WATERHAMMER EXPERIMENTS IN SUPPORT OF A FEEDWATER LEAKAGE CONTROL SYSTEM MODIFICATION

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ABSTRACT

A BWR feedwater system modification involved the addition of a leakage control system (LCS). The LCS was designed for use following a postulated design basis LOCA to inject relatively cool water from the RHR system into the hot, steam filled feedwater piping. Experiments were commissioned to supplement the analyses of the potential for producing condensation induced waterhammers during LCS operation.

A scaled set of experiments which simulated the pipe geometry, valve lineups, initial feedwater pipe wall and steam conditions and the injection water flow rate and temperature but not the specific anchorage and supports were conducted. Each test was conducted by heating the test element's pipe wall with electrical heaters, filling the test apparatus with steam and then injecting sub-cooled water into one end of the horizontal steam-filled pipe. A unique feature of these experiments which distinguishes them from other experiments in the literature is the initial elevated pipe wall temperature. The elevated temperature resulted in significant thermal gradients between the hot upper portion of the pipe and the bottom of the pipe that was cooled following sub-cooled water injection. The experiments demonstrated that the collapse of the thermally induced pipe deflections (bowing) triggered impulsive pressure events. The test was of value, in that it created a stratified flow regime under a variety of flow temperatures and rates. The tests established that the developed internal bending moments for the scale test configuration were significant enough to displace the pipe more than ½ the test pipes' inner diameter.

This paper utilizes the test results as a means to benchmark predictive methods, established in the literature, that may be used to define internally developed stratified load definitions. This paper also investigates the application of the stratified loads to the actual full scale system. The predicted full scale loading for the system yielded high support reactions as expected. However, the support arrangement limited displacements of any significant magnitude. Therefore, in the absence of significant displacements and the associated wave motion encountered in the scale test, steam bubble collapse induced waterhammer is not expected for the system.

INTRODUCTION

During the operation of a Leakage Control System (LCS) for a BWR containment, relatively cool water from the RHR system will be injected into the hot, steam filled feedwater piping. A horizontal portion of the feedwater piping will be completely filled with water and all the steam within it will be condensed. Two modes of operation were investigated for the LCS: Mode 1 completely isolates the feedwater piping segment and Mode 2 which isolates one end of the feedwater piping segment but leaves the other end open to the RPV. These were the bounding modes of operation based on the combination of valves and valve line-ups which could be used as part of the LCS.

The design basis accident which leads to the use of the LCS system will result in the feedwater piping being hot (approximately 218°C/425°F) and filled with low pressure steam (approximately 10^5 Pa/1 atm and 100°C/212°F) at the time that the LCS system is manually initiated. The injected water is supplied from the RHR system which has several modes of operation such that a range of injection flow rates (1.7E-3 - 1.0E-2 m^3/s; 27 - 160 gpm) and temperatures (4.4 - 82°C/40 - 180°F) could be experienced. The experimental matrix was designed to incorporate this expected range of operating conditions.

Experimental Investigation

A review of the planned feedwater LCS system and its use was conducted to identify its susceptibility to producing condensation induced waterhammer events. For waterhammers evaluations in the affected part of the feedwater system, the set of physical processes of interest are:

1. The configuration of the feed water piping including orientation and open or closed end boundaries,
2. Flashing of LCS water due to the heated feedwater pipe and steam condensation, and
3. The water refill rate and temperature when the LCS water flow is established.

These physical configurations and processes are important considerations when assessing the likelihood of producing condensation induced waterhammer events during the refilling of horizontal steam filled pipe segments.

A scaling assessment addressed the pipe configuration for both modes of operation. Two horizontal test elements made of 0.05 m/2 inch schedule 80 pipe that preserved the L/D ratio and heat capacity ratio were selected. The horizontal test element lengths were 0.43 m/1.42 and 3.35 m/11 feet. Due to the essential lack of inclination of the feedwater piping in the station the test elements were installed in a horizontal configuration without a designed inclination. Furthermore, the refill rate was established for the tests by applying a Froude number scaling in an effort to assure that the hydrodynamic effects could be properly addressed.

The effect of the hot piping and its potential for flashing sub-cooled LCS water was addressed in the experimental program by preheating the test element pipe walls. Thus, in each of the tests the initial pipe wall temperature was approximately 425°F (219°C). This is a unique aspect of these experiments which does not appear to have been reported in the open literature on waterhammer.

To minimize the effect of non-condensable gases on potential waterhammer events, the initial condition for each test was established by pulling a vacuum on the test element before admitting steam. The goal was to minimize the non-condensable gas content to represent the expected low mass fraction for the actual plant. The initial test element evacuation is judged to produce a conservative (small) to best estimate non-condensable gas concentration.

The test apparatus and Mode 2 element are illustrated in Figure 1. Each test element was wrapped in a heater tape and insulated. The heater tape was used to establish the initial hot pipe conditions and then turned off when the data was collected. The hot water injection rate was pre-set for each test with the scale and the steam generator was used to fill the evacuated test element with steam.

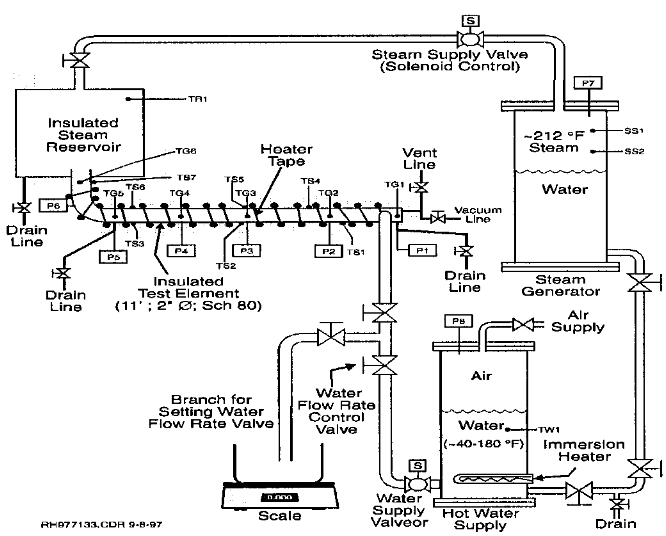

Figure 1 Test facility configuration for Mode 2.

The Mode 1 configuration test element was closed at both ends. The Mode 2 configuration test element had a closed end and an open end that connected to the steam reservoir and steam generator. The steam reservoir and steam generator represented the RPV in the full scale system which can serve as a source of steam to the feedwater piping as steam is condensed during the LCS system injection.

The principal instrumentation used to conduct these experiments and record their results were thermocouples and pressure transducers. Type K thermocouples (0 - 1250°C) and diaphragm pressure transducers (3.44E5 - 3.44E6 Pa/50 - 500 psig) were used. A data sampling frequency of approximately 500 hz to 600 hz was used for the pressure transducers that sensed waterhammer in the test elements. The thermocouples were distributed axially along the top and bottom outside pipe surface, as well as, along the pipe centerline. The pressure transducer taps were also distributed along the bottom of the test element.

Test Results

No waterhammer events were observed for any of the Mode 1 (short pipe with two closed ends) tests. This included the entire range of injection water temperatures and flow rates. Even sensitivity cases which exceeded the LCS maximum injection flow rate did not result in a rapid steam bubble collapse and a waterhammer event.

For the Mode 2 configuration with water injection near the closed end of the test element and an open steam supply at the open downstream end of the test element, no waterhammer events were observed for the lowest injection flow rate for either of the water injection temperatures tested. Waterhammer events were observed for the other four Mode 2 tests including the two sensitivity cases with the injection flow rate which exceeded the maximum to be used by the LCS in the plant. The typical range for the maximum overpressure due to waterhammer events was in the (6.9E5 - 9.05E5 Pa/100 to 130 psi) range. For these longer test element tests (Mode 2) with the injection end restrained by an anchor to the concrete floor and the open steam supply end held in place by the weight of the heavy steam reservoir and attached piping a deflection was observed in each of these tests. The initially hot test element pipe was cooled at the bottom of the pipe upon the initiation of the injection flow. The cooling effect caused the bottom of the pipe to contract while the top of the pipe remained hot and thermally elongated. The differential thermal growth caused the pipe to be deflected such that it bowed in the upward direction. For the eleven foot span of the test element the vertical displacement of the mid-span of the pipe was seen to be approximately an inch (one inside pipe radius). No waterhammer events were observed during the initial water injection and the growth of the maximum pipe deflection. The timing of the initiation of waterhammer events was seen to correspond to the return of the pipe to its non-deflected original configuration. As the pipe wall was cooled such that the upper and lower pipe cross sections approached thermal equilibrium, the deflection rapidly was relieved. Once the deflection had been reduced to within approximately a quarter of an inch the original non-deflected state, waterhammer events were initiated. Typically, three to ten pressure pulses were produced for a single pipe filling transient.

The unique feature of the experiments performed in this test program which distinguishes these tests from other experiments in the literature on the filling of horizontal steam filled pipes with sub-cooled water is the initial pipe temperature. The elevated initial temperature results in the establishment of significant thermal gradients between the hot upper portion of the pipe and the bottom portion of the pipe upon the initiation of the sub-cooled injection water flow. The cooling of the bottom of the pipe as the water flows along it causes it to contract such that thermal stresses are induced. Depending upon the length of the affected piping between anchor points, the thermally induced stresses can lead to significant upward deflection of the horizontal pipe. This "bowing" behavior was unexpected at the onset of the test program and was not a planned phenomena for investigation. However, the potential for bowing given the injection of cold water into a hot pipe should be expected as a possible behavior in the plant as well. The degree of such bowing which may be produced in the feedwater piping depends upon the specific geometry and anchorage in the plant and was not specifically investigated nor reported in this document. Furthermore, the experimental program did demonstrate that the collapse of the thermally induced pipe deflections (bowing) triggered the impulsive pressure events measured in these tests.

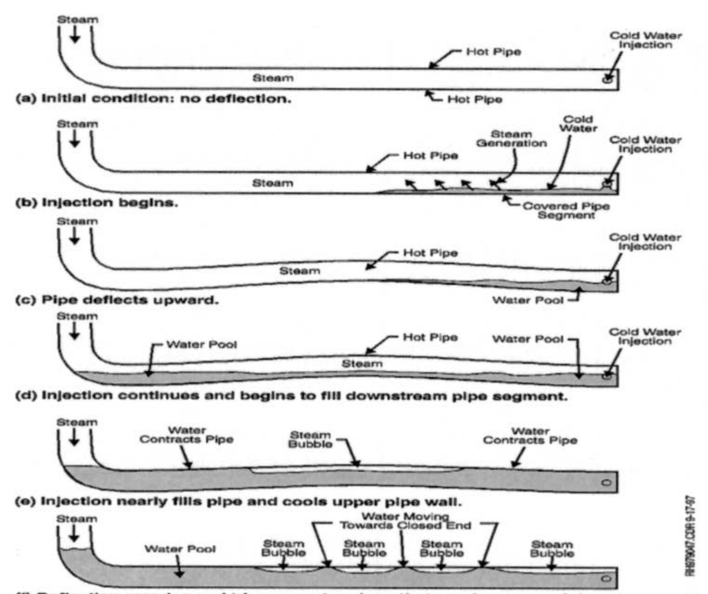

Figure 2 Mode 2 test element bowing due to thermal gradient.

Figure 2 illustrates the sequence of events for the Mode 2 test configuration. When the cold injection flow is started steam in the vicinity of the injection opening which is near the closed end of the test element is condensed. The cold injection water runs along the bottom of the hot pipe where it is heated and steam is produced. The cold water on the bottom of the pipe removes heat from it causing it to cool, contract and to initiate the upward deflection of the test element. The bowing of the pipe leads to an intermediate situation with a water pool formed between the raised middle portion of the test element and the closed injection end of the test element. The end of the test element downstream of the bow will cause any water there to be heated and turned into steam and perhaps even dry out until enough water is injected to overflow the elevated middle section of the test element. Steaming on the downstream piping segment continues and the net steam produced in the test element can exit the pipe into the steam reservoir, which simulates the RPV in the plant. The upstream water pool remains relatively cold since it continues to receive the cold injection water. As the injection continues, the pipe begins to fill up until eventually the water starts to contact the sides and the upper pipe surface regions that were not significantly displaced upwards. The contact of the water with the upper pipe wall initiates cooling of the upper portion of the heated pipe until sufficient thermal equilibrium and contraction is achieved and the pipe straightens out such that the deflection is reduced or eliminated. The steam trapped in the region bounded by the hot bowed mid-span of the pipe and the hot water surface in the pipe is forced into contact with the cold water in the pipe when the pipe deflection is eliminated. The data suggests that a series of waterhammer events are produced upon the elimination of the pipe's deflection. This implies a series of wave induced motions which may trigger condensation induced waterhammer events. The surge waves are hydrodynamically induced events which can also produce waterhammer events even without steam void formation and subsequent condensation induced collapse. Steam condensation may also be involved in hydrodynamic surge wave induced events but the precise flow regime is not observable. Since the insulated metal pipe walls do not allow direct observation of the fluid motion it can not be determined if both waterhammer mechanisms (hydrodynamic surge waves and condensation induced bubble collapse) are produced in these experiments.

The test data does not allow these two waterhammer mechanisms to be separated. However, the data was reviewed from both perspectives and a procedure was developed for applying these test results to the full scale system. The procedure addressed the possibility that either waterhammer mechanism could occur and established a means of specifying the magnitude of such events in the full scale application.

Piping and Supports Investigation

Many known or postulated instances of stratified flow have occurred. These events occur during operating conditions and flow regimes that can not always be well established over the full course of the events' duration. The test demonstrated that the stratification induced displacements were the primary contributing factor for the observed transient loading. However, the scaled test did not completely reflect the specific anchorage and support scheme provided by the actual installation.

The experiments performed in the test program under Mode 2 involved water injection into a relatively long piping segment. The combination of a stratified flow regime and a relatively long unsupported pipe segment could easily result in significant displacements depending on the magnitude of the developed internal bending moments and the boundary conditions defined by the test configurations' support arrangement. The influence of these factors was not fully anticipated at the onset of the test. The tests established that the developed bending moments for the scaled test configuration were significant enough to displace the pipe more than ½ the test pipe's inner diameter.

For the purpose of evaluating the stratification induced bowing observed in the Mode 2 test configuration, a simplified model is utilized in lieu of more sophisticated Computational Fluid Dynamic (CDF) and Finite Element (FE) techniques. In order to study the beam bowing effect of the stratified horizontal pipe segment, the fixed end forces and moments option for the finite element beam element, static routine is utilized. These fixed end forces and moments [1] [2] for straight elements can be determined from the first harmonic of the temperature distribution across the pipe cross section as follows:

$$\theta_B = \frac{1}{\Pi}\int_0^{2\Pi} \theta(\phi)\sin\phi \, d\phi \tag{1}$$

Where θ_B is the bending temperature profile.

$$\varepsilon_b = \alpha\theta_B \tag{2}$$

Where ε_b is the stain amplitude.

The resultant pipe bending moment is then defined:

$$M = E_{\varepsilon_b} Z \tag{3}$$

Where E is the modulus of elasticity and Z is the pipe section modulus.

For all Mode 2 tests the initial pipe wall temperature was established as 218°C/425°F. The temperature range of the injected cold water was 19°C/66°F to 82°C/180°F. Although detailed heat transfer calculations could be used to establish time and location dependent cold water temperatures, such refinements were not applied to this investigation. An intermediate average water temperature (50.6°C/123 °F) is used for investigative purposes.

Given the three cold fluid temperature values, the average pipe temperatures are established as 118.6°C/245.5°F, 134.4°C/274°F, and 150.3°C/302.5°F for the initial cold water temperatures of 19°C/66°F, 50.6°C/123°F and 82°C/180°F respectively. These values are used to account for the pipe thermal expansion coincident with the stratification loading.

Using Equations 1, 2, and 3, the bending temperature amplitude and associated internal pipe bending moments are calculated and summarized in Table 1.

Table 1 Mode 2 Test Parameters

Initial Pipe Temperature		Cold Water Temperature		Average Pipe Temperature, θ_{avg}		Bending Temperature Amplitude, θ_B		Internal Pipe Bending Moment	
(°C)	(°F)	(°C)	(°F)	(°C)	(°F)	(°C)	(°F)	(N-m)	(ft-lbf)
218	425	19	66	118.6	245.5	109.2	228.6	3430	2530
218	425	50.6	123 (est)	134.4	274	89.1	192.3	2885	2128
218	425	82	180	150.3	302.5	68.9	156	2341	1727

A simplified piping model representing the stratified pipe test section shown in Figure 1 was developed and the average pipe temperature and predicted pipe bending moment due to stratification were applied. Two models were investigated; Case 1, based on a fixed – simple configuration and Case 2, based on a fixed (with moment released)– simple configuration. The second model was used since the actual rotational stiffness, at the anchored end, was not known or easily established. This case would yield the maximum expected stratified displacement. The results are summarized in Table 2.

Table 2 Summary of Predicted Pipe Deflections

Cold Water Temperature		Evaluation Case	Maximum Vertical Deflection		Ratio of Deflection to Pipe Inner Diameter
(°C)	(°F)		(m)	(inches)	
19	66	Case 1	0.02	0.802	0.42
19	66	Case 2	0.069	2.728	1.40
50.6	123 (est.)	Case 1	0.017	0.673	0.35
50.6	123 (est.)	Case 2	0.058	2.293	1.18
82	180	Case 1	0.014	0.545	0.28
82	180	Case 2	0.047	1.860	0.96

As expected, the predicted stratification moments can cause significant deflections as observed by the Mode 2 test and as experienced during actual plant occurrences. As noted previously, the Case 2 results yielded maximum displacements and as expected, greater than measured by the test. The actual test configuration would provide a significant degree of rotational constraint, but not to the degree the Case 1 model represents. The Case 1 and 2 results clearly demonstrate the significance of correctly establishing boundary conditions as well as the influence of heat transfer between the cold to hot surface interfaces in any assessment of stratification loads. However, while the Case 2 results yield the largest predicted displacements, Case 1 models predict maximum pipe reaction forces and bending moments which are of importance to the piping designer evaluating pressure boundary and support hardware integrity. Furthermore, as the test demonstrated, the displacements resulted in the triggering mechanism for the observed transient.

The plant specific investigation primarily focused on the pressure boundary integrity between the outboard and inboard isolation valves. This portion of piping is considered a no break region for BWR Mark III plants. Demonstration of pressure boundary integrity under the postulated stratified flow case was necessary to ensure that the leakage control system would create a complete water seal, as intended.

The actual support system for this region of piping is comprised of the outboard containment penetration anchor, an inboard (drywell) support and the guard pipe support system. The guard pipe support configuration was not captured by the scaled test arrangement.

The model of the actual piping arrangement accounted for all piping on the inboard (drywell) and all design bases supports. In addition, the plant specific analysis accounted for some degree of heat gain by the cold fluid from the initially hot pipe, the mean thermal expansion of the pipe and the system flexibility's inherent to the piping / support system. As demonstrated by the Case 1 and 2 evaluations, system flexibility considerations are important when displacements can influence the thermal hydraulic and load distribution result.

The predicted full scale loading for the system yielded high support reactions as expected. A unique feature of the subject feedwater system's supports is that they were originally designed to mitigate load transfer to the isolation valve area under postulated pipe break loading upstream and downstream of the subject piping region. As a result, these supports had sufficient load capacity to accommodate the postulated stratification loading. Such design margins generally would not exist for less critical balance of plant systems, which might experience stratified loading. The feedwater support arrangement limited piping displacements to a maximum value of approximately 0.00635 m/0.25 inches. The calculated expected displacements in the region of interest are limited by the constraints provided by the pipe support arrangement (containment penetration anchor, the guard-pipe guide support and pipe guides inside the dry well). Unlike the test results, the calculated displacements were not considered significant with respect to the 20-inch pipe's inner diameter as the ratio of calculated displacement to pipe inner diameter is only 0.0125. Therefore, in the absence of significant displacements and the associated wave motion encountered in the scale test, steam bubble collapse is not expected for the system.

CONCLUSIONS

Scaled experiments were used to investigate the possibility of waterhammer events in steam filled horizontal pipe when they are filled with cold water. The experimental results were used to define procedures, which could be used to screen for the possibility of waterhammer events and estimate their dynamic characteristics in the full scale system.

This paper utilizes the test results as a means to benchmark predictive methods, established in the literature, which may be used to define internally, developed stratified load definitions. This paper also investigates the application of the stratified loads to the actual full scale system. The predicted full scale loading for the system yielded high support reactions as expected. However, the support arrangement limited displacements of any significant magnitude. In this case, the piping supports had inherent load carrying capacity to accept the stratification loading and limit displacements. Therefore, in the absence of significant displacements and the associated wave motion encountered in the scaled test, steam bubble collapse induced waterhammer is not expected for the system.

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