WATERHAMMER IN HORIZONTAL LINES DURING THE VOIDING PHASE

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1.0 INTRODUCTION

This paper considers the potential for waterhammer to occur in a horizontal pipe when cold water is being voided (pushed out) by steam. Specifically, when considering the two-phase conditions in which waterhammer may occur in the service water system for safety grade fan coolers, it is necessary to evaluate both the voiding and refill phases of the transient. The voiding phase is that interval immediately following the onset of the Design Basis Accident (DBA) (large break LOCA to the containment atmosphere) combined with a Loss-Of-Offsite Power (LOOP). Under these conditions, the voiding phase occurs as steam is produced in the containment fan cooler due to heat transfer from the containment atmosphere, reduced flow due to the temporary loss of the service water pumps and potentially due to column separation for those fan coolers located at a high elevation relative to the service water discharge header. Substantial voiding can occur in the service water piping assuming that the water remains in the cooler tubes to support continued steam generation. Figure 1 is a schematic of a typical service water piping arrangement for a fan cooler. Depending on the specific system configuration, steam voiding may progress a substantial distance through the service water system and into horizontal piping. As the continued steam flow pushes water through this cold piping, waterhammer events have been observed to occur but only to a limited magnitude, i.e. less than 100 psig.

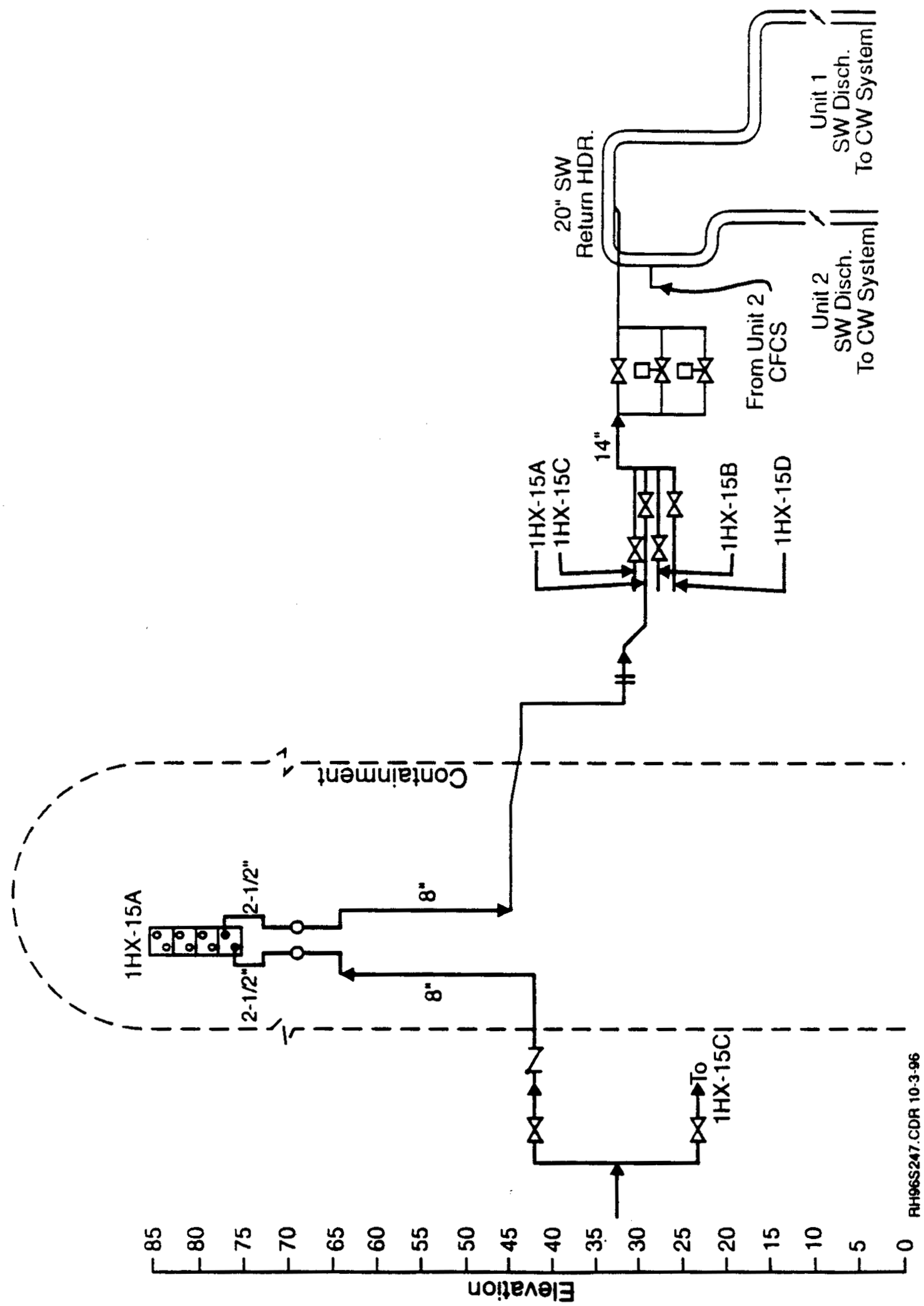
Numerous experiments have been reported in the literature related to waterhammer in various configurations including those reported by Block (1980), Chou and Griffith (1990) and Rothe et al. (1977). Many of these experiments show substantial pressures developed as a result of waterhammer phenomena (several hundred psi). Most of these situations are established with water filling a steam void. Those configurations of interest in the service water system (steam “pushing” water) represent a substantially different geometry than has typically been examined. Also, this represents a unique configuration since the steam is displacing water from a given region and the pipe wall under these conditions is cold. As is discussed below, this has a substantial influence on the local two-phase flow characteristics which are responsible for the waterhammer events.

2.0 ANALYTICAL APPROACH

As voiding occurs through the cold piping, the rate of voiding (U_v) can be related to the steaming rate in terms of an energy balance on the pipe wall heat sink:

$$\rho_g \frac{\pi D_P^2}{4} U_g h_{fg} = \rho_S \pi D_P \delta_P c_S \left(T_{sat} - T_{So}\right) U_v \qquad (1)$$

Figure 1: Schematic of a typical service water cooling piping for containment fan coolers.



where $?_g$, U_g and h_{fg} are the steam density, velocity and latent heat of vaporization respectively, D_P and d_P are the pipe diameter and wall thickness with $?_S$, c_S and T_{So} being the density, specific heat and initial temperature of the steel pipe wall; T_{sat} is the saturation temperature at the local pressure. Rearranging this equation in terms of the dimensionless parameters gives

$$\frac{U_v}{U_g} = \left(\frac{D_P}{4\delta_P}\right)\left(\frac{\rho_g}{\rho_S}\right)\left[\frac{h_{fg}}{c_S\left(T_{sat} - T_{So}\right)}\right] \qquad (2)$$

Experiments in a 2-inch Schedule 40 carbon steel pipe result in a measured voiding rate of approximately 1 ft/sec when the pressure is approximately 1 atm. Furthermore, the voiding process appears to occur in a one-dimensional manner even though the water voiding velocity corresponds to a Froude number much less than unity, i.e. an air-water mixture would be expected to stratify.

It is instructive to investigate the steam velocity that corresponds to this measured voiding rate. For this size of pipe, the internal diameter is 2.067 in (0.053 m) with a wall thickness of 0.154 in (3.9 mm). Assuming that the pipe wall is initially at 20°C and the system pressure is at 1 atm, results in a calculated steam velocity of 57 ft/sec (17 m/sec). This is nearly identical to the water flooding velocity in a vertical configuration as given by Kutateladze as

$$U_f = 3\sqrt[4]{\frac{g\sigma\left(\rho_f - \rho_g\right)}{\rho_g^2}} \qquad (3)$$

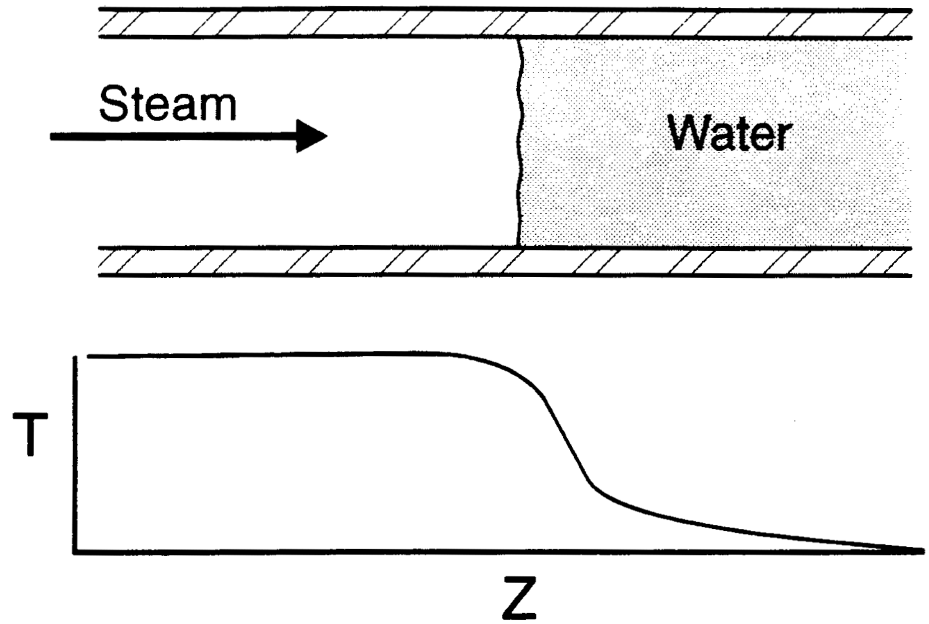
where g is the acceleration of gravity, s is the steam-water surface tension and $?_f$ is the density of saturated water.

This is not a coincidence since the water cannot stratify in the presence of a steam flow sufficient to "flood" the water surface. Hence, a situation develops (Figure 2) where the continued steam flow "floods" and perhaps entrains the water that is attempting to drain (stratify) and a thermal boundary is developed that moves along the horizontal piping in a one dimensional manner determined by the steam flow. In this configuration, waterhammer events are observed to occur on a regular basis during the voiding phase but with limited magnitude, i.e. pressure increases 0.2 to 0.4 MPa.

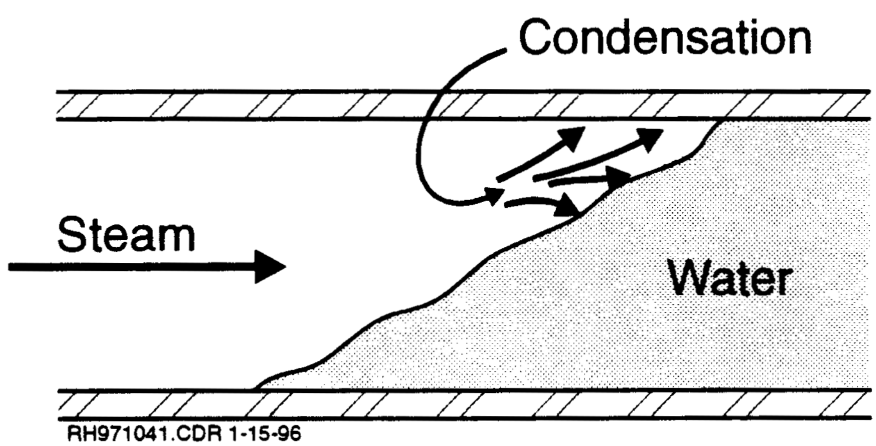
With a configuration like Figure 2, the upper surface can separate from the pipe boundary and expose a cold wall thereby promoting condensation. The pressure difference of importance is that which results in a steam velocity sufficient to "flood" the water surface, cause a wave to form and capture a steam bubble as illustrated in Figure 3. This pressure difference is expressed by

$$\Delta P_e = \frac{1}{2}\rho_g U_f^2 \qquad (4)$$

Figure 2: Influence of water attempting to form a separated configuration in a horizontal piping segment.

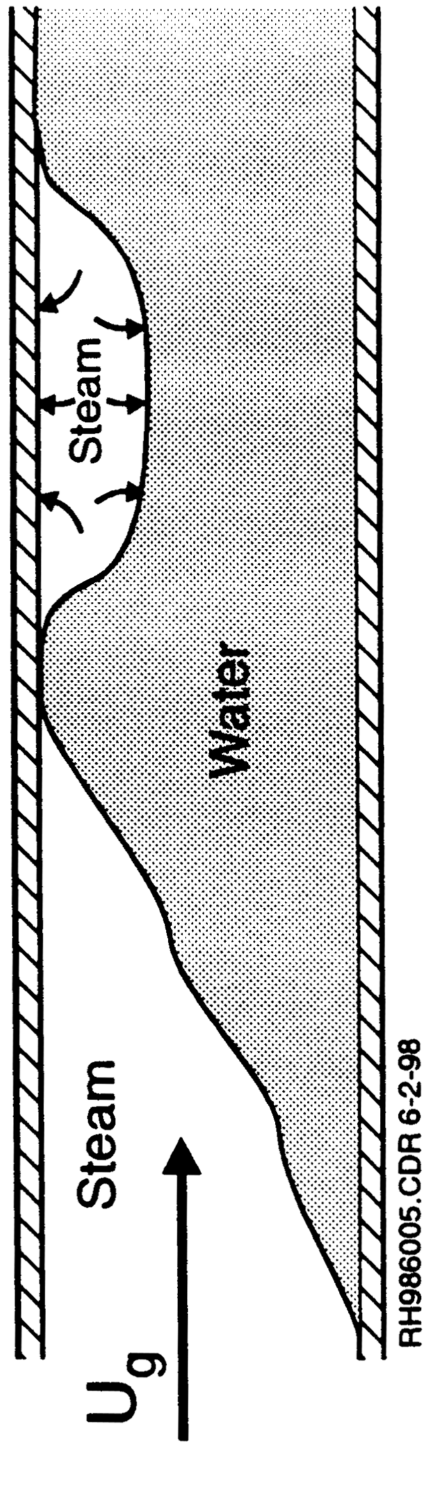


1(a)



1(b)

Figure 3: Entrapping of a steam bubble to create a waterhammer condition.



Once the wave is formed and reaches the top of the pipe such that a steam bubble is captured, this pressure difference is available to accelerate a water slug. Given this geometry a waterhammer could occur due to the collapse of the entrapped gas space that is being pushed into a region with a cold steel wall surrounded by cold water. For such conditions, the waterhammer can be expressed by the Joukowski equation for one water slug colliding with another,

$$\Delta P_{WH} = \frac{1}{2} \rho_f \, a_w \, U_w \tag{5}$$

where a_w and U_w are respectively the velocity of sound in water and the water slug velocity. Considering the available pressure difference, the water slug velocity is given by

$$U_w = \sqrt{\frac{\Delta P_e}{\rho_f}} = U_f \sqrt{\frac{\rho_g}{2 \rho_f}} \tag{6}$$

Substituting this into the previous equation results in

$$\Delta P_{WH} = \frac{a_w}{2} \sqrt{\frac{\rho_g \rho_f}{2}} \, U_f \tag{7}$$

Further substituting for the flooding velocity gives the expression

$$\Delta P_{WH} = 1.06 \, a_w \left[\rho_f^3 \, g \, \sigma\right]^{1/4} \tag{8}$$

This equation enables one to realistically estimate the low energy waterhammer events that are developed for a condition with steam pushing water through horizontal cold piping.

It is to be noted in this evaluation that the waterhammer events discussed in this paper are occurring in a pipe of constant diameter. This is an important feature since the controlling mechanism for developing condensation is the rate at which the pipe wall uncovers. This is substantially different than the “water cannon” experiments reported by Block et al. (1977) as illustrated in Figure 4. In these experiments, steam was added to the top of the test apparatus and slowly displaced water out the bottom of the test tube. This could be accomplished since a stable thermal boundary layer separated the steam and water as the water was displaced downward. However, when the water cleared the bottom of the tube, the protective thermal boundary layer was pushed away and cold water came into direct contact with steam. This resulted in a depressurization of the steam space and a rapid entry of the water into the tube due to condensation. Water impacting on the top of the tube generated the large pressure pulses illustrated in Figure 5. In this case, the geometry at the bottom of the tube provided for a configuration in which the thermal layer could be

Figure 4: Schematic of a basic experiment on condensation induced waterhammer reported by Block et al. (1977).

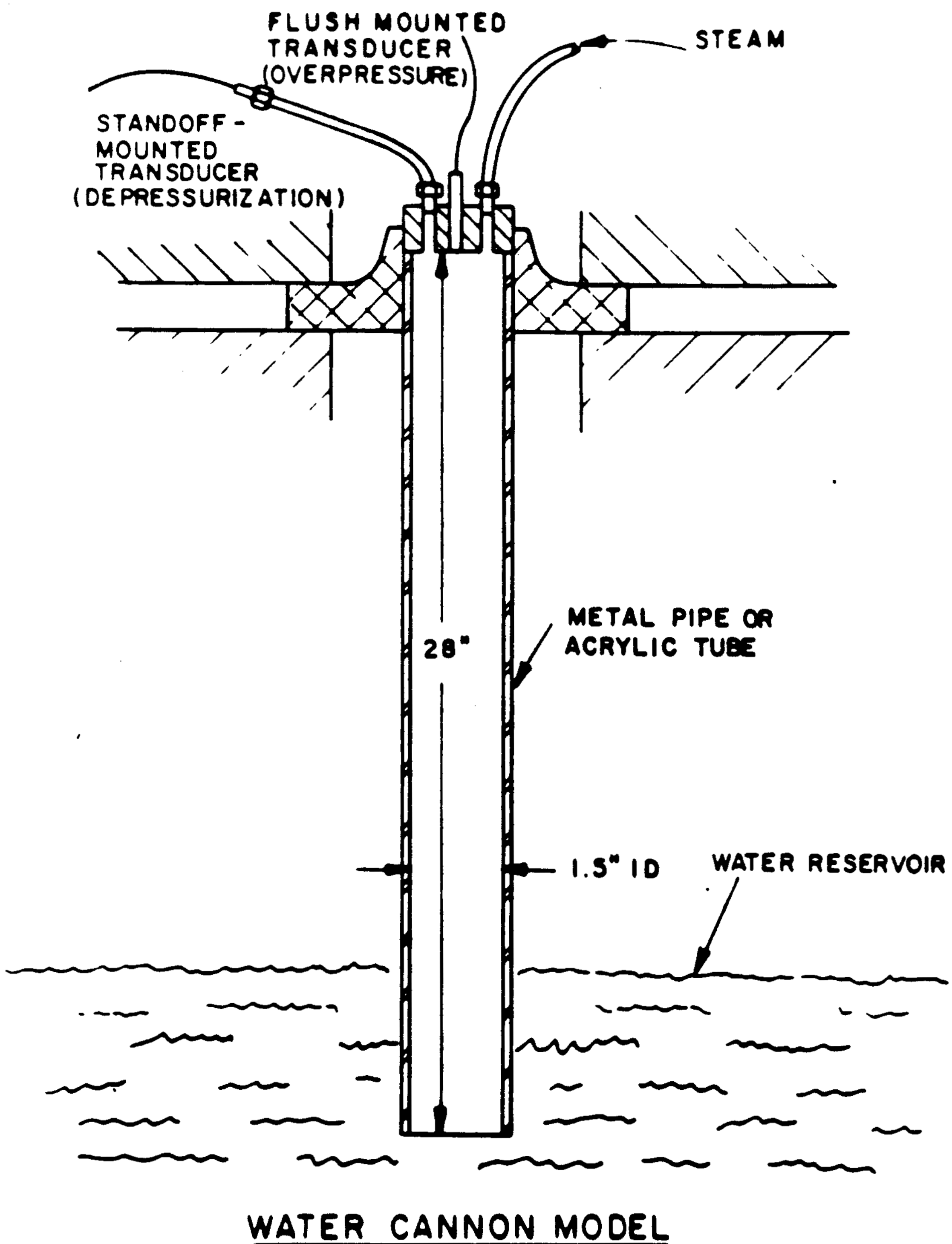
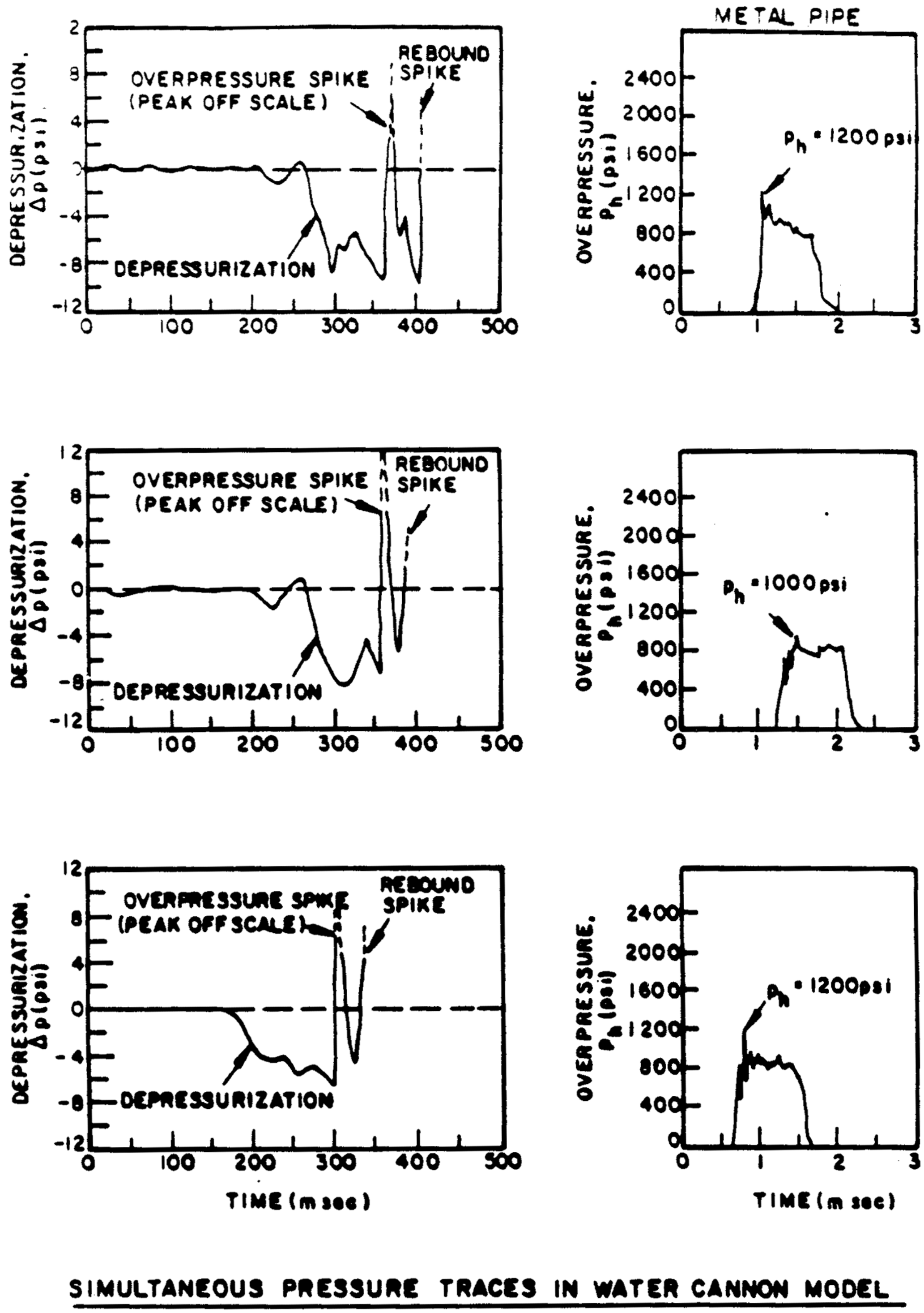


Figure 5: Expanded plots of selected waterhammer pressure reported by Block et al. (1977).



easily destroyed and cold water could be brought into direct contact with the steam. In the piping arrangements typical of service water systems, this is not the case. Particularly, when substantial voiding of the piping configuration occurs there is considerable energy in the pipe wall that acts to develop important thermal layers in the water during both voiding and refill. The combination of this, and the fact that the geometry essentially remains with a constant cross-sectional area, means that there is virtually no way of rapidly removing a thermal boundary layer as was the case for the apparatus shown in Figure 4. Hence, the nature of the waterhammer events are strongly influenced by the flow configuration. Substituting typical values for saturated water in Equation (8) results in a calculated waterhammer pressure of about 0.2 MPa which is in general agreement with the data.

3.0 COMPARISON WITH DATA

FAI has performed numerous waterhammer experiments on different configurations related to the geometries of components, in particular fan coolers, for open service water systems. These include one-inch and two-inch diameter experimental configurations with elevated configurations which experience column separation. Moreover, the test programs have net steam generation with no reverse flow permitted in the supply riser as well as with reverse in the supply riser. A typical experimental configurations is shown in Figure 6.

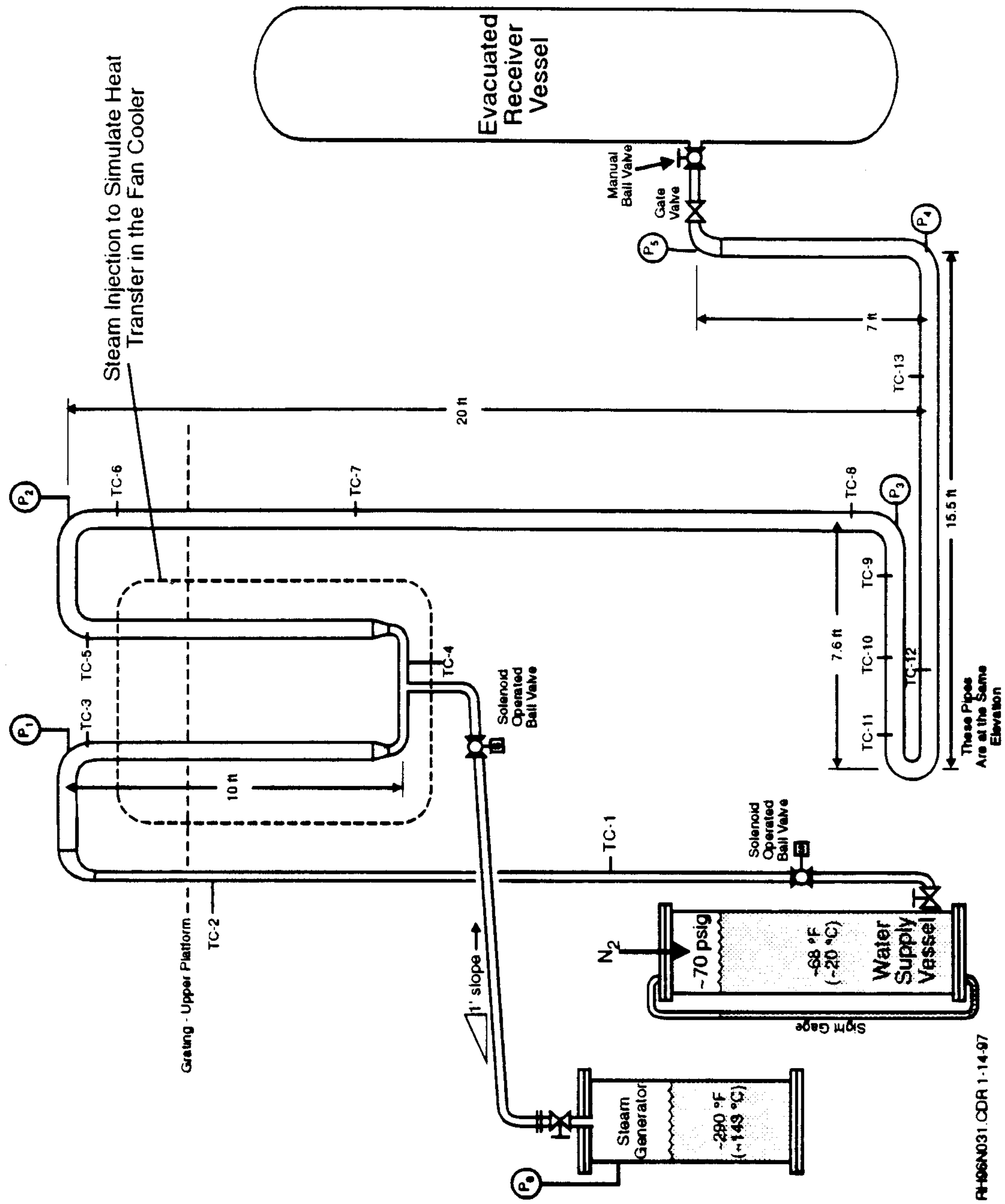
A typical procedure for these experiments was to set the water flow rate through the test apparatus (from the water supply vessel to the evacuated receiver vessel) to represent a desired steady-state condition. To accomplish this, the gate valve immediately upstream of the evacuated receiver vessel and that valve immediately downstream of the water supply vessel were used. This is representative of the plant condition since the gate valve at the exit of the water supply vessel enables the experiment to control the water addition rate during refill in a manner that approximates the service water pumps restarting.

Once steady-state conditions were established, the solenoid operated ball valve on the water supply line was closed to simulate the loss of service water pumping capabilities. Simultaneously, the solenoid operated ball valve on the line from the steam generator was opened to admit steam to the downstream piping configuration. This net steam addition represents the result of heat transfer from the containment atmosphere to the fan coolers for the DBA condition. In the experimental test matrix, the rate of steam generation was varied as was the steam addition interval. All of the experimental configurations investigated included tests in which sufficient steam was added to completely void the downstream piping to the gate valve on the receiver vessel.

Thermocouple measurements were recorded along the centerline of the discharge piping, which enabled one to observe the void progression into the cold piping configuration as well as the water refill transient. This provided measurements on the single-phase/two-phase transients within the pipe and greatly aided the interpretation of the two-phase flow state during the voiding and refill portions of the hydrodynamic transient.

Once a range of net steam generation rates and duration of steaming were investigated, an additional consideration to be addressed was whether an extended length in the horizontal segment of the loop seal for the downstream piping would substantially alter the waterhammer pressures. As shown, the bottom of the loop seal has a length of 23 ft., which corresponds to a length-to-diameter ratio of approximately 138. This is more than sufficient to initiate condensation induced

Figure 6: Experimental configuration for investigating possible waterhammer conditions in the service water system.


Evacuated Receiver Vessel
Steam Injection to Simulate Heat Transfer in the Fan Cooler
Manual Ball Valve
Gate Valve
P1
P2
P3
P4
P5
P6
TC-1
TC-2
TC-3
TC-4
TC-5
TC-6
TC-7
TC-8
TC-9
TC-10
TC-11
TC-12
TC-13
20 ft
7 ft
15.5 ft
7.6 ft
10 ft
Solenoid Operated Ball Valve
Solenoid Operated Ball Valve
These Pipes Are at the Same Elevation
Grating - Upper Platform
1' slope
N2
~70 psig
~68 °F (~20 °C)
Water Supply Vessel
Sight Gage
Steam Generator
~290 °F (~143 °C)
RH96N031 CDR 1-14-97

waterhammers from a stratified (steam over cold water) situation if this could occur for the parameters investigated. With the other 2-inch configuration, this extended downstream length also has thermocouples in the center of the flow stream to monitor the progression of the steam void during the voiding phase and the water front during the refill transient.

3.1 Summary of Results

As will be discussed, waterhammer events were observed, some during the voiding phase and some during the refill phase (discussed in the next section). As will be presented, these events had pressure increases of tens of psi, i.e. substantially less than those shown in Figure 5.

The first concern for such experiments is that the appropriate pressure increases could be monitored. In all of the experiments performed this was tested at the end of the experiment by rapidly closing the downstream manual ball valve and monitoring whether the measured pressures are sufficient to stagnate the water flow by a single increase (waterhammer) given by

$$\Delta P = \rho_w a_w U_{ss} \qquad (9)$$

In this equation ?$_w$ and a_w are the water density and sonic velocity with U_{ss} being the steady-state water velocity before the valve closure. If the velocity in this equation is replaced with the refill velocity, the calculated pressure is twice the column rejoining pressure assuming water impacts on water.

As will be shown, the resulting experiments always demonstrated the capability to measure such pressure increases at the end of the experiment. This was a convenient way to assure that the experimental apparatus could monitor the waterhammer events of interest. Furthermore, the measured pressure increases are bounded by the column rejoining pressures.

The experiments performed as if there was a check valve on the fan cooler supply piping were those in which there was no drain-down of the supply riser. Figure 7 illustrates one of the measured pressure histories for an experiment in the 2-inch configuration. As illustrated, this particular transient was initiated by opening the manual ball valve immediately upstream of the receiver vessel, thereby causing column separation, which was followed by opening of the solenoid operated ball valve to establish normal flow through the test apparatus. During this normal flow period, the pressure in the loop seal of the discharge piping is approximately 35 psig. After normal flow was experienced for approximately 5 seconds, the solenoid valve for the water supply flow was closed and, simultaneously, the solenoid valve controlling steam addition was opened. This caused a short term pressurization transient as a result of the steam addition. The subsequent behavior resulted in a depressurization to approximately 15 psig as the steam "void" pushed the water column through the discharge piping into the receiver vessel, which was at a pressure of approximately -28 in. Hg. During the first 5 seconds of the steam addition transient, some small pressurization events were observed, which is typically the interval over which the horizontal run at the highest elevation was voided. After approximately 5 seconds, the steam void was pushing the water column through the downcomer and there were essentially no waterhammer events recorded, which is expected since this is a stable configuration.

After 22 seconds of steam addition, the thermocouples in the flow stream indicated that the steam void had penetrated through the downcomer to the bottom of the loop seal. At this stage, some waterhammer events of approximately 10 psi are observed. The voiding rate for this test was a "velocity" of about 1.5 ft/sec. At the end of this interval the steam void ingresses into the vertical riser and somewhat stronger waterhammer events are recorded with the largest being approximately 60 psig. This was the largest event observed in any of the experiments performed in this configuration during the voiding phase of the test sequence. After this time the entire test apparatus was voided as indicated by the increasing pressure in the system as the piping structural heat sink increases in temperature due to sustained steam flow. During the interval of complete voiding, the thermocouples in the voided region also demonstrate an increasing temperature corresponding to the increasing system pressure.

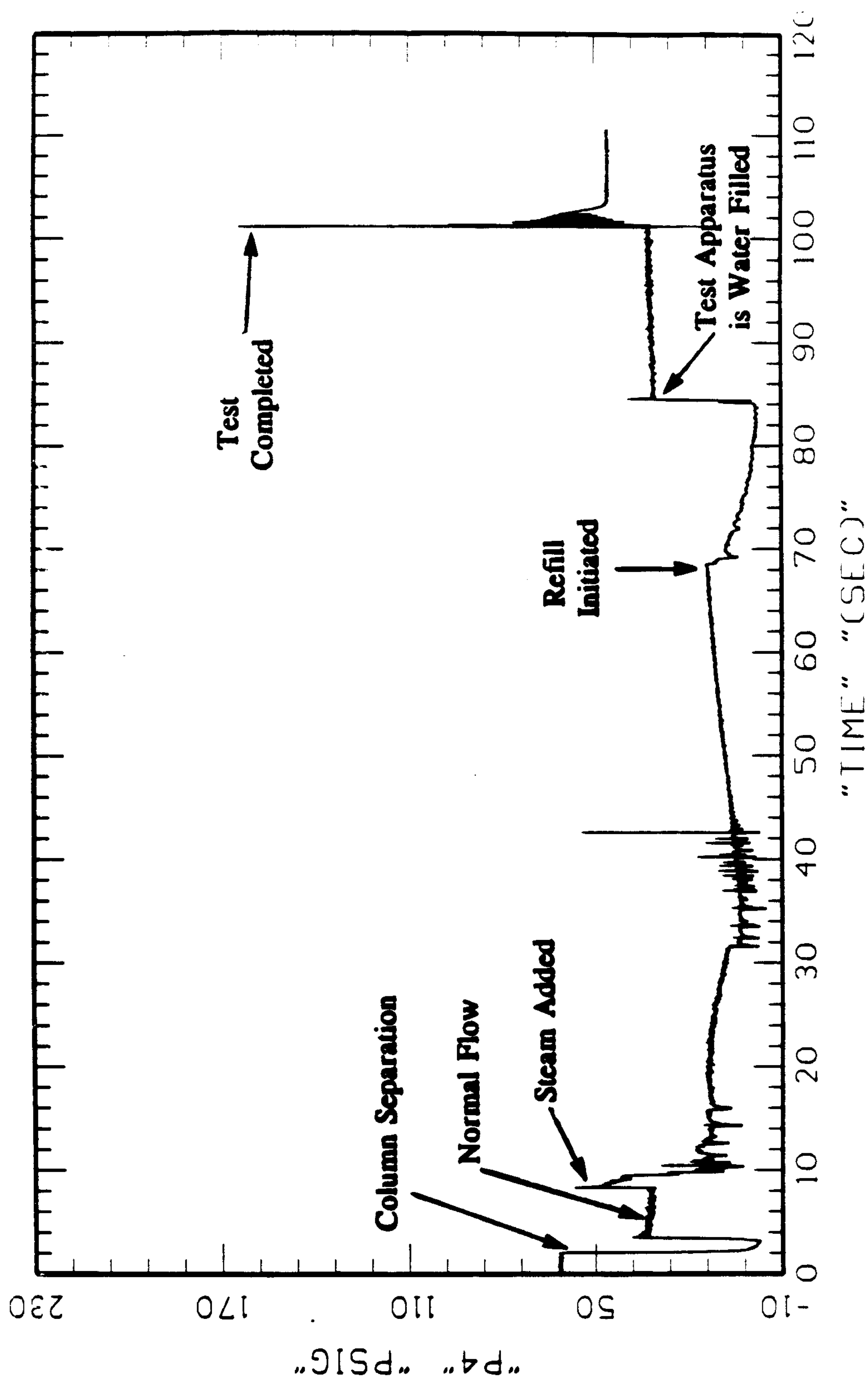
After 60 seconds of steam addition, the refill transient was initiated as shown in Figure 7. With the water addition, the system pressure in the loop seal decreases from approximately 15 to 0 psig as a result of the condensation process. During this time, the pressure transducer at the top of the apparatus (P_1) observes some waterhammer events that are approximately 20 psi in magnitude. However, these are not observed at the measurement station represented in Figure 5 due to the large compliance of the steam void separating the two. In fact, with the measured refill rate in this experiment, the thermocouples show a rate of 3 ft/sec, the Froude number is greater than unity and one would expect the refill process to be proceeding in essentially a "plug flow" manner. For these conditions, the Froude number is defined as

$$F_r = \frac{U_{refill}}{\sqrt{gD}} \tag{10}$$

where g is the acceleration of gravity and D is the channel diameter. (The Froude number is a dimensionless parameter requiring the use of consistent units in this equation.) Certainly the behavior observed by the experiment is consistent with this refill characterization since no significant waterhammer events were recorded. In fact the pressure measurement in the loop seal region sees no such events. Moreover, calculating the column rejoining pressures assuming water properties gives a pressure of 86 psi and 172 psi for the column stagnation. These bound the measured pressures.

As the water column arrives at the gate valve upstream of the evacuated vessel, it is traveling at a velocity greater than the normal flow velocity since it is representative of a pressure difference between the supply vessel and the test apparatus of about 70 psig at this point in time. Consequently, the pressurization experienced by the coolant when it encounters the large restriction represented by the valve is sufficient to slow the water column to the normal flow velocity. Hence, the pressurization history indicates that the system pressurizes approximately 10 psig greater than that which is representative of the pressure in the apparatus under the normal flow condition. As this pressure increase propagates back through the water coolant, the coolant is slowed to that velocity representative of the normal flow.

Figure 7: Typical pressure history during voiding and refill.



This experiment shows that those conditions in which the supply riser remains full would experience waterhammer events during the steam voiding phase, but that these events would be in the range of tens of psi. The strongest event tends to be when the system encounters a loop seal and the steam void progresses to the vertical riser part of that loop seal. However, even in this case the observed events are tens of psi. Figure 8 illustrates typical measured pressures and temperatures during voiding of the horizontal pipe segment. As shown, the waterhammer event are numerous but small. Their magnitudes are consistent with the proposed model.

4.0 CONCLUSIONS

In this paper, a model has been proposed for evaluating the waterhammer events in a horizontal line when steam attempts to push cold water out of equally cold piping. In this evaluation, the capabilities of the system to attempt to stratify were evaluated and are considered to be limited by the entrainment velocity of steam flowing over the water surface. Through these considerations, the potential for "flooding" the water surface to form a wave that captures a steam bubble next to cold piping was developed. With this configuration, the magnitude of such waterhammer events can be calculated and are found to be in the range of 2 atm for the systems examined to date. As a result, these are helpful in evaluating the potential waterhammer events for nuclear power plant service water systems under postulated DBA conditions. The resulting expression for such waterhammer events is found to be in agreement with experimental results, i.e. the waterhammer events are tens of psi for such configurations.

5.0 REFERENCES

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Rothe, P. H. et al., 1977, "An Evaluation of PWR Steam Generator Waterhammer,” CREARE Report TN-251, NUREG-0291.

Figure 8: Comparison of waterhammer incidents and the thermocouple response during voiding of the horizontal loop seal.