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Evaluation of Prompt Nucleation of Bubbles in Annular Fuel Elements During the Initial Depressurization Transient of DEGB LOCA (U)

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Evaluation of Prompt Nucleation of Bubbles in Annular Fuel Elements During the Initial Depressurization Transient of a DEGB LOCA.

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Background

In the first moments following the pipe break, of a DEGB LOCA, the depressurization wave is postulated to propagate rapidly through the system, in the manner of an acoustic or water hammer wave. This is immediately followed by a (reflected) repressurization wave, as the flow of coolant through the break is established. The pressure history is then dictated by the flow from the break and the ability of the pressurizer, pumps and accumulators to supply coolant.

The initial sudden drop in pressure may result in the system pressure falling below the saturation pressure of the coolant. This could, in turn, result in bubble formation. Such immediate vapor formation (prompt nucleation of bubbles), in the period before the repressurization wave restores the system pressure to a level above the saturation pressure, might initiate flow instability. Such an interruption in flow would allow the fuel tube clad temperature to increase rapidly. Depending on the duration of the flow interruption, the reactor might not be able to survive the initial moments of a DEGB LOCA.

It has generally been assumed that this phenomenon would not actually occur in an operating reactor. There were two reasons for this assumption: First, because the duration of the period between the rarefaction and repressurization waves would be too short for bubble nucleation to occur. Second, because of the elasticity of the various components, a real reactor would not respond as quickly to such an initial rarefaction wave as the analytical model.

The purpose of this investigation is to evaluate the possibility of occurrence of bubble formation as a result of this initial depressurization. For convenience, this phenomenon will be referred to as "prompt nucleation" in the following discussion.

Review of Literature

The question of the response of a system at high pressure to a sudden drop in pressure is of interest in many processes. It is of particular importance in evaluating the response of nuclear reactors to rupture of coolant supply lines. As a result there is extensive literature on the discharge of pressurized liquid from reservoirs and through pipe breaks. However, in these studies, the time between the break opening and the appearance of the first bubbles is so short compared to the rest of the event that it is of interest only in that it has an effect on the initial conditions. Because of the design of the cores of commercial nuclear power reactors (which employ rod bundles), prompt

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bundles), prompt nucleation would not result in any particular adverse effects, if it should occur. Although the delay time between the break opening and the first appearance of bubbles is generally recognized, it has been the subject of only a few studies. In addition, the studies of bubble growth under various conditions generally address growth at pre-existing active sites.

References 1, through 6 address the inception of bubble nucleation under sudden depressurization or a step change in heating. Alamgir and Lienhard, Reference 1, provide a means for evaluating the pressure at which nucleation occurs, during a rapid depressurization, in which the pressure falls below saturation (pressure undershoot). This is illustrated in Figure 1, from their paper, which shows an example of their experimental data and the process path on p-v coordinates.

Fig. 1 The depressurization process

Figure 1. Pressure time history and depressurization process illustrations, (Reference 1)

In very rapid depressurization, nucleation occurs close to the homogeneous nucleation limit (which is close to the spinodal line, for the liquid to vapor transformation). Such a process can be evaluated by a stochastic treatment. If the depressurization is not so rapid, nucleation may be evaluated deterministically, considering conventional active sites. Reference 1 provides a criterion for distinguishing between these regimes, by determining where the stochastic model is no longer able to correlate diverse data. In practice this is a means of determining whether bubble

formation takes place because of pressure undershoot, or because of the liquid superheat in the boundary layer adjacent to hot surfaces.

Alamgir and Lienhard's analysis is based on the postulate that nucleation occurs when the "potential barrier to nucleation" (the work required to create a bubble of critical radius) is on the order of the energy of a molecule, kT . They develop an expression for the pressure undershoot, which is limited by the homogeneous nucleation of the maximum possible number of critical bubbles which can form on a surface:

$$p_{\text{sat}} - p_n = 0.252 \frac{\sigma^{3/2} T_r^{13.73} (1 + 14 \Sigma'^{0.5})^{0.5}}{\sqrt{kT_c} \left(1 - \frac{v_f}{v_g}\right)}$$

Where: p_{sat} is saturation pressure
 p_n is pressure at which nucleation occurs
 σ is surface tension
 T_r is reduced temperature
 T_c is the critical temperature
 k is the Boltzman constant
 v_f is specific volume of liquid
 v_g is specific volume of vapor
 Σ' is depressurization rate
 ϕ is the heterogeneity factor (incorporated into correlation)

The difference between this idealized case and heterogeneous nucleation is accounted for by the heterogeneity factor. The pressure undershoot correlation was found to be applicable when the depressurization rate is greater than 0.004 Matm/sec. For depressurization rates lower than this, nucleation occurs at conventional active sites and is dependent upon liquid superheat. Although this limit is not a sharply defined threshold, it provides an effective means of determining whether the depressurization is rapid enough for pressure undershoot to result in bubble nucleation.

Starting from the same nucleation conditions, Nghiem, Merte, Winter and Beer, Reference 2, develop an expression for evaluating the liquid superheat required for inception of boiling, as a function of time. The analysis supported experimental studies of boiling inception conditions in Freon-113 and water. Under steady state conditions, some superheat is required for bubble nucleation. Under transient conditions, inception of bubble nucleation depends on time as well as temperature. The degree of superheat varies from the homogeneous nucleation condition to the steady state bubble nucleation superheat.

Fig. 6 Transient superheat ΔT versus time τ with different heat-fluxes Q''_{ss} (system platinum-wire/water, $T_s = 373$ K, $p = 1$ bar). Inception points are marked with (IB)

Figure 2. Transient superheat vs. time for water (from Reference 2).

Nghiem, et al, also employ a "nucleation factor", like that used by Ref. 1, to account for the difference between homogeneous nucleation and heterogeneous nucleation. Based on their experimental study, they postulate that the rate of nucleation is inversely proportional to time. The following expression for superheat, as a function of time, is then developed:

$$\frac{T - T_s}{T_s} = \left\{ 1 - \left(\frac{P_l v_v}{\lambda} \right)_{T=T_s} \ln \left[\left(\frac{16\pi\sigma^3 F}{P_l^2 3kT \ln \frac{nkT\tau}{h}} \right)^{1/2} + 1 \right] \right\}^{-1} - 1$$

Where: T is superheat temperature
 T_s is saturation temperature
 P_l is pressure of liquid
 v_v is specific volume of vapor
 λ is latent heat of vaporization, h_{fg}
 σ is surface tension
 F is nucleation factor
 k is the Boltzman constant
 h is Planck's constant

- τ is time
 n is number of molecules per unit volume
(Avagadro's number / v_f)

The "heterogeneity factor", in Reference 1, and the "nucleation factor", in Reference 2, are the same term with different names.

Miller's photographic study, Reference 3, found heterogeneous bubble nucleation on surfaces, rather than in bulk. This observation supports the assumption used by Alamgir and Lienhard, that nucleation occurs on surfaces. The depressurization rates for this study were on the order of 0.0016 Matm/sec.

RELAP and Upflow Test Results

The possibility of prompt bubble nucleation was recognized when calculational models of the HWR-NPR LOCA transients indicated that the initial depressurization could result in system pressure falling below the saturation pressure, in some cases. The 150 psia reference cases provided for the Upflow Test, Reference 7, did not predict a pressure drop to below saturation pressure. The pre-LOCA outlet temperature was essentially the same as the post LOCA outlet plenum saturation temperature. The values of the principal parameters are given in Table 1.

The Mk-22 Upflow tests, Reference 7, included a series of LOCA simulations with various initial and final conditions. The results for the case corresponding to the reference LOCA and selected as an example for this evaluation are shown on the accompanying plots of the test data. The rate of depressurization achieved in the test apparatus was less than that obtained in the RELAP models. These results are shown on Figures 3, 4 and 5.

Plan of Evaluation

As has been indicated above, Prompt nucleation due to depressurization can occur if the depressurization rate is greater than 0.004 M atm/sec. Below this depressurization rate, a clearly defined undershoot pressure is no longer obtained and the Alamgir-Lienhard approach is no longer able to correlate diverse data. Alamgir and Lienhard attribute this to the presence of substantial inhomogeneities and indicate that the process should be treated deterministically as conventional nucleation sites.

The inability to achieve a clear undershoot pressure is apparently the result of sufficient time being available for non-homogeneous nucleation to occur, at conventional active sites, before the homogeneous limit is attained.

The depressurization rate for the Reference RELAP case was found to be 1530 psia/sec, or 0.000104 Matm/sec.

The depressurization rate for the corresponding Upflow test case was 573 psia/sec, or 0.000039 Matm/sec.

Both of these are far below the limiting value of 0.004 M atm/sec for prompt nucleation to be caused by pressure undershoot.

Therefore, if prompt nucleation is to occur it must be as a result of nucleation due to sufficient superheat at the surface (active sites) for sufficient time, as shown by Nghiem, et al. The expression developed by Ngheim, et al, above, was used to determine the superheat required for prompt nucleation of bubbles under NPR-HWR conditions. Inherent in this is the assumption that, if nucleation occurs at conventional active sites on a hot wall, the results are the same regardless of whether the hot wall condition is obtained by raising the wall temperature or dropping the saturation pressure.

The following procedure was used for this evaluation: The results for onset of voiding in the Mk-22 Upflow apparatus are used to determine the nucleation factor, F. This is used in the correlation to determine the superheat required for nucleation in the period of the depressurization wave to re-pressurization wave. The time of void inception is taken from the void fraction plot. The time when the saturation temperature falls below the wall temperature and the temperature at void inception are taken from the plot of inner fuel metal temperatures. The temperature of the liquid at the wall is assumed to be equal to the wall temperature. The results of this calculation is shown in Figure 6, for the the conditions of the reference LOCA test.

The results show that the superheat required for prompt nucleation, within the initial period between the depressurization wave and the re-pressurization wave, is much greater than the available superheat in the fuel assembly, either measured experimentally or calculated by RELAP. Accordingly, prompt nucleation will not occur in this initial time period.

The analysis also permits determination of the time for which nucleation cannot occur, regardless of the superheat available. The expression for ΔT becomes arbitrarily large when the argument of the logarithmic term is 1, ($\ln 1 = 0$). This occurs when:

$$\text{time} = h/nkT$$

This corresponds to a time of about 0.0012 sec for the conditions of the reference LOCA test.

Conclusions

The methodology developed permits evaluation of the possibilty of bubble formation in the early stages of a depressurization event.

The methodology also establishes the initial time period within which bubble formation will not occur, regardless of the superheat present.

As applied to the conditions of the referenced LOCA test, this methodology demonstrated that prompt nucleation of bubbles would not lead to flow instability in the NPR fuel assembly in the initial phase of the LOCA event.

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LM3A011.00

Figure 3. Pressure vs. Time for LOCA Test with Power Trip. Initial Conditions were: 5.0 MW, 1034 KPa, 52°C Inlet Temperature.

M03A011.12

Figure 4. Inner Fuel Wall Temperatures for LOCA Test with Power Trip. Initial Conditions were: 5.0 MW, 1034 KPa, 52°C Inlet Temperature.

MEGA011.11

Figure 5. Void Fraction Results for LOCA Test with Power Trip.
Initial Conditions were: 5.0 MW, 1034 KPa, 52°C Inlet Temperature.

**Figure 6. Superheat Required for Bubble Nucleation
for Conditions of the Reference LOCA Test.**