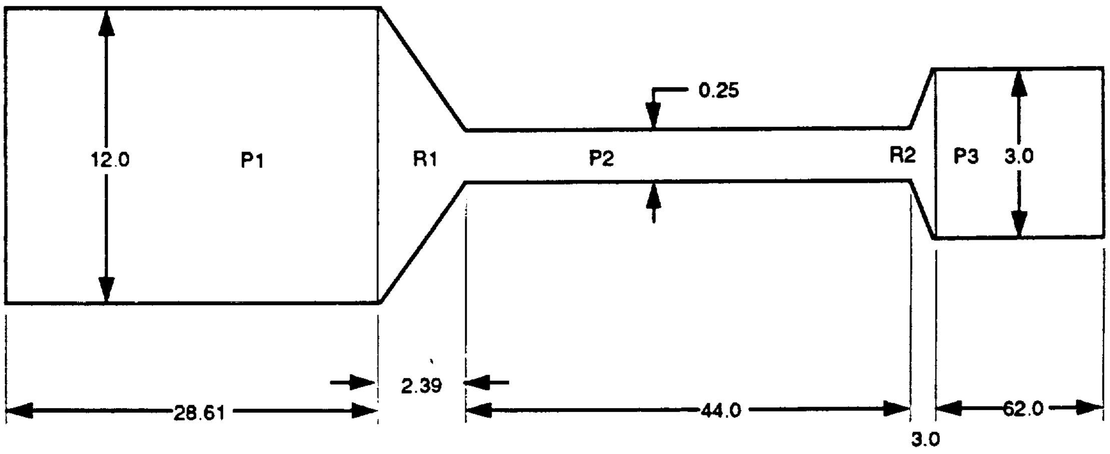


Figure 2. Ammonia dump computational model

The computational model consists of pipe P1, representing the supply tank, a reducer R1 between the supply tank and the vent line P2. Expander R2 and pipe P3 are approximations of space conditions. There are no reliable methods available that could be used to solve liquid-vapor plume problems. Only crude approximations of external conditions can be made, as were done in the present analysis. To approximate the external conditions, the flow was allowed to expand from a 0.25 in. diameter line to a 3.0 in. diameter line. Results of such analysis can give a qualitative indication of possible ice formation outside of the exit plane.

The supply tank void fraction, mixture pressure, and temperature histories are shown in Figures 3, 4, and 5, respectively. The aim of a liquid dump system is to vent as much of the liquid as possible without freezing the liquid. As shown in Figure 3, the tank approaches a void fraction of 1.0 at approximately 350 seconds. At this point the temperature, as shown in Figure 5, is well above the freezing temperature. It can be concluded that the tank can be vented without freezing. At 350 seconds the tank vent line exit temperature is well above the freezing point, as shown in Figure 6. It can also be concluded that the liquid in the line will not freeze.

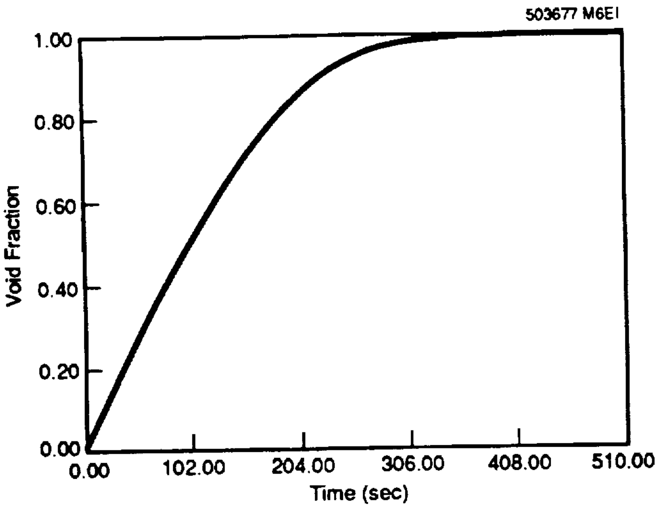


Figure 3. Storage tank void fraction history

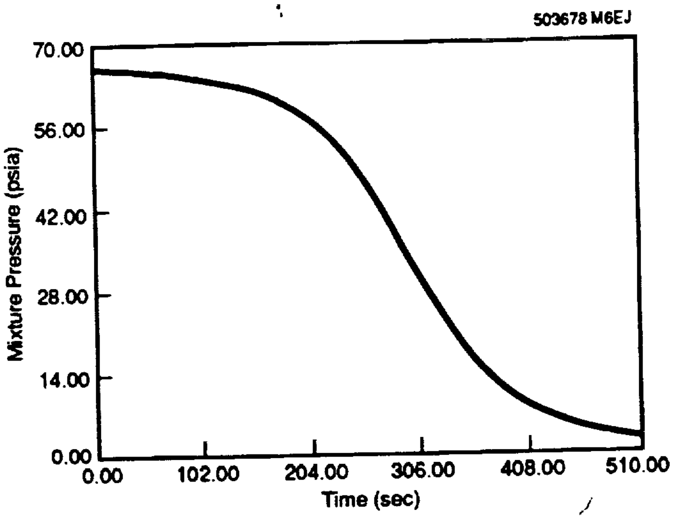


Figure 4. Storage tank pressure history

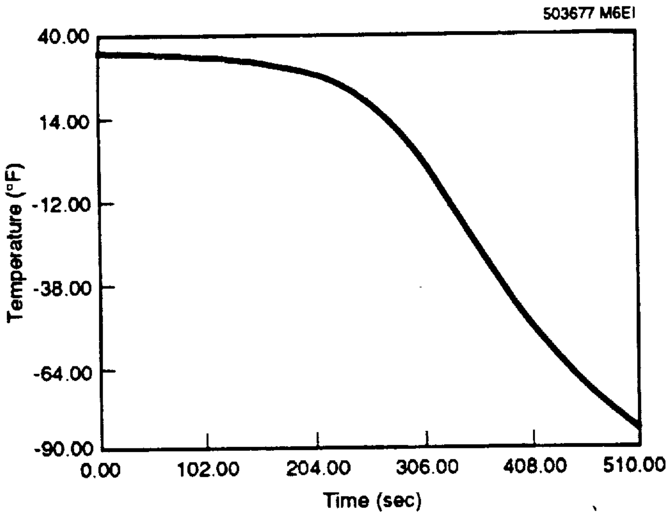


Figure 5. Storage tank temperature history

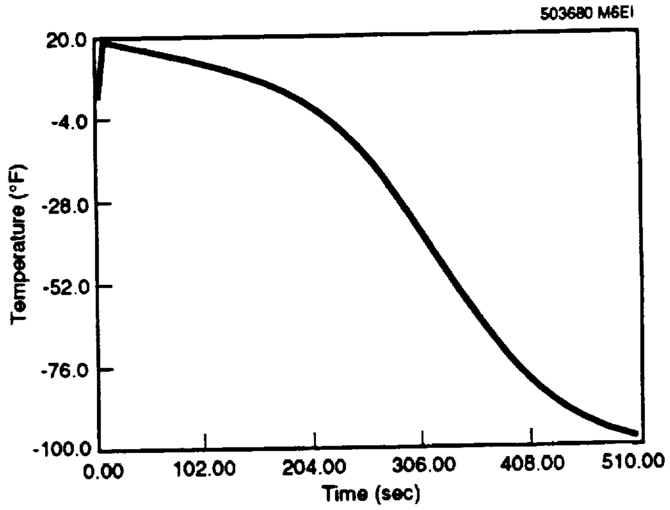


Figure 6. Mixture temperature at vent pipe exit

Temperature distribution along the length of the circuit is shown in Figure 7. Results show that the temperature at the exit drops substantially between 200 and 300 seconds, getting close to freezing between 300 and 400 seconds. It can, therefore, be concluded that conditions outside of the vent exit could cause some freezing. The total mass that could freeze is small because the void fraction during this time period is large as shown in Figure 8.

2. Effect of Geometry and Initial Conditions on the Vent System Performance

A flow circuit with contracting-expanding cross section was constructed to get some understanding of the effect of the flow circuit geometry and initial conditions on the freezing potential. The flow circuit geometry is shown in Figure 9; the conditions analyzed are given in Table I. Circuit exit boundary conditions are shown in Figure 10. In this particular case the exit pressure was reduced to 0.2 psia, thus creating a potential to reach temperatures below freezing. However, it should be realized that temperatures below freezing have no physical meaning. The solution gives an indication that a freezing condition is approaching but gives no quantitative answers.

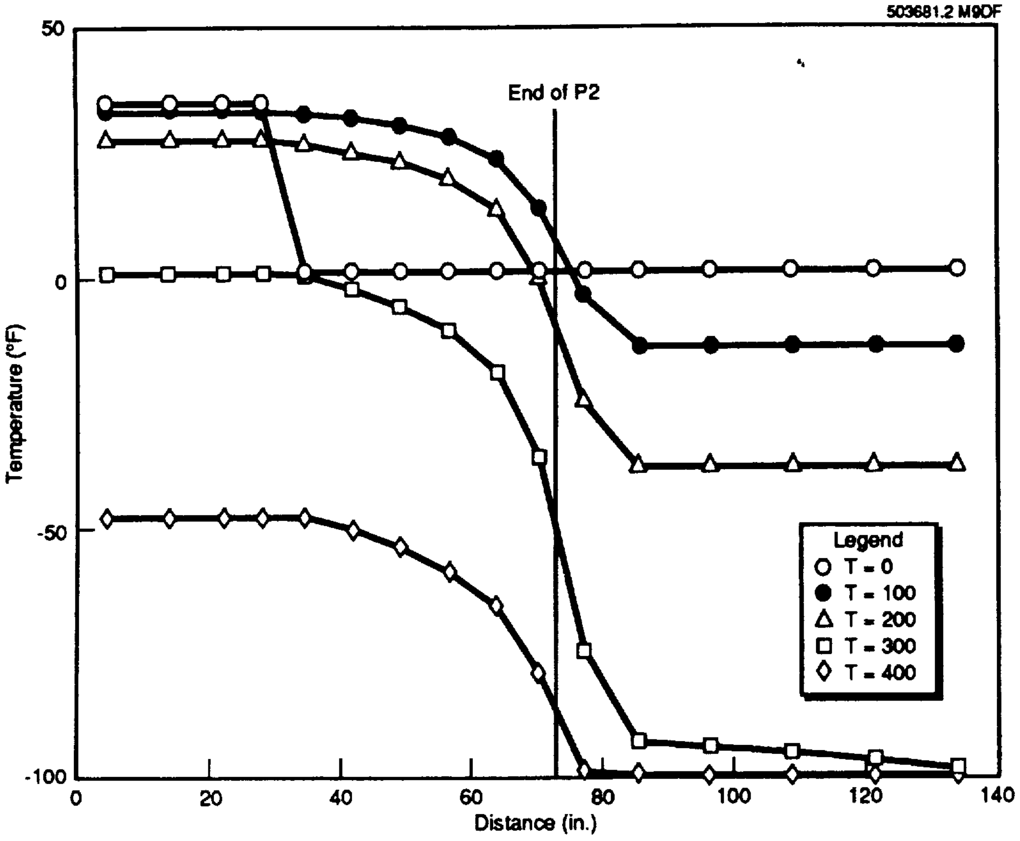


Figure 7. Temperature distribution along the length of the flow circuit

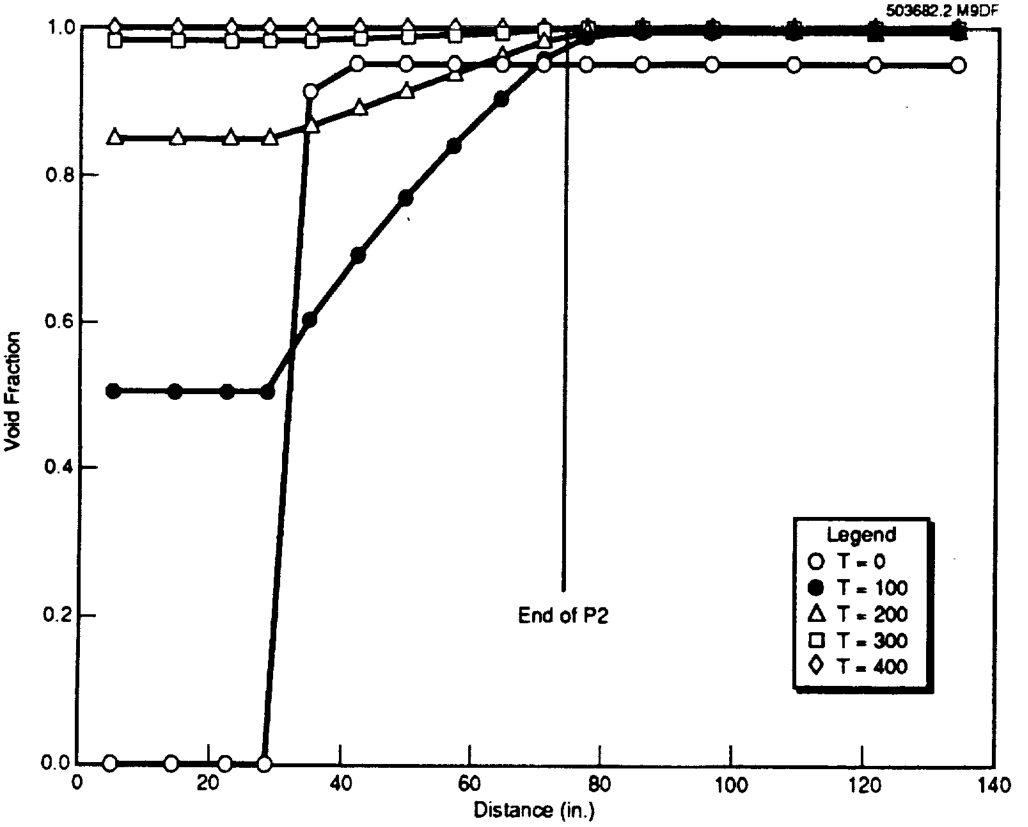
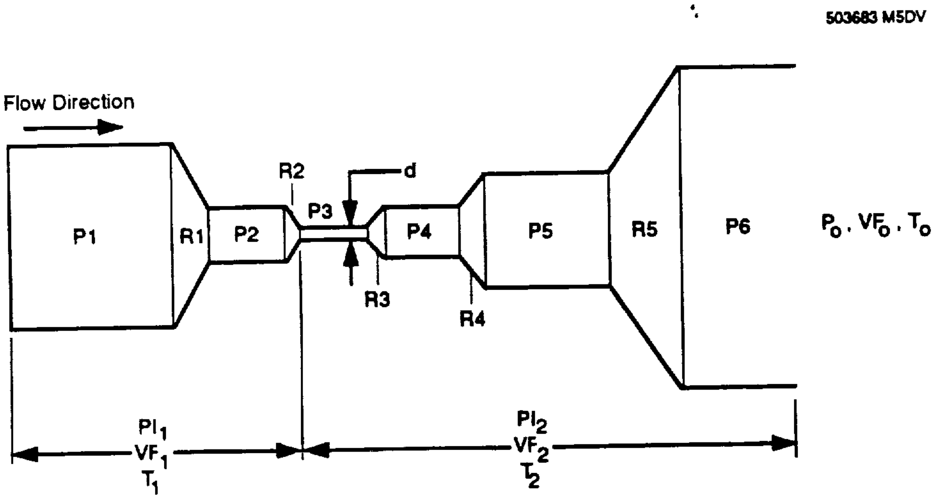


Figure 8. Void fraction distribution along the length of the flow circuit



Component	Length (in.)	Diameter (in.)
P1	25.6	12.0
P2	29.1	0.25
P3	2.0	Variable (See Table 1)
P4	2.9	0.25
P5	3.4	0.50
P6	5.7	3.00

PI, VF, T – initial pressure, void fraction, and temperature (Table 1)
P_O – boundary pressure (Figure 10)

Figure 9. Flow circuit geometry

TABLE I. INITIAL CONDITIONS AND THE THROAT DIAMETER

	Case 1	Case 2	Case 3	Case 4
PI_1 (psi)	67.0	8.0	8.0	8.0
VF_1	0.001	0.99	0.99	1.0
T_1 (°F)	35.0	-50.0	-50.0	-50.0
PI_2 (psi)	32.0	8.0	8.0	8.0
VF_2	1.0	1.0	1.0	1.0
T_2 (°F)	2.0	-50.0	-50.0	-50.0
d (in)	0.056	0.056	0.20	0.056

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To conserve computer time, the four cases were run for 2.0 seconds. Temperature histories for the four cases are shown in Figure 11. Plots start at 0.5 seconds to give a better resolution of the results. Case 1, which is similar to the first long-duration case described in this paper, shows a very gradually decreasing temperature, well above the freezing point. Case 2, which has a low supply tank pressure and a high void fraction (a condition that could be encountered partially into the vent cycle) shows a rapidly decreasing temperature, reaching a point well below freezing. Case 3, similar to Case 2, but with a larger restriction diameter, shows much higher temperature. This gives some quantitative evidence to an intuitively obvious fact that severe restrictions can hasten the formation of ice within the flow circuit. It is, therefore, prudent to avoid such restrictions whenever possible. Case 4 shows the temperature response of a pure vapor, to show the difference in response to a two-phase medium.

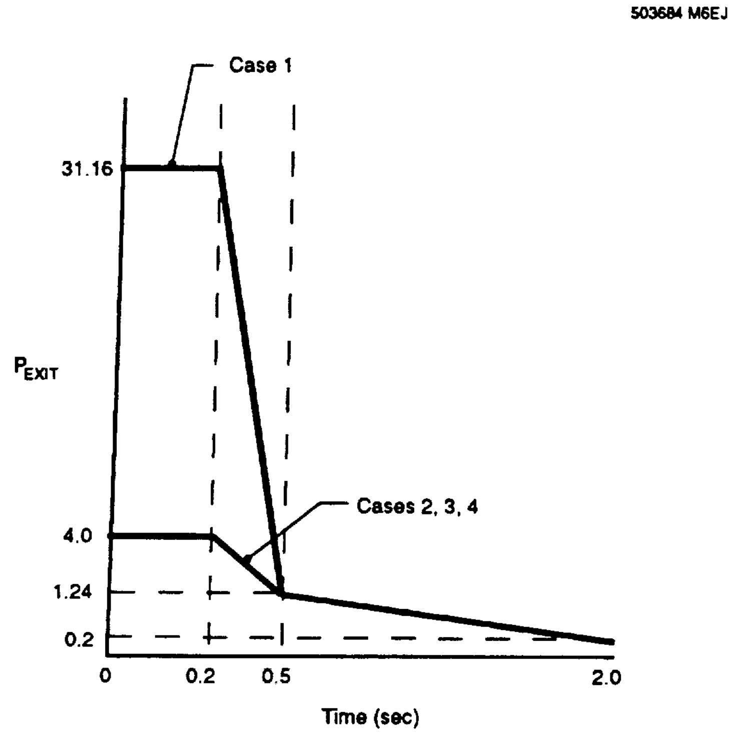

Figure 10. Exit pressure histories

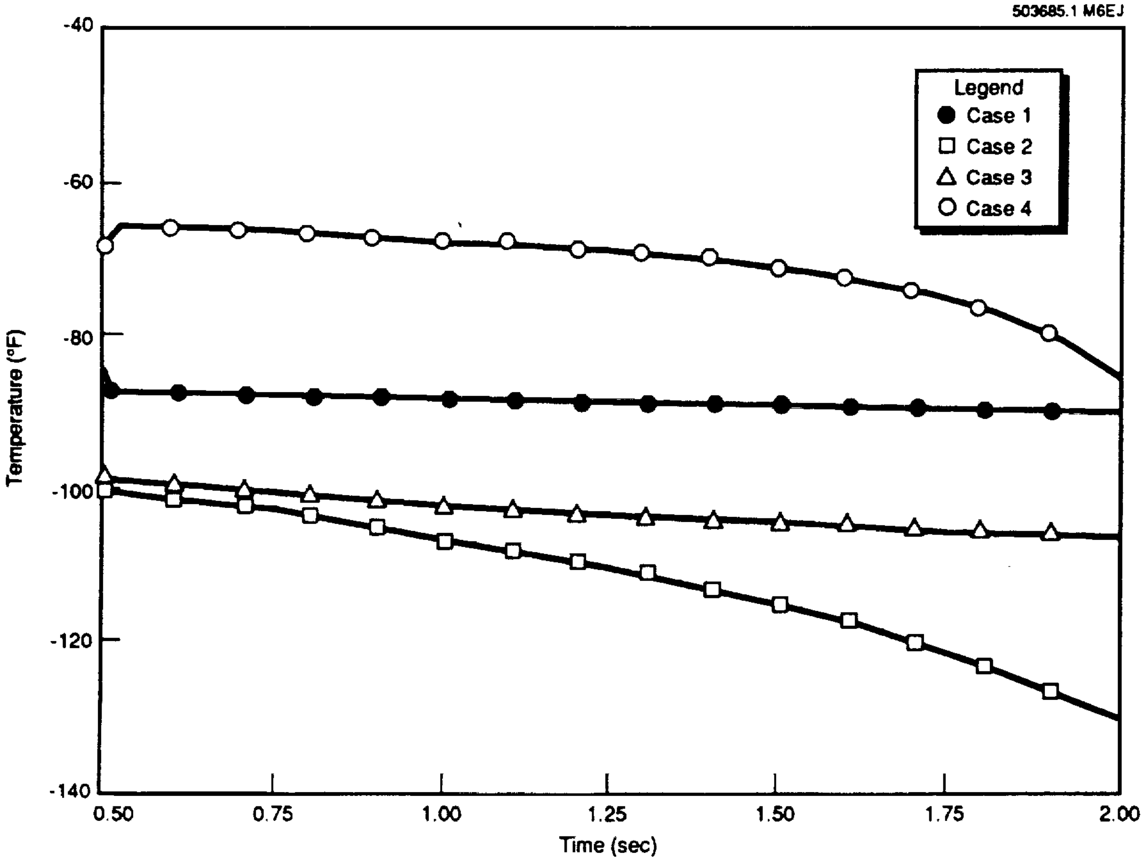

Figure 11. Pipe P5 exit temperature history

CONCLUSIONS

The ammonia dump analysis results indicate that ammonia can be readily vented overboard either in an emergency situation or under normal operating conditions with little danger of freezing. For a typical flow circuit considered in the analysis, practically all of the ammonia could be vented with temperatures remaining well above freezing. Freezing potential developed outside of the vent nozzle toward the end of the dump operation, when the liquid quantity in the system is low. Restriction in the flow circuit can greatly enhance the possibility of freezing and should be avoided. When such restrictions cannot be avoided, they should be included in the computational model.

No difficulties were encountered using the FLOW-NET program. The cases analyzed are rather difficult cases computationally, since the flow starts out as essentially a pure liquid in the supply tank, undergoes a phase change in the flow circuit, then expands into essentially space environment. All results were stable and the solutions well-behaved.

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