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Environmental Requirements for Bubble Pressure Tests on Fine-Mesh Screen

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A laboratory-scale test program was conducted to investigate candidate mechanisms that could explain the unacceptably low bubble pressures that were obtained during the reaction control system (RCS) tank tests. It was concluded that liquid evaporation from the fine-mesh screens was the cause of the observed test results. Correlations of the data were developed for two mechanisms of liquid evaporation from the screens: evaporation caused by temperature gradients and evaporation caused by unsaturated pressurant gas. These correlations identify the environmental requirements for conducting successful RCS tank bubble pressure tests.

I. Introduction

THE bubble pressure tests of the reaction control system (RCS) tanks for the space shuttle orbiter use a fill-and-drain technique to wet the fine-mesh screens prior to bubble pressure tests on the propellant acquisition device. The test fluid is isopropyl alcohol (IPA). Previous test data[1] indicated that screens wet with IPA would remain wet for approximately an hour when the pressurant gas was dry nitrogen. When the pressurant gas was nitrogen saturated with IPA vapor, the screens would remain wet even longer. Since the RCS tank test procedures required that individual screen elements remain wet only for times on the order of 30 min, the possibility of screen dryout using IPA was not considered.

The first series of RCS tank bubble pressure tests were conducted during May and June of 1977 and produced unacceptably low and random bubble pressure results. The first tests used dry nitrogen to displace the liquid during draining and used saturated nitrogen during pressurization. The bubble pressure test results were unacceptable. They ranged from 0 to maximum screen capability with random high and low values obtained during retest of the same screen. Because of the possibility of liquid evaporation from the screen, the next tests used saturated nitrogen for both draining and pressurization. The bubble pressure results were again unacceptable and random, with unacceptably low bubble pressures occurring after the screen had been exposed to ullage gases for only 20 to 30 min.

This laboratory-scale test program was initiated to investigate candidate mechanisms that could explain the observed bubble pressure results. The candidate mechanisms selected for investigation were: 1) liquid evaporation from the screen, 2) mechanical shock to the screen, and 3) contamination of the screen. Note that an acceptable explanation must account for the random nature of the observed bubble pressures as well as for the range of bubble pressures from zero to greater than design point. Because earlier tests had demonstrated the extreme sensitivity of screen bubble pressure performance to temperature differences,[2] the measurement and control of temperature were prime objectives of this test program.

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II. Data Acquisition

The tests were of laboratory scale that used 325 × 2300 mesh Dutch-twill weave screen samples welded on a 3.75 × 16.25-inch frame. The test fluid was isopropyl alcohol (IPA) and the pressurant gas was nitrogen. Figure 1, a photograph of the test apparatus, shows the major components. Nitrogen enters the control console from the supply bottle on the right. The control console regulates nitrogen pressure and measures nitrogen flow rate using a variable area flowmeter. The nitrogen then goes directly to the test device for tests using dry nitrogen. For tests using saturated nitrogen, the nitrogen first goes through a vapor saturator. The vapor saturator, which is out of view on the left of the photo, is a cylindrical tank of 4-in. diameter, 24-in. long. The nitrogen enters at the tank bottom, bubbles upward through approximately 18 in. of IPA, and exits from the top where there are two thermocouples to measure wet- and dry-bulb temperature differences. The potentiometer displays the temperature difference in mV. The temperature recorders for the other temperature measurements are also out of view on the left. Bubble pressures are measured by the manometer.

The two test screens are shown in Fig. 2. The screen is sealed to the frame by welding in the same manner as the RCS production tanks. The screen frame is mounted inside the test model and is sealed with rubber gaskets.

Figure 3 shows the three replaceable ullage chambers for the test model. The internal channel volume is simulated with a 0.52-in. space between the screen and the closure plate as shown in the photograph of Fig. 4.

Bubble pressure determinations were made using both horizontal and vertical bubble pressure tests. In the horizontal test, the screen surface is horizontal with a thin layer of liquid on top. The ullage volume beneath the screen is pressurized until bubbles are observed coming through the screen. This test was particularly useful for evaluating contamination. In the vertical test, the screen is first wet by sloshing liquid over the screen as it is rocked back and forth through the horizontal attitude. Then the screen is rotated to the vertical attitude. When bubble pressure is determined, the ullage volume on one side of the screen is pressurized and screen breakdown is observed on a manometer. As the bubble pressure of the screen is reached, the manometer height increase slows, reaches a maximum, then decreases as the screen breaks down.

Mechanical shock was applied to the test device by lightly tapping with a 6-in. crescent wrench. The tapping was equivalent to a free-fall drop of the wrench from approximately 2 in. The tapping was applied at several different locations.

Contamination was applied in small patches on the screen. The contaminants tested were body oil from fingerprints,

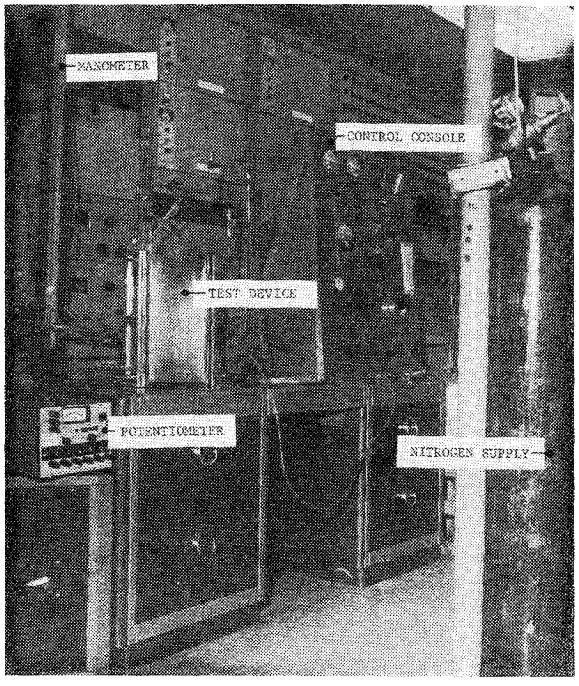


Fig. 1 Test apparatus set-up.

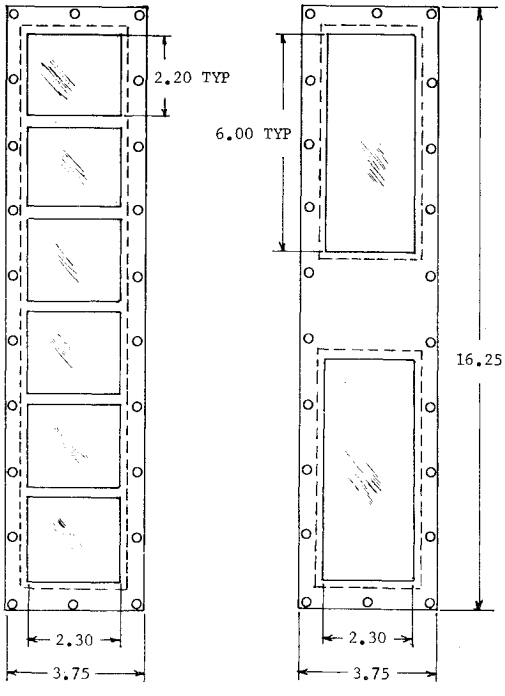
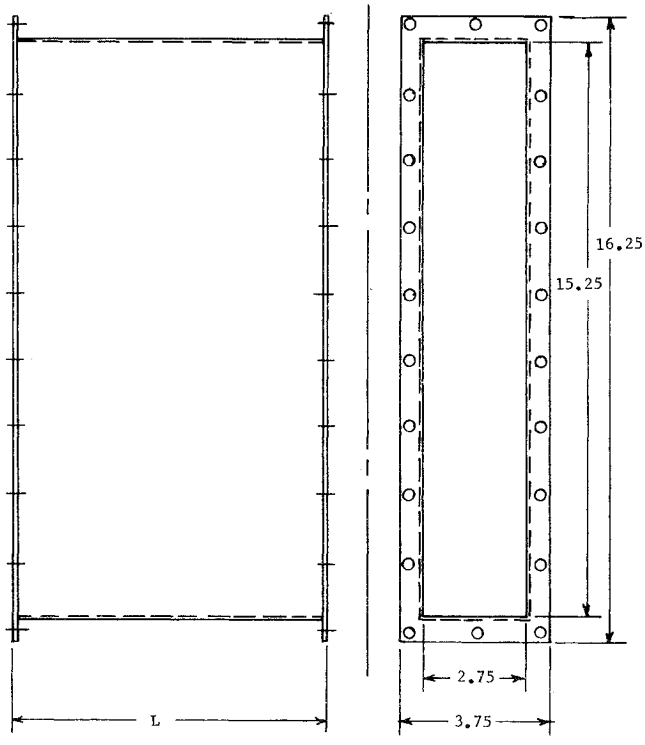


Fig. 2 Test screens.



THREE ULLAGE CHAMBER SIZES
L = 3-IN
L = 6-IN
L = 8-IN

Fig. 3 Ullage chambers.

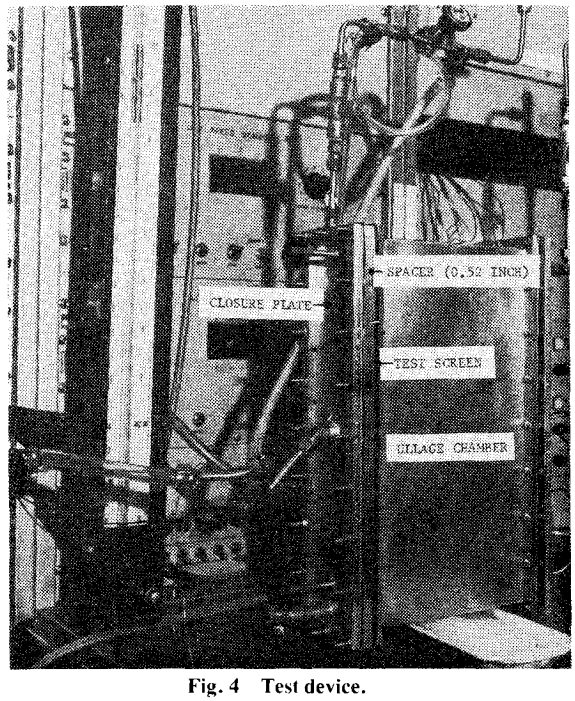


Fig. 4 Test device.

grease pencil, vinyl paint after removal with acetone, and Krytox grease in Freon 113.

Tests to evaluate liquid evaporation due to draining and pressurization were conducted in several ways. Some actual draining tests were conducted where the nitrogen displaced IPA. Other tests simulated the draining process by flowing nitrogen through the ullage volume. Both dry nitrogen and nitrogen saturated with IPA vapor were used for draining, simulated draining, and pressurization. Tests to evaluate evaporation from the screen caused by temperature differences between the screen and the residual liquid puddle were conducted by cooling the liquid puddle. The test device was placed on top of a tray of ice, as shown in Fig. 4.

III. Data Analysis

Mechanical Shock

Figure 5 shows the effects of continuous tapping on the test device as the differential pressure across the screen is increased. Nothing happens until the Δp reaches approximately 60% of maximum. At this point, a cloud of gas bubbles pass through the screen with each tap to the device. The screen pores reseal between taps. This phenomena persists until the

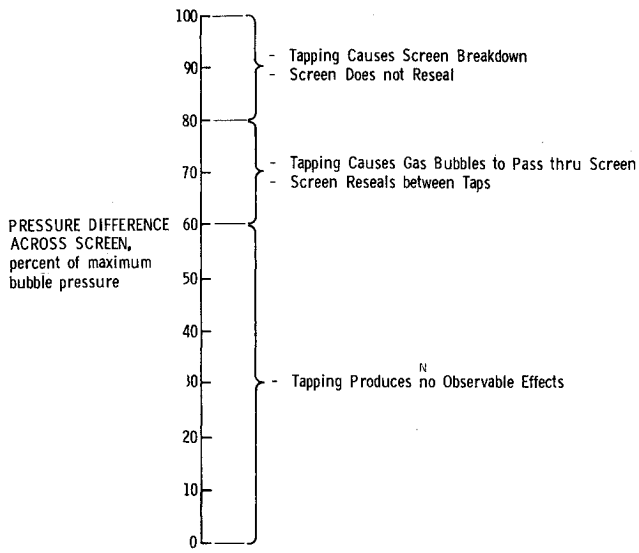


Fig. 5 Effect of mechanical shock.

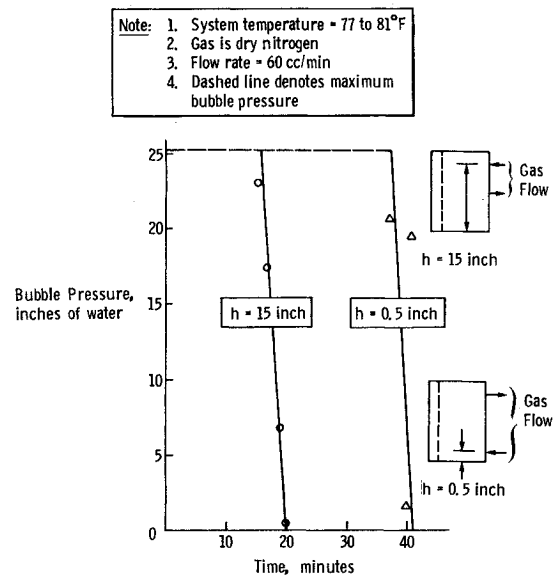


Fig. 7 Effect of gas inlet location.

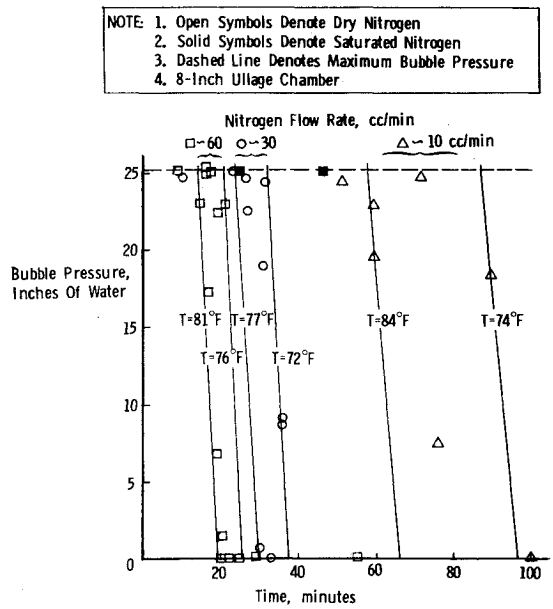


Fig. 6 Example of uncorrelated nitrogen flow data.

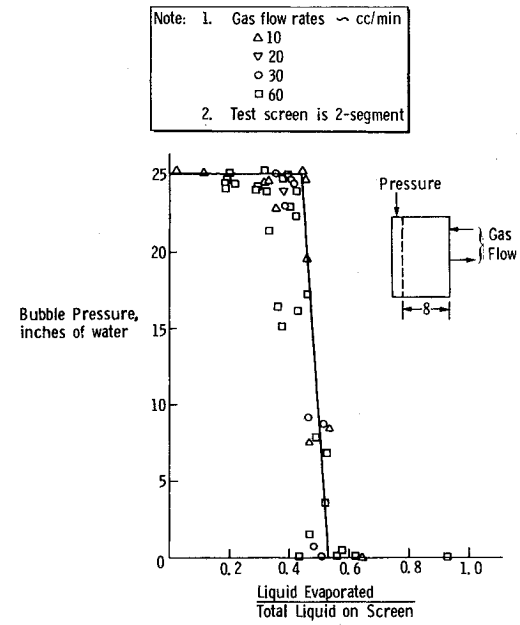


Fig. 8 Gas-flow correlation for 8-in. ullage.

Δp reaches approximately 80% of the screen maximum. At 80% and above, the screen breaks down and is not able to reseal the pores. This breakdown occurs with liquid on one side of the screen and gas on the other as well as with gas on both sides. Since the mechanical shock did not produce screen breakdown at the low Δp values that occurred during the RCS tank tests, mechanical shock by itself was not responsible for the RCS tank test results.

Contamination

The contaminants tested were fingerprints, grease pencil, vinyl paint followed by removal of the vinyl with acetone, and a solution of Krytox grease dissolved in Freon 113. Of these candidate contaminants, only the solution of Krytox in Freon effected bubble pressure. Bubble pressure was reduced to 90% of screen maximum and returned to maximum value with repeated bubble pressure tests. The reduction in bubble pressure is believed to be due to the Freon 113 wetting the screen instead of the IPA. As the Freon evaporates and IPA again wets the screen, the bubble pressure returns to the screen maximum value. Thus, the candidate contaminants do not explain the RCS tank test results.

Evaporation Due to Nitrogen Flow

When liquid is drained from the tank, nitrogen flows into the tank to maintain tank pressure. The screen in the vicinity of the nitrogen inlet location will be washed by the nitrogen flow during the entire drain time. One way to simulate the potential for screen dryout is to simply flow nitrogen through the ullage volume for time durations representative of full-scale drain times. This was done for different ullage volumes, different nitrogen inlet locations, different nitrogen flow rates, and for both dry and saturated nitrogen.

Figure 6 shows bubble pressure vs flow time for three values of nitrogen flow rate. The open symbols are for dry nitrogen, the solid symbols for saturated nitrogen. The dashed line denotes maximum bubble pressure. Note that the screens remain wet and support full bubble pressure for flow times greater than 45 min when flowing saturated nitrogen at the highest flow rate.

Figure 7 shows the effect of introducing the nitrogen flow near the surface of the residual liquid puddle. These data indicate that if the nitrogen flow picks up vapor from the

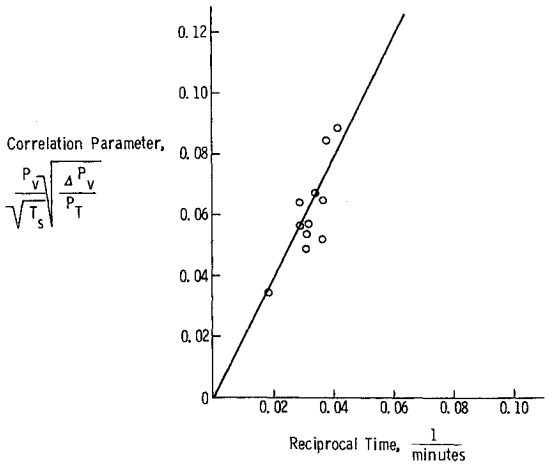


Fig. 9 Temperature difference correlation.

liquid surface before it reaches the screen, the screen will remain wet longer.

In order to develop a correlation for the wide diversity of data, it was reasoned that there should be a critical amount of liquid removed from the screen that just begins to degrade bubble pressure, and that the potential for nitrogen to evaporate the critical amount of liquid should be proportional to the vapor pressure defect of the nitrogen. The critical amount of liquid evaporated should also be proportional to the amount of gas that has flowed over the screen. The ratio of critical amount of liquid evaporated to total amount of liquid in the screen can be expressed as follows:

$$\frac{M_v}{M_l} = \frac{\Delta P_v \dot{Q} t}{R_v T_s \xi \rho A} \tag{1}$$

where

M_v = liquid evaporated
M_l = total liquid on screen
ΔP_v = $P_{v\,\text{out}} - P_{v\,\text{in}}$ = vapor pressure defect in nitrogen flow
$\dot{Q}$ = nitrogen flowrate
t = flow time for screen dryout
R_v = vapor gas constant
T_s = screen temperature
ξ = screen void volume per unit area
ρ = liquid density
A = screen area

The total amount of liquid on the screen is assumed to be the liquid that initially fills the screen void volume. The screen void volume is defined as the open volume between planes tangent to the screen surfaces. The vapor pressure defect in the nitrogen flow is evaluated for either dry or saturated nitrogen flow into the ullage volume and for saturated flow out. Wet- and dry-bulb temperature measurements substantiate that the nitrogen flowing through the vapor saturator becomes saturated.

Figure 8 shows the data of Fig. 6 in terms of the ratio of critical amount of liquid evaporated to total amount of liquid on the screen. The correlation of the data is considered very good. The remaining scatter in the data is believed to be due to small temperature differences between the screen, liquid, and nitrogen that developed during the tests.

In general, these data show that if the pressurant gas is not completely saturated, the screen can dry out. In the first RCS tank test, dry nitrogen was used to displace the liquid during draining. In the second RCS test, the nitrogen was bubbled through IPA, but the level of saturation was not determined. Thus, liquid evaporation from the screen due to unsaturated nitrogen flow is a possible explanation for the RCS tank test results.

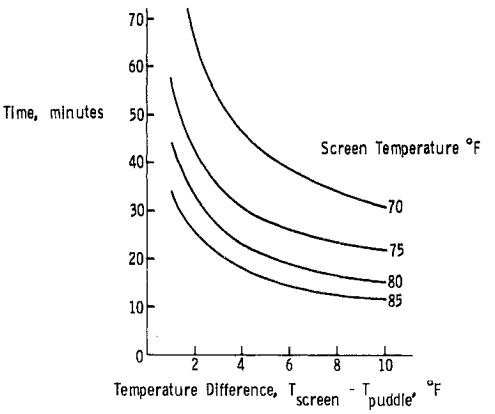


Fig. 10 Screen dryout due to temperature effects.

Evaporation Due to Temperature Differences

When a temperature difference is established such that the residual liquid puddle is cooler than the screen, vapor from the high vapor pressure region at the screen can migrate to the lower vapor pressure region at the liquid surface. Liquid is vaporized at the screen to maintain vapor pressure at the screen temperature and the vapor condenses at the liquid surface to maintain vapor pressure at the liquid surface temperature. The rate of liquid evaporation is a function of the magnitude of the vapor pressure as well as of the vapor pressure difference between the respective screen and liquid surfaces. This is similar to the evaporation/condenstion cycle in a heat pipe.

Tests were conducted using the 6-in. screen windows mounted in the 8-in. ullage compartment. The test device was placed on an ice tray after wetting the screen by sloshing. Temperatures of the screen upper window (or ullage volume) and liquid puddle were monitored. After a hold time, the channel-side ullage volume was pressurized to determine screen bubble pressure. The screen was then re-wet by sloshing, and another test was begun.

The approach to correlating these data was similar to that for the nitrogen flow data except that, in this case, the vapor from the screen is transported by a convection flow induced by the vapor pressure difference between the screen and the residual liquid puddle. Thus, the ratio of liquid evaporated to total amount on the screen can be expressed as follows:

$$\frac{M_v}{M_l} = \frac{P_v}{\sqrt{T_s}}\sqrt{\frac{\Delta P_v}{P_t}}\,Kt \tag{2}$$

where

P_v = vapor pressure at screen
ΔP_v = $P_v - P_{vl}$ = vapor pressure difference between screen and liquid puddle
P_t = system pressure
K = a proportionality constant which may be a function of screen void fraction and additional liquid properties
t = time that screen will remain wet to support full bubble pressure

Figure 9 shows the correlating parameter

$$\frac{P_v}{\sqrt{T_s}}\sqrt{\frac{\Delta P_v}{P_t}} \tag{3}$$

plotted vs $1/t$.

Note that pressure is in in. H_2O, temperature is in °R, and time is in min.

From this correlation, it is now possible to construct temperature/time predictions for how long a wetted screen with gas on both sides can support full bubble pressure. Such

a prediction is shown in Fig. 10 for a 325×2300 mesh screen wetted with IPA. The time that the screen will remain wet is plotted vs the temperature difference between the screen and the liquid puddle for lines of constant screen temperatures. For example, if the screen temperature is 75°F and the liquid puddle is 5°F cooler, the screen will remain wet for approximately 28 min.

Evaporation from the screen caused by screens warmer than the liquid puddle is an extremely good candidate for explaining the observed RCS tank test results. Although temperatures of the screens and of the residual liquid puddle were not measured during the tank tests, it is logically deduced that temperature differences did exist. The tanks were loaded with test fluid (IPA) for screen conditioning for approximately 12 h. After this time the tank, screen and liquid should be at the same temperature. The tanks then were drained and bubble pressure tested as the daytime environmental temperatures rose on the order of 20°F. As the tank warmed, it heated both the screens and the liquid puddle, but because the liquid puddle has a larger thermal mass than the screens it would heat slower.

IV. Conclusions

It is concluded that liquid evaporation from the screens was the cause of the RCS tank test results.

It was found that mechanical shock did not produce permanent screen breakdown unless the Δp across the screen was 80% or greater of the maximum screen bubble pressure. Thus, shock does not explain the low values of bubble pressure from the tank tests.

Of the contaminants tested, only Krytox grease in Freon 113 degraded bubble pressure. Bubble pressure was reduced to 90% of maximum value and recovered to maximum value with continued testing. Thus, contamination does not explain either the low values or the random values of bubble pressure obtained during the tank tests.

During this test program to evaluate liquid evaporation from the screens, the entire range of bubble pressures from 0 to screen maximums were obtained and the length of time that the screen would remain sufficiently wet to support a bubble pressure varied with gas flow rate, saturation level of gas, screen temperature, and temperature difference between the screen and the residual liquid puddle. If these parameters were neither controlled nor monitored, the bubble pressure results could indeed appear random. Thus, evaporation provides the required range and random nature of bubble pressure values to account for the observed tank test results.

It is also concluded that the correlations developed for the evaporation data can be used to predict screen dryout for between-flight checkout tests. However, substantiation of the correlations using a higher vapor pressure liquid (F-113 for example), is required.

The conclusion that liquid evaporation is the cause of the low and random bubble pressure results is supported by recent events. Two follow-on tests of RCS tanks were successfully completed. Care was exercised in controlling temperatures so that they were within the ranges required to prevent screen dryout.

Acknowledgments

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