Letter Report No. 243-1

Review of EPRI/Industry Technical Basis Report for Resolution of GL 96-06 Waterhammer Issues

Hossein P. Nourbakhsh
25 East Loop Road
Stony Brook, NY 11790

December 1999

Prepared for:
U.S. Nuclear Regulatory Commission
Office of Nuclear Reactor Regulation

Under Consultant Agreement No. C210131
From SCIENTECH, INC.
11140 Rockville Pike
Suite 500
Rockville, MD 20852

Contract N0. NRC-03-95-026, Task 243,
TAC NO. M97252

Enclosure 2

1. INTRODUCTION

NRC Generic Letter 96-06 (GL 96-06) " Assurance of Equipment Operability and Containment Integrity During Design Basis Accident Conditions" [1] included a request for licensees to evaluate cooling water systems that serve containment air coolers to assure that they are not vulnerable to waterhammer conditions. More specifically, the issue of concern is :[1]

> " .....Cooling water systems serving the containment air coolers may be exposed to the hydrodynamic effects of waterhammer during either a loss-of-coolant accident (LOCA) or a main steam line break (MSLB) with a concurrent loss of offsite power(LOOP). These cooling water systems were not designed to withstand the hydrodynamic effects of waterhammer and corrective actions may be needed to satisfy system design and operability requirements."

The waterhammer concerns discussed in GL 96-06 are primarily associated with low pressure systems. While the analytical methodology contained in NUREG/CR-5220, "Diagnosis of Condensation-Induced Waterhammer,"[2] is considered by NRC to be acceptable for analyzing waterhammer effects in fluid systems, licensees feel that this methodology is overly conservative for low pressure applications.

Industry initiated a testing and analysis program in 1998 to develop methods for realistic evaluation of the waterhammer loads in low-pressure fluid systems . This initiative has been sponsored by 14 utilities and the technical work has been coordinated by Electric Power Research Institute (EPRI). An interim Technical Basis Report (TBR)[3], documenting the results of the EPRI/Industry collaborative project , was submitted to NRC in September 1999 for review and approval .

Scientech, Inc. was requested (Contract NRC-03-95-026, Task Order No. 243) to assist the NRC staff in evaluating the development and adequacy of analytical methods that are being developed by industry representatives for assessing waterhammer effects in low- pressure fluid systems.

This letter report summarizes the review comments on the results of the industry initiative as documented in the interim TBR issued by EPRI . Section 2 provides a general overview of the analytical methodology that has been developed , noting strengths and limitations in the approach. Specific comments on significant limitations and weaknesses with the methodologies for evaluation of Condensation Induced Waterhammer (CIWH) and Column Closure Waterhammer (CCWH) are discussed in Sections 3 and 4 respectively. Section 5 provides a brief summary together with conclusions.

2. GENERAL OVERVIEW AND COMMENTS

The interim TBR provides a comprehensive approach for evaluating the GL 96-06 waterhammer issues. The major components of the utility approach are shown in Figure 1. Determination of the "worst case" sequence of events together with the most limiting plant configuration provide the foundation for performing the waterhammer evaluation . Guidance on these subjects, including single failure consideration, is provided in Section 3 of the interim TBR.

Transient system thermal hydraulic and voiding analysis is an important component of the waterhammer issue evaluation process . This analysis determines the important initial and boundary conditions (such as the flow , pressure, temperature and voids formation) for the subsequent evaluation of the different waterhammer mechanisms. The interim TBR recognizes the importance of these parameters for waterhammer evaluation. However, no specific guidance has been provided for system thermal hydraulic and voiding analysis to quantify these parameters.

An integrated testing and analysis program was undertaken to develop methods that allow for the evaluation of loads associated with two waterhammer mechanisms: (1) condensation induced waterhammer during the voiding phase, and (2) column closure waterhammer during the refill phase. Section 4 of the interim TBR discusses the mechanisms of occurrence of these two types of waterhammers including the following criteria (suggested in NUREG/CR-6519[4]) to determine what piping is susceptible to condensation induced waterhammer:

(a) Near horizontal (i.e. vertical lines are excluded),
(b) subcooling greater than 36°F (20°C), and
(c) L/D > 24.

However, the "road map" for an approach to the overall issue, described in Section 1.5 of the interim TBR (see also Figure 1) , uses the uncovering of the horizontal lines during the voiding phase as the only criterion for the assessment of the condensation induced waterhammer. Further clarifications on validation and endorsement of the above criteria (suggested in NUREG/CR-6519) by EPRI/Industry approach are needed.

Specific review comments on the interim TBR suggested methodologies for evaluation of loads associated with CIWH and CCWH are provided in Sections 3 and 4 of this Letter Report.

The interim TBR also recognizes the potential for occurrence of other waterhammer mechanisms and they have been expected to be insignificant for most cases (Section 6 of TBR). The interim TBR provides a checklist (see Figure 1) that should be utilized to assure that specific plant conditions are not conducive to such waterhammer events. If any of these checklist items are present, a plant-specific evaluation is required. However, the interim TBR provides no specific guidance for such plant-specific evaluations.

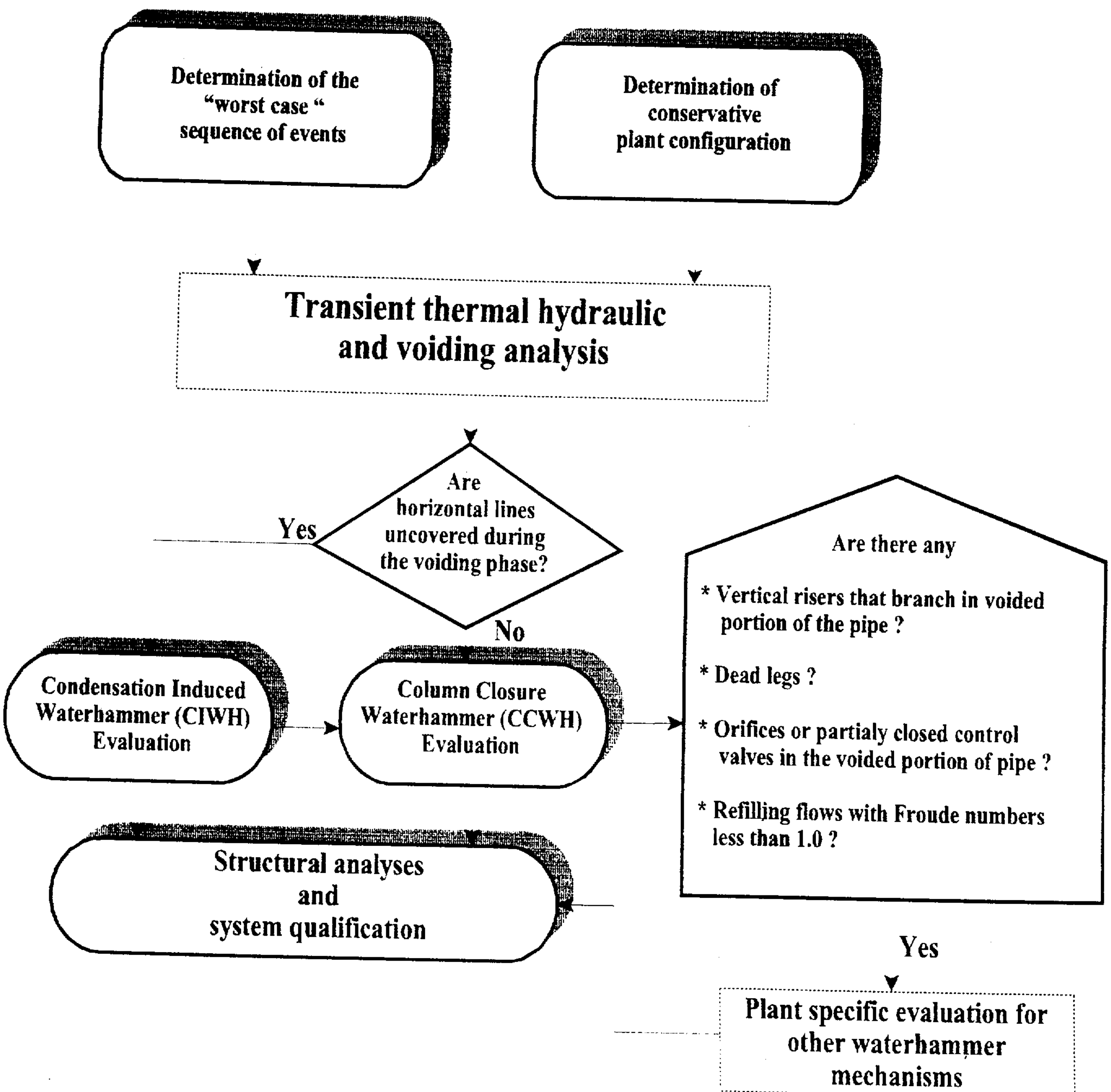

Figure 1. Flow diagram and topics addressed in TBR (items in dotted boxes are not detailed in TBR)

Structural analysis and system qualification is another important component of the waterhammer evaluation process . Guidance on this subject is provided in Section 11 of the interim TBR.
It should be noted that the review of EPRI/Industry suggested approach for the structural analyses and system qualification is beyond the scope of this Letter Report.

3. CONDENSATION INDUCED WATERHAMMER

The uncovering of horizontal runs of pipe during the voiding phase creates the potential for condensation induced waterhammer. As horizontal section of lines are exposed, steam will enter the space formed at the top of the pipe. The space between the top of the pipe and the exposed water can allow condensation of steam and trapping of steam bubbles. The rapid condensation of the trapped steam and the subsequent closing of the void by water causes a condensation induced waterhammer pressure pulse.

The interim TBR presents a simple equation, which is derived from the Joukowski equation and an energy balance, to determine the magnitude of the resulting waterhammer pressure pulse. Testing of condensation induced waterhammer events was also performed to show that the magnitude of pressure pulses generated during the voiding of actual configurations are less than the magnitude predicted by the analytical model. Two configurations were tested. One featured a straight voiding section and one featured a rise at the end of the test leg to establish a "loop seal" in the test section.[3] The diameter of the test section was 4 inches. The length of the test section was 20 ft, which was greater than 24L/D "rule of thumb" (suggested in NUREG/CR-6519) for piping length required to get CIWH. The testing was performed considering both normally aerated and deaerated water and conservatively simulating no thermal layer, no air in the steam, and with steam driving pressure (15-30 psia) higher than that is expected in most plants. CIWH testing was also performed in a separate study using 2" pipe with normal tap water and system pressures of 10 to 20 psia.

The results of the CIWH testing include the following:

- The tests produced waterhmmer pressure pulses that increased with steam driving pressure.
- The deaerated water tests had peak pressures that were more than twice as high as the normal aerated water.
- Loop seal data gave somewhat higher waterhammer magnitude but had lower impulse than the straight pipe tests.
- Waterhammer occurrences generally follow a constant impulse behavior.
- Waterhammer pressures were independent of draining flow rate.

The interim TBR (page 8-24) also concluded that the waterhammer pressures are independent of pipe size (Froude number) for the range of concern here (2" to 16"). This conclusion was made primarily by comparison of 2" and 4" CIWH tests results. The interim TBR also used a simple scaling rational, based on an equation for steam velocity obtained from a heat balance on the water/steam interface, for further explanation of size (diameter) independence. It was demonstrated that the steam velocity is primarily dependent on the slope of water/steam interface. However a proper justification was not provided for the statement , " as the pipe size changes no significant changes in the slope is expected" .

One major conclusion that was drawn from the CIWH testing program was that the CIWH waterhammers, for low pressure water systems, are limited in magnitude or duration such that they are not a credible threat to pressure boundary integrity. In terms of application for the suggested utility approach to the overall issue, Section 8.5 of the interim TBR provides guidance for the system performance parameters to be met (see figure 2) so that CIWH will not have to be explicitly calculated. These conditions include a somewhat qualitative requirement that the water that is draining contains non-condensables. A more explicit quantitative requirement on the concentration of non-condensables in the water is needed. It should also be noted that the interim report does not provide any guidance for plant-specific CIWH evaluation if these performance requirements are not met.

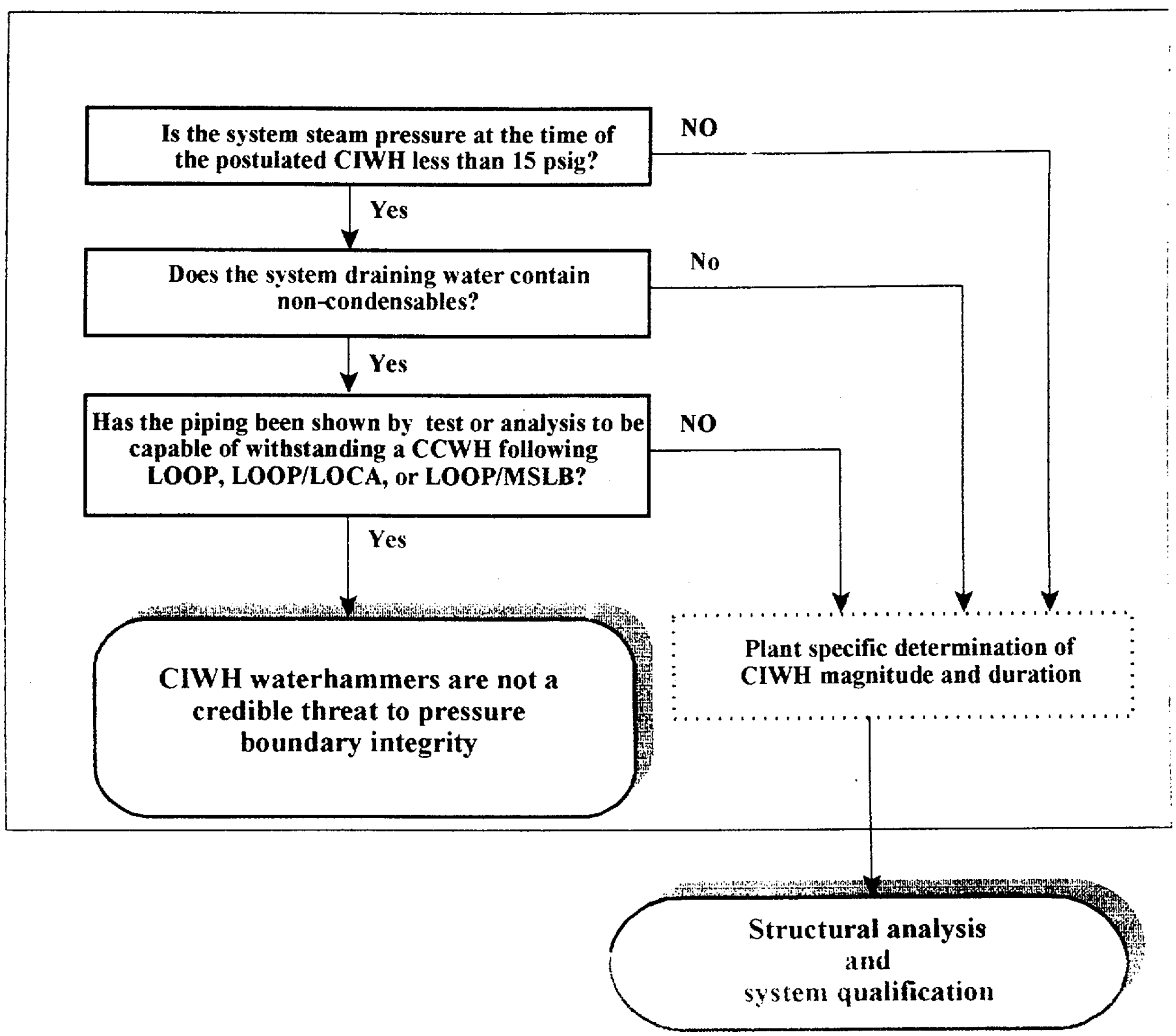

Figure 2. Flow diagram for CIWH evaluation (items in the dotted box is not detailed inTBR)

3. COLUMN CLOSURE WATERHAMMER

During refill of the containment coolers, hydrodynamic loads could be experienced due to column closure (water column closing) waterhammer. The waterhammer pressure developed by the impact is primarily dependent on the closure velocity. The Joukowski equation shows that the magnitude of waterhammer can be reduced by lowering the closure velocity of the water columns. Non-condensables and /or steam that are in the void can become pressurized as the void closes. The effect of void pressure is to slow the oncoming water column and to accelerate the downstream column. This is referred to as "cushioning". Relative velocity is decreased and the peak waterhammer pressure is reduced. As a part of the EPRI/Industry collaborative project, an integrated testing and analysis program was undertaken to develop methods that allow for the reduction in closure velocity due to cushioning.

The interim TBR presents methods to determine the CCWH pressure pulse magnitude and shape (rise time and duration). A finite difference model was developed to simulate the column closure waterhammer event. This model (referred to as the MOC model in the interim TBR) uses Wylie and Streeter's well known application of the method of characteristics[5]. The method of characteristics is used to solve the hyperbolic partial differential equations (of continuity and momentum) to obtain the liquid velocity and pressure at a known grid location. MOC model simulates the main void as an internal boundary condition. This model provides a means of accurately simulating all aspects of the column closure event including steam condensation, air compression, reflections, and pulse attenuation as it travels through the system.

Although The MOC model is well suited for the analysis of column closure waterhammer, its application may require significant time and effort. An alternate simpler model , referred to as the Rigid Body Model (RBM), was also presented in the interim TBR. The potential weakness of the rigid body modeling approach is that the compressibility of water is not considered. Water compressibility and wave propagation causes the peak pressure in the void to be limited .[3] However, by imposing the pressure limit (represented by Joukowski equation), the pressure pulse may be closely characterized by using the rigid body model.

Column closure waterhammer tests were performed to provide data under controlled laboratory conditions. This data was used to benchmark the analytical models described above. Several different pipe configurations were used to produce column closure waterhammer events utilizing a water column driven by compressed air. The piping system consisted primarily of 2", schedule 80 pipe, with a waterhammer producing section isolated by ball valves.

The first configuration (referred to as configuration#1 in the interim TBR) featured a test section into which steam was introduced from an outside source, which permitted independent control of the steam and the water conditions. Configuration #1 investigated waterhammer without the mitigating effects of air in the void. The second configuration (referred to as configuration#2 in the interim TBR) featured a test section in which steam was created by boiling water in a portion of test pipe. Configuration #2 was more representative of real piping systems subjected to external heating. Configuration #2a and 2b were similar configuration but had some geometrical differences, including the length of the steam void section. Another difference between the configurations #2 a and #2b was the boiling sequences. The #2a system was heated until the steam progressed past the UT level sensors, and then some portion of the steam was condensed back to the void length desired. In the #2b configuration, sight glasses were used to monitor the void, and the water was only boiled until the steam void grew to the desired void length.

Configuration #1 test data (Figure 9-18 of the interim TBR) shows some cushioning from steam at higher closure velocities, when the steam condensation rates cannot keep up with void pressurization. The Rigid Body Model was used to simulate the column closure. This model considered steam cushioning in the void, and by adjusting the condensing heat transfer coefficient to a fixed value of 64,000 BTU/hr ft^2 °F (independent of closure velocity), closely matched the test data. The method of characteristic was also used to predict the column closure waterhammer. The result for a specific case reported in the interim TBR (Table 9.5) shows consistency between experimental data and both the MOC and the RBM modeling approaches.

The Cofiguration #2a and 2b test results (Figures 9-23 and 9-24 of the interim TBR) show the effects of dissolved non-condensables (air) in the test water. The results of the Configuration #2a column closure test indicate that as the dissolved oxygen content in the water increases, the waterhammer peak pressure decreases due to cushioning . However , it should be noted that in the Configuration #2a test, the void was developed by boiling the steam to a larger size than required, and then condensing it back to the desired size. As it was discussed in the interim TBR, this contributed to variability in the actual air concentration of the void and scatter in the 2a test data. Therefore, without quantifying the uncertainties associated with the air concentration, use of this data for model validation is questionable.

The Configuration #2b column closure tests do not indicate any pronounced effects of the increased dissolved air in the water on the waterhammer peak pressure, especially for low closure velocity (driving pressure) conditions. The Rigid Body Model predictions were also presented in the interim TBR and they show more sensitivity to the dissolved oxygen content than the test results.

Small scale testing (using one inch copper piping) was also performed to provide a basis for the prediction of free gas in the steam void (see Section 9.2.3 of the interim TBR). No scaling rational for these tests was provided. The conclusion of this testing was that water with dissolved gas will release at least 40% of its gas (down to the gas saturation point at the highest temperature). However, without quantifying the biases due to scale distortion or due to non-prototypical conditions of these tests, the above conclusion is questionable and may not be conservative for plant applications.

An alternate method of calculating the mass of non-condensable gas released is also described in section 9.3.1. By calculating the mass of water that boils and then condenses and knowing the initial concentration of gas in the water, the amount of gas that becomes concentrated in the void can be calculated. A simplified equation (Equation 9.8 of interim TBR) was obtained by balancing the heat transferred from the condensing steam with the heat absorbed by the piping during the void formation. It should be noted that, in the presence of external heat transfer from the containment atmosphere to the piping , the validity of this equation is questionable and may not be conservative.

The major components of the suggested utility approach for evaluating the column closure waterhammer are shown in Figure 3 (see also Appendix H of the interim TBR). This evaluation requires many important input parameters (such as void length and location, void temperature, and flow distributions in the system) which are obtained from thermal hydraulic analysis of the voiding phase. However , as discussed earlier in Section 2, the Interim TBR does not provide any guidance for such system thermal hydraulic and voiding analysis to quantify these parameters. It should be noted that the element of " determination of equivalent void & water column lengths", shown in Figure 3, only refers to calculation of equivalent lengths (based on the actual void and water column locations) required for the simplified representation of the system for the proposed evaluation methodology and does not refer to a thermal hydraulic and voiding analysis.

The term "first order velocity" refers to the impact velocity which can be approximated by the inertia or friction limits (see section 9.6.2.1 of the interim TBR). The interim TBR also recognizes that in an actual plant system, a previously qualified system hydraulic model can also be used to determine a more accurate value for the 1st order velocity.

The term " second order velocity " refers to the impact velocity that is calculated after considering the effects of steam condensation and /or gas compression in the void (cushioning). The interim TBR presents a series of plots which characterize the ratio of the second order velocity to the first order velocity. The second order velocity was calculated using the Rigid Body Model. Multiple simulations were performed with the different flow coefficients, lengths, velocities, and air masses . In terms of using the suggested utility approach for evaluating CCWH, the interim TBR establishes limitations for the velocity, air mass, temperature, water column size ,and void length(see Table 9.6 of interim TBR) so that plant specific simulation, using RBM or MOC models, is not necessary. As noted in the interim TBR, an alternate condensing model may be required if the velocity, air, or temperature limits are not met. However , the interim TBR does not provide any guidance about how this alternate condensation model should be obtained and how to validate the RBM or MOC models when these limits are not met.

Theoretically, a waterhammer event produces a square wave with a finite duration based on the water-solid length through which the wave travels to a reflecting surface. However, in reality , the analytical square wave model is modified due to several phenomena including partial reflections from changes in direction . The leading edge of the wave front does not have an instantaneous rise but has a finite " rise time" over which the pressure magnitude increases from the steady state value to the elevated transient pressure. The rise time is particularly important to the structural loading of the piping, since loads are dependent on the slope of the rise.[3] The interim TBR recommends a trapezoid representation of the pressure pulse. In developing a trapezoid pulse model, the area of a square wave was conserved.

Utilizing the Joukowski equation , the peak waterhammer pressure pulse (without any clipping) can be calculated by using the 2nd order velocity. The interim TBR also provides guidance for determination of the rise time, sonic velocity, duration, transmission coefficients, flow area attenuation, and peak pressure clipping to determine the peak pressure pulse and the shape and attenuation of the pulse as it travels through the system.

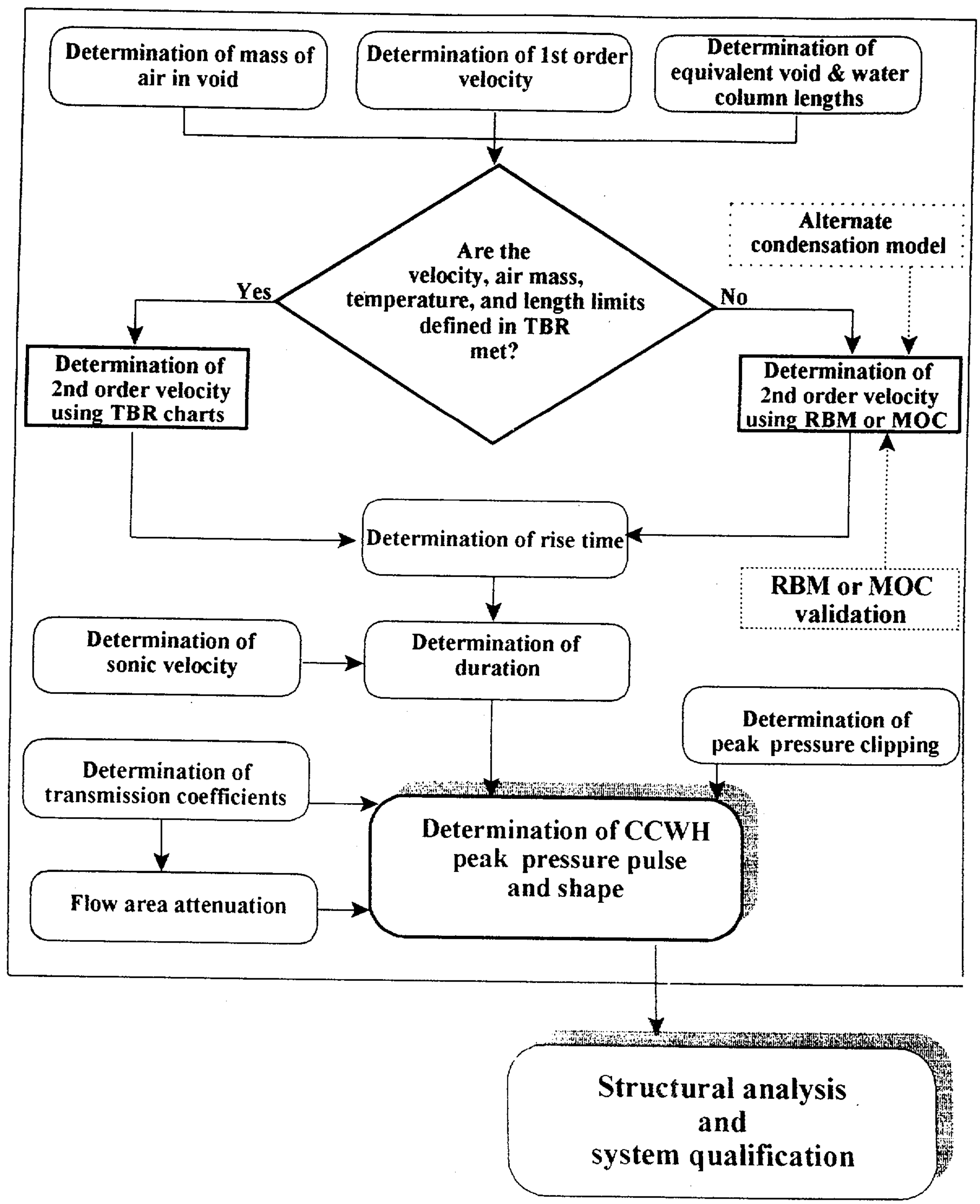

Figure 3. Flow diagram for CCWH evaluation
(items in dotted boxes are not detailed in TBR)

The rise time was assumed to be inversely proportional to the impact closure velocity . A conservative bounding proportionality constant was derived from the results of RBM simulations for a range of cases and from the actual Configuration #1test data (see Section 9.2.4 of interim TBR).

It should be noted that , at a separate facility, tests referred to as the thermal layer tests were also performed. Although, the interim TBR provides the description of the test configuration and results, no guidance has been provided on whether or how the results of these tests are used for CCWH evaluation.

5. SUMMARY AND CONCLUSIONS

The results of the industry initiative for realistic evaluation of the GL 96-06 waterhammer loads , as documented in the interim TBR, has been reviewed. The interim TBR provides a comprehensive approach for evaluating the GL96-06 waterhammer issues. A general overview of the analytical methodology, noting strengths and limitations in the approach, was provided and the following weaknesses were noted :

- No specific guidance for system thermal hydraulic and voiding analysis was provided.

- Further clarifications on validation and endorsement of the criteria (suggested in NUREG/CR-6519) for the assessment of the condensation induced waterhammer are needed.

- No specific guidance for plant-specific evaluations of other waterhammer mechanisms was provided.

An integrated testing and analysis program was undertaken to develop methods that allow for the evaluation of loads associated with two waterhammer mechanisms: (1) condensation induced waterhammer during the voiding phase, and (2) column closure waterhammer during the refill phase. The following limitations and weaknesses with these methodologies were discussed:

- A proper justification for the conclusion that the CIWH pressures are independent of pipe diameter (Froude number) for the range of concern (2" to 12") is needed.

- A more explicit quantitative requirement on the concentration of non-condensables in the water, so that CIWH will not have to be explicitly calculated, is needed.

- Without quantifying the uncertainties associated with the void air concentration, use of the Configuration #2a data for model validation is questionable.

- Without quantifying the biases due to scale distortion or due to non-prototypical conditions of the small scale testing, the conclusion of this testing (that water with dissolved gas will release at least 40% of its gas) is questionable and may not be conservative for plant applications.

- In the presence of external heat transfer from the containment atmosphere to the piping, the validity of the alternate method of calculating the mass of non-condensable gas released is questionable and may not be conservative.

- No guidance was provided on how an alternate condensation model should be obtained, and how to validate the RBM or MOC models, if the velocity, air, or temperature limits are not met.

Although the important physical processes of interest to GL 96-06 waterhammer issues have been identified , no systematic scaling methodology has been adopted to ensure that the models are valid for actual plant conditions. An integrated methodology similar to the one developed for severe accident technical issue resolution[6] may be useful for resolving the GL 96-06 water hammer issues. The RBM model , in particular , is very useful for a top-down or system approach to the scaling analysis.

6. REFERENCES

1. Nuclear Regulatory Commission (NRC), " Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions," NRC Generic Letter 96-06, 1996.

2. Izenson, M.G., P.H. Rothe and G.B. Wallis, "Diagnosis of Condensation- Induced Waterhammer," NUREG/CR-5220, October 1998.

3. Zysk, G., M. Zweigl, T. Esselman, R. Henry, and R. Hammersley, "Resolution of Generic Letter 96-06 Waterhammer Issues", EPRI TR-113594-V1&V2, EPRI Project Manager: A. Singh, Interim Report, September 1999.

4. Griffith, P. "Screening Reactor Steam/Water Piping Systems for Water Hammer", NUREG/CR-6519, September 1997.

5. Wylie, E.B. and Streeter, V.L., *Fluid Transients in Systems*, Prentice Hall,1993.

6. U.S. Nuclear Regulatory Commission, "An Integrated Structure and Scaling Methodology for Severe Accident Technical Issue Resolution," NUREG/CR-5809, Draft for Public Comment , November 1991.

NRC STAFF COMMENTS RELATED TO
EPRI INTERIM REPORT TR-113594,
"RESOLUTION OF GENERIC LETTER 96-06 WATERHAMMER ISSUES"
DATED JULY 1999

Technical Comments:

- Page 8-4, Section 8.1.4; it should be emphasized that the velocities of both the impacting and the impacted columns of water should be calculated and that the relative velocity between the two columns is the impact velocity of interest.

- Page 8-10, last paragraph, draws the conclusion that CIWH is independent of pipe size. However, the scatter in the data in Figure 8-5B makes this conclusion very suspect.

- Page 8-17, transducer limited to 1000 psig; what is effect on data?

- Figure 8-8, is there a bounding curve (other than Joukowski)?

- Figure 8-9, K_{imp}=3 is not bounding; a more conservative value should be used.

- Figures 8-11, 8-13, and 8-14, need to explain why 1000 psig limit is not a problem. Also, is there a bounding curve for this data?

- Figure 8-12, not bounding for much of the data; assumption for K seems non-conservative.

- Figure 8-17, need to explain why 1000 psig limit is not a problem. Also, what to make of the deaerated loop seal data, and what about aerated loop seal test data?

- Page 8-24, the discussion neglects the condensing effect of the pipe wall. I would think that this could change the conclusions for the range of pipe sizes being considered (i.e., 2" to 16").

- Page 8-26, the conclusion stated in the last paragraph needs to be reexamined based on test data in Figures 8-14 and 8-17, and lack of data for aerated loop seal configuration.

- Page 8-27, 7th bullet; there is no data for the aerated loop seal case for making this conclusion.

- Page 8-27, last bullet; this is not entirely correct. The occurrence of a CCWH does not necessarily represent the worst case condition since it may not include the worst case single active failure.

- Page 9-3, Section 9.1.2; it is not clear how the value "R" is determined. Also, the pulse duration is increased by a 1/R factor for the impulse to equal the momentum change in stopping the columns. However, the actual duration can be no more than 2L/C, which is fixed. Therefore, the method of letting a single impulse equal the total momentum, does not appear to apply.

- Page 9-7; the discussion about the condensation of steam on the piping surface (next to last paragraph) is not consistent with the condensing surface area that is described on Page 8-24.

- Page 9-11, Number 2 (at the bottom of the page); what other exceptions are there that are non-conservative that need to be identified and recognized as exceptions to the rigid body model? How is this addressed in the road map?

- Page 9-13, the test configuration is not representative of actual plant configuration, with horizontal tubes of the fan cooler connecting with vertical risers of various diameters, and various elevations relative to the rest of the piping system. Application of the test data is suspect and must be justified.

- Figure 9-9A; curve fit should be based on 0-to-40 second period to be more reflective of the actual scenario.

- Page 9-16; items 1, 2, and 3 are a stretch and probably non-conservative; also, not supported by test data.

- Page 9-17, Section 9.2.3.1; should include some discussion or comparison of the situation that could arise where all of the noncondensible gas is not concentrated in one place.

- Page 9-17, last paragraph; discussion about condensation on pipe surface is not consistent with the discussion on page 8-24. Also, Equation 9.5 fails to consider the effect of the containment temperature on the pipe wall.

- Page 9-18, Section 9.2.4; the inverse relationship between rise time and velocity appears to be based on observation only. Waterhammer theory does not appear to predict forcing functions other than simple rectangular shapes. Is there a theoretical basis for the assumed relationship?

- Page 9-18, eq. 9.5; what about contribution of pipe heat that is due to containment temperature?

- Page 9-19, 1st sentence; use of Appendix E in this fashion would be outside the scope of the NRC endorsement. This would be true for anything that falls outside the road map methodology.

- Page 9-34 (Figure 9-18), the data is not bounded by Joukowski on the low end, and the rigid body model also does not bound all of the data. Some explanation is needed to apparent reflect on this lack of conservatism.

- Page 9-35, Table 9-5; the rigid body model without the steam cushion appears to be conservative, while the other methods do not. Justification for use of the other two methods is needed.

- Page 9-36, 2nd paragraph; the conclusions are not at all obvious from the test data (Figure 9-19). Also, 3rd paragraph conclusion -- where is the data and figure that demonstrates this?

- Page 9-36, last paragraph; thermal layer discussion (especially with regard to upstream piping) is too speculative and does not take into consideration the various piping arrangements that can exist (e.g., check valves to prevent back flow). Also, the discussion in Number 2 is not consistent with the piping arrangement that is offered for the air release argument (Page 9-16), and the discussion that follows on Page 9-37 is mostly speculation (and intuitive), and not much can be made of it as far as the actual methodology is concerned.

- Page 9-38, Fig. 9-19; the question that was raised during a previous meeting (what to make of it?) remains to be addressed.

- Page 9-39, last paragraph; the value of K_R bounds most of the data (Figure 9-21), but why isn't a value selected that bounds all of the data? The specific exceptions must be identified and justified in establishing a conservative approach.

- Pages 9-43 & 9-44; (Figures 9-23 & 9-24); some additional explanation and consideration is needed. The effect of air is evident in Figure 9-23, but the exact amount of air is unknown due to the 2a test arrangement. The effect of air is not evident in Figure 9-24 where the amount of air is known (2b test arrangement). Also, the rigid body model is not bounding for all data.

- Page 9-44; the effects of air cushioning do not seem very obvious.

- Page 9-47, Figure 9-26; does this include the effects of pipe heating from containment atmosphere?

- Page 9-49; how to determine the flow coefficient K?

- Page 9-50, is the 200 °F temperature low enough to include the anticipated low pressure situations that can result from column separation?

- Page 9-51; the approach described in Number 3 would not be included in the NRC endorsement without a better understanding of how this would be applied to assure conservative results. Also, the exact approach for crediting attenuation due to rarefaction waves must be clear for NRC endorsement, and amplification effects must be included in the approach.

- Page 10-11, Section 10.2; it is recommended that for consideration of the effects of fluid-structure interaction (FSI), the peak pressure should be increased by 15% while the pressure pulse would be attenuated by system specific geometry, structural stiffness, and pulse characteristics. However, the waterhammer test data does not appear to indicate a significant correlation between the peak pressure and piping structural characteristics. Additionally, there is significant uncertainty in the modeling parameters involved in evaluating a coupled fluid and structure, such as the fluid and structural wave speeds (especially when there is air or phase separation), the duration and timing of structural and fluid pulses, and the structural stiffness. For these reasons, the staff agrees with the final statement made in Section 10.2 wherein it is not recommended that FSI be specifically analyzed.

- Page 10-16, Section 10.2.3; explain why attenuation of 10% at each change in direction only gives a 50% reduction in pressure after 8 changes in direction.

- Page 11-1, Section 11; a general discussion should be provided relative to how loads are applied to the piping structure, including the application of dynamic load factors to static loads and the application of force-time histories by direct integration techniques. A discussion of necessary bench marking of structural codes for the fluid dynamic loads and the necessary analysis parameters (such as frequency cutoff and time step size) should be provided.

- Page 11-3, Section 11.2.1; a discussion is provided wherein it is stated that there is little response from adjacent supports. However, the test piping has significant bending stiffness and would be expected to transfer some portion of the fluid dynamic loads to surrounding supports. To the extent that some load is actually transferred to points other than the immediate support, the resulting computation of dynamic load factors (DLFs) in Section 11.2.2 may be non-conservative.

- Page 11-5, Section 11.2.2; the DLFs for the proposed trapezoidal load shape are a family of curves lying between the triangular and square shape DLFs, and can approach a value of 2 for certain durations and/or rise times of a single pulse. It should be emphasized that DLF values may need to be increased in some cases to address uncertainties either in the load definition or in the structural model. In addition, waterhammer forces typically consist of several cyclic reversing pulses which repeat for several full cycles. For certain frequencies, structural response is amplified with each pulse such that the DLF will greatly exceed a value of 2.

- Page 11-8, Section 11.2.3; it is concluded that a trapezoidal characterization of the actual fluid pressure history is an accurate approximation. However, this conclusion is reached with knowledge of the actual pressure history for the test. In applying trapezoidal pressure loads in an analysis where the pressure loads are the result of a hydraulic analysis and only peak loads are determined, it is important to emphasize the need to address uncertainties regarding the pressure load duration and rise times.

- Page 11-8, Section 11.2.3; the comparison of analyzed trapezoidal loads to actual measured loads is made with good knowledge of the structural frequencies. It should be emphasized that uncertainties in the structural frequencies need to be addressed in the structural model, because the response of the piping structure is sensitive to both the duration and rise time of the pressure pulse loads.

- Page 11-8, Section 11.2.3; a discussion should be provided of the structural damping values assumed in the ADLPIPE and ANSYS analyses. If none were assumed, then it should be emphasized that the recommended method is to similarly assume no damping in order to be consistent with the verification of the proposed analysis method.

- Page E-9; the second bullet refers to FAI data to justify the 5 L/Ds. Where, specifically in the report, is this information and conclusion presented?

- Page E-9; the last bullet discusses steam condensation on the metal pipe surface. This discussion is not consistent with what is presented on Page 8-24.

- Page E-13, second paragraph; the discussion indicates that the exact amount of air in the void was not measured in either testing program. It is important to keep this "unknown" in mind when trying to draw conclusions from the data.

- Page E-33, under Pipe Size; indicates that it is unnecessary to simulate heat transfer to or from the pipe wall during the closure process. This seems inconsistent with some of the discussion in other areas of the report (Pages 9-7, 9-17).

- Page E-41; a void temperature greater than 200 °F may not include some of the low pressure applications that could result during column separation.

- Page E-42; if plant conditions fall outside the limits, pant-specific submittal will be required to address this.

- Page E-53, Section 2.3.1.1; how does licensee confirm that limitation is satisfied?

- Page E-58, Table 2.3; the MOC peak pressure is non-conservative in a couple of cases, indicating that some adjustment may be needed.

- Page E-87, Nos. 3 and 4 would be beyond scope of NRC endorsement.

- Page G-19, 8th line; the statement is not consistent with discussion in Appendix E and in other locations (e.g., Page 8-24). Also, relative to this discussion, the air concentration is an unknown quantity in the testing that was performed which limits the discussion to one that is qualitative in nature.

- Page G-22, Section 2.2, 2nd sentence; where's the data and graphical display that supports this conclusion?

- Page G-23, Table 2-3, Number 3; how was the initial air concentration determined if air measurements were not taken?

- Page G-24, 1st paragraph; "experimental scatter" may also be due to varying amounts of air (if this was an unknown). The reason for the "experimental scatter" should be looked at more closely and taken into consideration when evaluating the test results.

- Page G-24, Section 2.4; the discussion about heating of the surrounding pipe wall seems to be inconsistent with information discussed elsewhere (Page 8-24, and Appendix E).

- Page G-25, Section 3.1; the significant scatter (which could be due to variations in air content) is an important part of the data that must be considered when establishing a conservative analytical methodology. The TBR doesn't appear to appreciate this particular aspect of the data that has been collected.

- Page G-26, last sentence; not consistent with discussion in Appendix E, and probably incorrect as well.

- Page G-32, why is "Estimated Rise Time" called out?

- Page G-27, neglects heating of pipe wall from containment atmosphere -- could be substantial.

- Page G-44, discussion in 2nd paragraph about Figures 3-3a and 3-3b; the correlation of waterhammer strength with Jakob number is not really all that obvious for much of the data.

- Page G-51, 5th line from the bottom; discussion about "substantial increased noncondensible gas, due to the effect of heating the pipe wall..." is not consistent with discussion in Appendix E, and not necessarily true; speculative.

- Page G-57; discussion about the influence of thermal layer in comparison to noncondensible gases is not necessarily true, and has not been demonstrated. Also, it is speculative as to how much air will be released by heating of the pipe wall. In some plant-specific applications, much of the pipe wall heating will be from containment heating of the outside surface of the pipe and not so much from the inside out.

- Page G-61, 3rd sentence; this seems to be inconsistent with discussion about impulse on Page 8-16.

- Page H-10, Figure 3.1; the road map should reflect the complete methodology, not just CCWH. Criteria and exceptions need to be clearly indicated.

<u>Editorial Comments</u>:

- Symbol No. 43 has a typo in the description.

- Reference to NUREG-5220 should be NUREG/CR-5220 throughout.

- Page 1-1, 1st paragraph, last sentence -- use of "most" would be more accurate.

- Page 1-3, last sentence under Thermal Layer should be "waterhammers."
- Section 1.5, what are the limitations? Should they be listed?
- Page 1-5, use of "CCWH waterhammer" is redundant
- Page 3-2, power is restored "to the SW pumps"
- Page 4-2, Section 4.1.1, last paragraph, the last sentence should state "The Froude number is calculated as follows:" in order to avoid any confusion about 1.0 being the minimum acceptable value for this application.
- Page 5-1, last sentence should provide some explanation as to why this is so.
- Page 6-5, Table 6-2 is being crowded by the documentation below.
- Page 6-8, Section 6.4, last sentence of the first paragraph -- NRC expectation is that a best estimate approach is used to ultimately arrive at a "credible methodology" that is conservative. Some clarification is needed here.
- Tables 6-3, 6-4, 6-5, and 6-6; info should be better reflected in the Appendix H Road Map (e.g., vertical risers, closed end branches)
- Table 6-7, no reference to Appendix H in first bullet, typo in 2nd bullet (should end with period), and alternate wording is suggested for the 2nd bullet -- "which indicates that CCWH is more limiting than CIWH in most low-pressure service water system applications."
- Table 6-7, page 6-13, omit the 2nd sentence of the last bullet.
- Section 7 seems to be very short on data upon which decisions can be made. What can we make of this?
- Page 8-1, should state "NUREG/CR-5220."
- Page 8-2, "E=28E psi" typo?
- Page 8-5, move eq. 8.9 down below the paragraph.
- Page 8-10, a blanket statement that CIWH magnitude is independent of pipe size seems a bit too strong given the limited amount of data that's presented and the variation in data scatter between the two pipe sizes.
- Page 8-10, why was α of 0.5 selected for the comparison?
- Page 8-11, no Analytical Model in Fig. 8-5.B, remove from legend.
- Page 8-24, 3rd paragraph; should say "area."

- Page 8-26, 6th line from the bottom; is "The longer duration, lower duration events" what was intended here? I was expecting it to say "The longer duration, lower pressure events."

- Page 8-27, 2nd bullet; should it be "normal aerated water tests?"

- Page 8-27, last three bullets; need to reflect these in the road map; need to be clear on how much non-condensables is necessary to qualify; and last bullet should refer to "the worst-case CCWH."

- Page 9-2, 1st sentence; should state "The magnitude of the..."

- Page 9-16; how to determine air concentration of water for a given system configuration (i.e., open loop, closed loop)?

- Page 9-20, eq. 9.10; shouldn't there be parentheses after the 2?

- Page 9-37, 1st paragraph; this conclusion is not at all obvious and probably incorrect. The upstream boundary layer probably is formed for the most part after flow is reinitiated through the fan cooler. Also, "fil" should be "fill."

- Page 9-38, Figure 9-19; spelling of Jakob.

- Pages 9-43 & 9-44 (Figures 9-23 and 9-24); the title is incomplete, the units are missing from the oxygen content, and the key is incomplete.

- Page 9-36, No. 2 is rather speculative and dependent on system configuration (e.g., what if there is a check valve to prevent flow?).

- Page 9-50, 3rd paragraph and last paragraph, typos.

- Page 9-50, Info needs to be reflected in the road map. Also, is restriction on T(void) low enough for typical plant?

- Page 9-51, Reductions in second order velocity (nos. 3 and 4) and attenuation w/out amplification considerations?

- Pages 9-52 through 9-57; how to determine mg air for void, also distinction between open loop and closed loop systems.

- Page 10-8; 3rd bullet from bottom, should be "less than the distance."

- Page 10-15; Figures 10-10 and 10-11 appear to be labeled wrong.

- Page 10-16, Section 10.2.3, 1st paragraph; if attenuated 10% at each change in direction, why does it take 8 changes in direction to attenuate 50% (i.e., why not 5 changes in direction)?

- Page 11-6; page not numbered, and should include the results of ANSYS and ADLPIPE correlation.

- Page 11-8; page not numbered, sentence in the 2nd paragraph would be clearer if a hyphen was used "A set of 44 test-measured pressure traces from the tests was used," and where it refers to Figure 11-6 (end of 2nd paragraph) shouldn't this be Figure 11-7?

- Page 12-1; need to include guidance (in appropriate section of TBR) for evaluating LOOP only waterhammer, and include the 15% assumed amplification when crediting attenuation.

- Page 13-1; Reference 4 should be NUREG/CR.

- Page A-2; should give the table a name so it can be referred to.

- Page C-2; 1st paragraph talks about an analytical model presented above. There is no "above."

- Page D-2, 2nd paragraph; should state that "Voiding occurred in a horizontal pipe..."

- Page D-3; the sentence "The pressure measurements were made with..." is redundant to the previous sentence.

- Page E-9 and Figure 1.1-B; says piping surface area was ignored; not consistent with discussion in Appendix G.
- Page E-34, bottom of page; the equation that is referred to is missing.

- Pages E-35 & E-41; is this reflected in road map/screening criteria?

- Page E-45, 1st sentence; should it state "steam condensation rate"?

- Page E-60, No. 1 is incomplete.

- Page E-86, 1st line; should say "plant with a means for taking credit..."

- Page E-96; what happened to general recommendation that FSI not be included?

- Appendix G; this appendix is very confusing and not easy to follow. Except for the qualitative value (which is intuitive for the most part), it is not clear how the test data can be used in a more rigorous, quantitative fashion. Also, it is not clear why it was important to collect the test data in some arbitrary, random order (mentioned on the bottom of Page G-31). Some additional thought and effort is needed to determine how the data can be used (i.e., what can be made of it, especially since the air content was not measured), and how to best present the information so it can be easily understood.

- Page G-6 & G-7; the sentence that starts at the bottom of Page G-6 does not make sense.

- Page G-24, last line; should be NUREG/CR.

- Page G-25, 8th line; should state "on the abscissa were manipulated..."
- Pages G-26, Section 3.2; since the air content was not measured, the test results are limited in their application.
- Page G-35, in looking at the numbers, it appears that some of the data is not listed (Test Nos. 207 through 220, and 228 through 299). Also, there is no explanation about what the abbreviations are (WH, U, S).
- Page G-44, 1st sentence; not well written.
- Page G-46, Figure 3-3b; abscissa is not labeled.
- Appendix G, Figures 3-4b & 3-5b; check spelling of "Jakob."
- Page G-51, last sentence of 1st paragraph; should state "information shown in..."
- Page G-56, bottom half of page; the discussion is confusing and whatever the point is, it needs to be better explained.
- Page G-58; should move the figure to Page G-56.
- Page G-62, 2nd line of 2nd paragraph; should state "derivative of the acceleration or..." Also, should 3rd sentence say 100 msec instead of 10 msec?
- Page G-63, Figure 3-11; the figure appears to be out of place relative to the text.
- Page G-64 and beyond; many figures are illegible (especially axis information), some enhancement is needed.
- Page G-66, Figure 3-14; at top, should say "only the Condensate."
- Page G-69, what are units of ordinate axis?
- Page G-71, Ref 4; should be NUREG/CR.
- Page H-8, Section 3.7; should either say equation 9.9 or Figure 9.10.
- Page H-7, Section 3; should be in body of report, not in an appendix.
- Page H-10, Figure 3.1; there is no action referred to coming out of the LOOP waterhammer box, and the diamond should refer to Table 9-6, not Table 9-5.
- Page H-22, should refer to equation 9.9.