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Strainer Mid-Point Elevation Flashing Analysis

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1. Purpose and Scope

The following white paper outlines the general methodology for evaluating the acceptability of flashing along the top half (from the top of the strainer to the mid-point elevation) of ECCS sump strainers within PWR containments. The purpose of this document is to provide the necessary tools for plants to justify that flashing along the entire top half of ECCS sumps strainers is not expected to impede ECCS performance, and therefore, using the strainer mid-point elevation to determine the effects of flashing on post-LOCA ECCS performance within NARWHAL is acceptable.

2. Assumptions

1. Flashed steam does not escape the strainer. This produces the maximum accumulation of vapor within the strainer.

2. The pressure drop and flow rate across the strainer are uniform along the height of the strainer. This provides both a conservatively high flow rate and pressure drop for the top half of the strainer under clean strainer conditions and a reasonable generic approximation for the pressure drop and flow rate of a debris-loaded strainer.

3. Introduction

Several parameters influence whether sump fluid will flash to vapor (steam) upon transiting through the debris-covered sump strainer during post-LOCA recirculation. These parameters are as follows:

- Containment atmospheric pressure
- Sump fluid temperature
- Sump fluid elevation
- Pressure drop across the strainer

For a given break size and location, these parameters create a pressure profile in the sump that increases with increasing depth. Figure 1 gives a representative view of the situation.

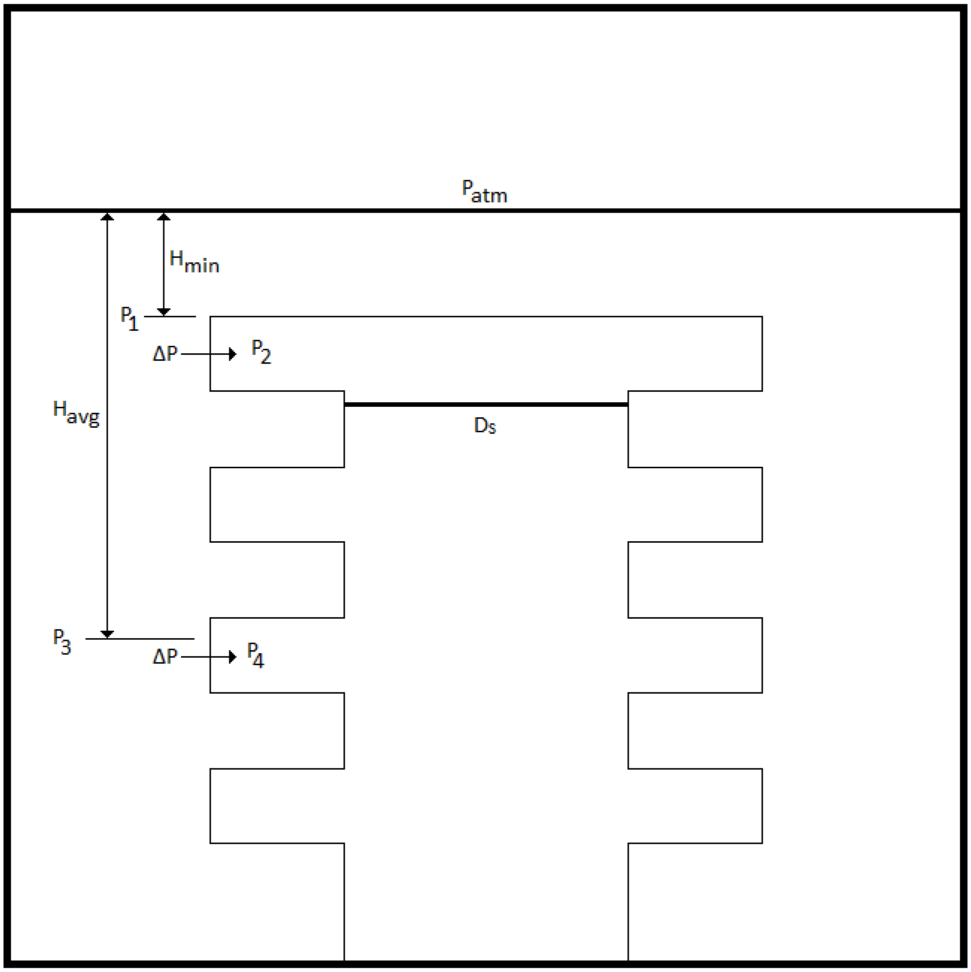

Figure 1 – Sump Strainer

The variables shown on Figure 1 are related in the following way:

$$P_1 = P_{atm} + \rho g H_{min} \quad \text{Equation 1.}$$

$$P_2 = P_1 - \Delta P \quad \text{Equation 2.}$$

$$P_3 = P_{atm} + \rho g H_{avg} \quad \text{Equation 3.}$$

$$P_4 = P_3 - \Delta P \quad \text{Equation 4.}$$

Where

P_1 = Sump pressure outside the sump strainer at an equal depth to the top of the strainer
P_{atm} = Containment atmospheric pressure
ρ = Sump fluid density
g = Gravitational acceleration
H_{min} = Elevation difference between the sump surface and the top of the strainer
P_2 = Pressure of fluid entering the strainer at H_{min}.

ΔP = Pressure drop across the strainer surface
P_3 = Sump pressure outside the sump strainer at the mid-point elevation of the strainer
H_{avg} = Elevation difference between the sump surface and the mid-point elevation of the strainer
P_4 = Pressure of fluid entering the strainer at H_{avg}.
D_S = Diameter of Strainer

Flashing occurs when the pressure drop across the strainer produces pressures inside the sump strainer that are less than or equal to the vapor pressure of the sump fluid (a function of sump fluid temperature). Since the pressure in the sump increases with increasing depth, the most likely location for flashing is at the top of the strainer.

For the specific case of flashing across the entire top half of the strainer, the pressure drop across the strainer (ΔP) must result in a pressure at the mid-point elevation inside the strainer that equals the vapor pressure of the sump fluid. Thus, the question to be evaluated is whether the ECCS will be negatively affected by sump fluid flashing to steam in the entire top half of the strainer.

The following sections of this report address this question.

4. General Methodology

This section is divided into a series of steps that are required to analyze the effects of flashing within a sump strainer.

Step 1. Calculate the superficial mass flow rates of vapor and liquid within the strainer.

The mass fraction of incoming sump fluid that flashes across the strainer at any given elevation can be calculated using Equation 5 [1].

$$x = \frac{h_{Lu} - h_{Ld}}{h_{Vd} - h_{Ld}} \qquad \text{Equation 5.}$$

χ = mass fraction of sump fluid flashed at any given height along the strainer

h_{Lu} = liquid enthalpy upstream of the strainer at the bulk sump temperature

h_{Ld} = saturated liquid enthalpy downstream of the strainer at the saturation pressure

h_{Vd} = saturated vapor enthalpy downstream of the strainer at the saturation pressure

As seen from Equation 5, the mass fraction of incoming sump fluid which flashes should decrease at increasing depths towards the mid-point elevation of the strainer. Using Assumptions 1 and 2 and the average mass fractions of sump fluid flashed across the height of the strainer, the superficial mass flow rates of vapor and liquid through the strainer ($\dot{m}_V$ and $\dot{m}_L$) can be calculated.

Step 2. Characterize the flow regime

Characterization of the two-phase flow regime within the strainer requires a number of flow properties. These properties are listed below alongside any equations required to calculate them.

- Pipe wall roughness – *k*
- Pipe inclination – *Θ* (-90° for vertical downward concurrent flow)
- Vapor density – ρ_V
- Liquid density – ρ_L
- Vapor viscosity – μ_V
- Liquid viscosity – μ_L
- Internal strainer annulus area – A_S

$$A_S = \pi(\frac{D_S}{2})^2$$ Equation 6.

- Superficial liquid velocity – u_L

$$u_L = \frac{\dot{m}_L}{\rho_L A_S}$$ Equation 7.

- Superficial vapor velocity – u_V

$$u_V = \frac{\dot{m}_V}{\rho_V A_S}$$ Equation 8.

- Superficial liquid Reynolds number– Re_L

$$Re_L = \frac{\rho_L u_L D_S}{\mu_L}$$ Equation 9.

- Superficial vapor Reynolds number– Re_V

$$Re_V = \frac{\rho_V u_V D_S}{\mu_V}$$ Equation 10.

- Vapor/liquid density difference

$$\Delta\rho = \rho_L - \rho_V$$ Equation 11.

- Superficial liquid Froude number– F_L

$$F_L = (\frac{\rho_L}{\Delta\rho g D_S})^{0.5} u_L$$ Equation 12.

- Superficial vapor Froude number– F_V

$$F_V = (\frac{\rho_V}{\Delta\rho g D_S})^{0.5} u_V$$ Equation 13.

- Superficial liquid friction factor– f_L

$$f_L = F(Re_L, \frac{k}{D_S})$$ [3] Equation 14.

- Superficial vapor friction factor– f_V

$$f_V = F(Re_v, \frac{k}{D_S})$$ [3] Equation 15.

- Lockhart-Martinelli parameter – *X*

$$X = (\frac{f_L}{f_V})^{0.5} \frac{F_L}{F_V}$$ Equation 16.

- Inclination or gravity parameter – *Y*

$$Y = \frac{sin\theta}{2 f_V F_V^2}$$ Equation 17.

Once calculated, these properties should be used along with the algorithm presented in [2] to characterize the flow regime within the strainer. Possible flow regimes within the strainer include non-transportable (vapor phase rises through liquid phase), bubbly (either dispersed bubble or intermittent/slug flow), or annular.

NOTE: Any plant whose vapor and liquid Froude numbers place them into the non-transportable flow regime (see Step 3) will be in the non-transportable flow regime regardless of the flow regime predicted from [2].

Step 3. Analyze the flow regime based on the results of Step 2. Each plant will only need to apply the one set of the concepts and equations presented below applicable to its flow regime.

Non-transportable

In concurrent vertical downward two-phase flow with $0 < F_L \leq 0.3$ and $F_V < 2$, the buoyancy of bubbles trapped within the liquid flow will overcome the momentum forces of the downward flow and rise up through the strainer (regardless of the flow regime predicted in Step 2) [4]. Using Assumption 1, this will lead to density driven phase separation and the formation of a unique vapor phase within the top of the strainer. It is expected that most plants will fall into this regime.

This phase separation will lead to the formation of a vapor/liquid phase interface whose elevation will be determined based on the phase equilibria present within the strainer: vaporization of the strainer fluid due to the pressure drop across the strainer and condensation of the vapor phase due to increasing pressure down the height of the strainer [5]. The rapid processes that govern the elevation of this equilibrium interface are discussed below.

As discussed above, the pressure of the fluid entering the strainer varies across the height of the strainer due to the increase in static pressure down the strainer. However, the bulk vapor pressure (P_{VB}) and bulk liquid pressure (P_{LB}) (far away from the strainer entrance and phase interface) equilibrate very quickly (almost instantaneously). Therefore, as the bulk vapor phase accumulates due to continued vaporization of the sump fluid across the top half of the strainer, the vapor/liquid phase interface moves down the height of the strainer to maintain bulk-phase pressure equilibrium.

This can be expressed mathematically as:

$$P_{LB} = P_{VB} = P_{atm} + \rho g H_I - \Delta P \qquad \text{Equation 18.}$$

where H_I is the height of the interface.

Additionally, as the vapor/liquid interface moves down the strainer, the pressure at the phase interface increases due to the increase in static pressure. This increase in pressure along the phase interface causes the rate of vaporization along the interface to decreases and the rate of condensation along the interface to increase. The equilibrium elevation of the interface along the height of the strainer is the elevation where the rate of vaporization equals the rate of condensation and there is no more net accumulation within the vapor phase [5].

The exact location of the vapor/liquid interface depends on a number of factors related to individual sump performance (i.e. head loss across the strainer, liquid temperature, and containment pressure). However, using the mid-point elevation of the strainer as the analyzed point below which flashing will stop, the interface will not be located significantly lower than the mid-point elevation of the strainer due to both the pressure of the vapor phase at the interface rising to equal the vapor pressure and the introduction of sub-cooled liquid flow at that elevation.

Therefore, the presence of a non-transportable flow regime, due to flashing across the top half of the strainer, will not impede ECCS performance, and using the strainer mid-point elevation to determine the effects of flashing on post-LOCA ECCS sump strainer performance under this flow regime is acceptable. Under this flow regime, any conditions that would cause the vapor/liquid interface to drop significantly below the mid-point of the strainer would require flashing below the mid-point of the strainer, and the NARWHAL analysis would conclude that flashing is unacceptable.

<u>Bubbly (dispersed bubble or intermittent/slug flow)</u>

In two-phase bubbly flow, the liquid Froude number generally exceeds the vapor Froude number by an order of magnitude or more. This means that the liquid superficial velocity is great enough to create liquid bridges trough the vapor phase. These liquid bridges form vapor pockets (bubbles) that are simultaneously transported within the liquid phase [2].

However, as the bubbly flow moves to lower elevations (from the strainer to the ECCS pump suction), the vapor bubbles begin to collapse due to the increasing static pressure in the fluid. If it can be shown that any vapor bubbles, formed and transported along with the flow, collapse prior to reaching the ECCS pump, then any concerns over flash vapor entering the ECCS pump suction due to bubbly flow transport are alleviated.

The additional ECCS variables of interest for the bubbly flow analysis are listed below.

- Smallest inner diameter of the ECCS suction piping – D_P
- Elevation difference from bottom of sump to ECCS pump inlet – H_E
- Major head losses due to pipe friction– $h_{L,major}$
- Minor head losses due to fittings– $h_{L,minor}$
- Strainer height – H_s
- Length of pipe from bottom of sump to ECCS pump inlet – L_P

- Pressure at pump suction – P_P
- Vapor pressure of sump fluid - P_V
- Bulk fluid pressure far from the bubble - P_∞
- ECCS pump flow rate – Q_P
- Incoming sump flow rate – Q_S
- Initial bubble radius – R_o
- Vapor temperature – T_V
- Average travel time from strainer mid-point elevation to ECCS pump suction – t_A
- Time required for bubble collapse – t_C
- Total volume of water contained in ECCS pump suction piping – V_P
- Total volume of liquid contained in the strainer – V_S

To obtain the amount of time allowed for a bubble to collapse when travelling from the mid-point elevation of the strainer to the ECCS pump suction, calculate the volume of water between the strainer mid-point elevation and the ECCS pump suction.

$$V_P = \pi L_P \left(\frac{D_P}{2}\right)^2 \quad \text{Equation 19.}$$

$$V_S = \pi \left(\frac{H_S}{2}\right)\left(\frac{D_S}{2}\right)^2 \quad \text{Equation 20.}$$

The pipe volume and the strainer volume are then divided by their applicable flow rates. (The ECCS pump suction piping flow rate (Q_P) will be equal to the total ECCS pump flow rate while the incoming strainer flow rate (Q_S) will vary as the number of strainer modules per ECCS pump suction line varies.) The average travel time from the strainer mid-point elevation to the ECCS pump suction (t_A) is then calculated by adding these two values.

$$t_A = \frac{V_P}{Q_P} + \frac{V_S}{Q_S} \quad \text{Equation 21.}$$

As the bubbles are carried down in elevation toward the ECCS pump, the pressure of the bulk fluid surrounding the bubbles increases due to increasing the static pressure. The pressure at the ECCS pump suction can then be calculated using the pressure at the mid-point elevation of the strainer (P_v) and the head gains and losses through the piping system.

$$P_P = P_V + \rho_L g\left(\frac{H_S}{2} + H_E - h_{L,major} - h_{L,minor}\right) \quad \text{Equation 22.}$$

The bulk fluid pressure far from the bubble (P_∞) varies along the length of the pipe from P_V (at the mid-point elevation of the strainer) to P_P (at the ECCS pump suction). To simplify the analysis, P_∞ can be assumed to be the average of P_V and P_P.

With this information, the time required for a bubble of initial radius (Ro) to collapse can be calculated using the following equation (Equation 4.36 of [6]). Due to the uncertainty associated with the empirical equations for bubble formation, the initial bubble radius is assumed to be the internal radius of the strainer, thereby providing a conservative value for the initial bubble radius.

$$t_C = 0.915\left(\frac{\rho_L R_O^2}{(P_\infty - P_V)}\right)^{0.5} \quad \text{Equation 23.}$$

Section 4.2.4 of [6] notes that the results of Equation 23 possess some uncertainty due to complicated physical phenomena. Therefore, it is recommended that this methodology only be used to justify ECCS performance in cases where t_C is calculated to be much less than t_A, as is seen in the example case presented at the end of this section. In such cases, the time required for bubble collapse is sufficiently short to justify that any bubble transported in the two-phase bubbly flow regime will collapse well before reaching the ECCS pump suction, and ECCS performance will not be impeded.

Bubbly Flow Example

The following example demonstrates use of the above methodology for determining whether a bubbly flow regime will transport flashed sump fluid to the ECCS pump suction. The following table of representative ECCS values is used within this example.

Table 1 – Inputs for Bubbly Flow Example

Input	Value
D_P	1.10 ft
D_S	1.00 ft
g	32.2 ft/s^2
g_c	32.2 (lbm-ft)/(lbf-s^2)
H_E	50.0 ft
$h_{L,major}$	5.0 ft
$h_{L,minor}$	18.0 ft
H_S	4.0 ft
L_P	160.00 ft
P_V	14.40 psia
Q_P	4,500 gpm
Q_S	1,125 gpm
ρ_L	60.00 lbm/ft^3

Using Equation 19, V_P is calculated as follows:

$$V_P = \pi \cdot 160.00\text{ ft} \cdot \left(\frac{1.10\text{ ft}}{2}\right)^2 \cdot \frac{7.4805\,gal}{1\,ft^3} = 1{,}137.43\,gal$$

Using Equation 20, V_S is calculated as follows:

$$V_S = \pi \left(\frac{4.00\text{ ft}}{2}\right)\left(\frac{1.00\text{ ft}}{2}\right)^2 \cdot \frac{7.4805\,gal}{1\,ft^3} = 11.75\,gal$$

Using Equation 21, t_A is calculated as follows:

$$t_A = \left(\frac{1{,}137.43\,gal}{4{,}500\,gpm} + \frac{11.75\,gal}{1{,}125\,gpm}\right) \cdot \frac{60\,sec}{1\,min} = 15.79\,sec$$

Using Equation 22, P_S is calculated as follows:

$$P_P = 14.40\,psia + 60.00\,\frac{lbm}{ft^3}\cdot 32.2\,\frac{ft}{s^2}\cdot\left(\frac{\frac{4.0\,ft}{2} + 50.0\,ft - 5.0\,ft - 18.0\,ft}{32.2\,\frac{lbm\cdot ft}{lbf\cdot s^2}\cdot 144\,\frac{in^2}{ft^2}}\right) = 26.48\,psia$$

P_∞ is assumed to be the average of P_V (14.40 psia) and P_P (26.48 psia). Thus, P_∞ is 20.44 psia. The initial bubble radius is conservatively assumed to be equal to the internal radius of the strainer (R_o = D_S /2 = 0.50 ft). Using Equation 23, t_C is calculated as follows:

$$t_C = 0.915\left(\frac{60.00\,\frac{lbm}{ft^3}\cdot(0.50\,ft)^2}{(20.44\text{ psia} - 14.40\text{ psia})\cdot 32.2\,\frac{lbm\cdot ft}{lbf\cdot s^2}\cdot 144\,\frac{in^2}{ft^2}}\right)^{0.5} = 0.021\,sec$$

The bubble collapses within 0.021 seconds of being transported from the strainer, which is much sooner than the average time required for flow to reach the ECCS pump suction (15.79 seconds).

Therefore, for cases like the example above, where $t_C << t_A$, bubbly flow regimes will not transport flashed sump fluid to the ECCS pump suctions, and ECCS performance will not be impeded by flashing along the top half of the sump strainer.

Annular

As the superficial velocity of the vapor phase increases within the sump strainer, the flow pattern shifts from bubbly to annular flow. The annular flow pattern is characterized by the creation of a cylindrical vapor channel within the middle of the pipe that is surrounded by a liquid film formed along the sides of the piping system. It is expected that very few, if any, plants will operate in this flow regime.

However, as the vapor phase flows to lower elevations and toward the ECCS pump suction, the pressure of the bulk fluid increases due to increased static pressure, and condensation occurs, as discussed above. As condensation occurs, the volumetric flowrate and superficial velocity of the vapor phase decrease while the volumetric flowrate and superficial velocity of the liquid phase increase. This causes the flow pattern to shift from annular flow to large bubble (intermittent/slug) flow then to small bubble flow and finally to single-phase liquid flow once the entire vapor phase has condensed. This process is shown graphically in Figure 2.

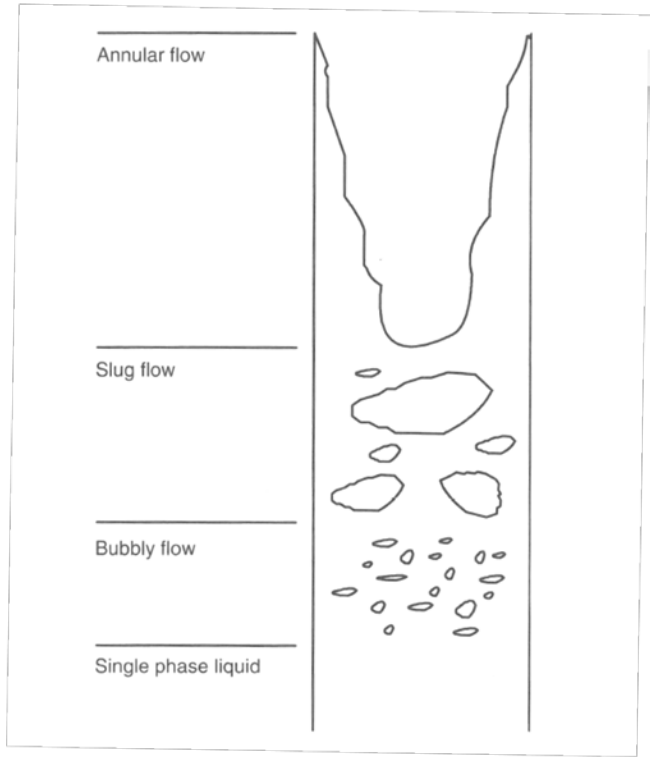

Figure 2 – Schematic of Condensing Flow Regimes in a Vertical Tube (Reproduced from [2])

Unfortunately, calculating the exact conditions and flow regime dynamics within the various vertical and horizontal segments of ECCS pump suction piping requires extensive numerical analysis and/or testing. Therefore, in lieu of numerical analysis and/or testing, if flashing of sump fluid within the strainer produces annular two-phase flow (that is **not** in the Froude number ranges associated with the non-transportable regime) the flashing analysis should conservatively use the top of the strainer instead of the strainer mid-point elevation to eliminate the possibility of flashing within the strainer.

5. Conclusions

The two-phase flow regime corresponding to the flashing of sump fluid along the entire top half of the sump strainers should be determined for each plant.

Plants within the non-transportable flow regime are not expected to experience any impediment to ECCS performance due to flashing across the top-half of the sump strainer. Therefore, using the strainer mid-point elevation to determine the effects of flashing on post-LOCA ECCS sump strainer performance for this flow regime is acceptable. It is expected that most plants will fall into this regime.

Plants that fall into the bubbly flow regime may use the methodology described within this report to show no impediment to ECCS performance due to flashing across the top-half of the sump strainer. It is expected that a few plants may fall into this regime.

Due to the vapor superficial velocities required to support an annular two-phase flow regime, it is expected that very few, if any, plants will operate in this flow regime. However, due to the complexity of analysis required to resolve vapor transport in annular two-phase flow, any plant shown to be in an annular flow regime should conservatively use the top of the strainer instead of the strainer mid-point elevation to eliminate flashing as a concern for post-LOCA ECCS sump strainer performance.

6. References

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