April 3, 2002

Mr. Vaughn Wagoner, Chairman
EPRI Waterhammer Project Utility Advisory Group
Carolina Power and Light Company
411 S. Wilmington Street, CPB 6A1
Raleigh, NC 27601

SUBJECT: NRC ACCEPTANCE OF EPRI REPORT TR-113594, “RESOLUTION OF GENERIC LETTER 96-06 WATERHAMMER ISSUES,” VOLUMES 1 AND 2

Dear Mr. Wagoner:

The NRC staff has completed its review of the subject Electric Power Research Institute (EPRI) report that was submitted by letter dated December 15, 2000, as supplemented by letters dated July 10, August 9, September 17, 2001, and February 1, 2002. The staff finds this report acceptable for performing evaluations addressing GL 96-06 waterhammer concerns to the extent specified and within the limitations delineated in the EPRI report and in the associated NRC safety evaluation (enclosed). The safety evaluation presents the bases for our acceptance of the EPRI report.

In accordance with procedures established in NUREG-0390, the NRC requests that EPRI publish accepted versions of the submittal (as modified by the supplementary information that was provided), proprietary (-P) and non-proprietary (-NP), within 3 months of receipt of this letter. The accepted versions shall incorporate (1) this letter and the enclosed safety evaluation between the title page and the abstract and (2) an “-A” (designating “accepted”) following the report identification symbol. The supplementary information that was submitted by letters dated July 10, (without the enclosures), August 9, September 17, 2001, and February 1, 2002, shall be appended to the approved version of the EPRI report.

Pursuant to 10 CFR 2.790, the staff has determined that the enclosed safety evaluation does not contain proprietary information. However, the staff will delay placing the safety evaluation in the NRC Public Document Room for 15 calendar days from the date of this letter to allow you the opportunity to comment on the proprietary aspects only. If, after that time, you do not request that all or portions of the safety evaluation be withheld from public disclosure in accordance with 10 CFR 2.790, the safety evaluation will be placed in the NRC Public Document Room.

If the NRC's criteria or regulations change so that its conclusion that the submittal is acceptable are invalidated, EPRI or the applicant making use of the EPRI report, or both, will be expected to revise and resubmit the respective documentation, or to submit justification for the continued applicability of the EPRI report without revision of the respective documentation.

Should you have any questions or want further clarification, please contact James Tatum at 301-415-2805.

Sincerely,

/RA/

John N. Hannon, Chief
Plant Systems Branch
Division of Systems Safety and Analysis
Office of Nuclear Reactor Regulation

Enclosure:
Safety Evaluation

rcc: Dr. Avtar Singh
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304-1395

Dr. Thomas C. Esselman, President
Altran Corporation
451 D Street
Boston, MA 02210

Mr. Kurt Cozens
Nuclear Energy Institute
17761 I Street NW, Suite 400
Washington, DC 20006-3708

Should you have any questions or want further clarification, please contact James Tatum at 301-415-2805.

Sincerely,

/RA/

John N. Hannon, Chief
Plant Systems Branch
Division of Systems Safety and Analysis
Office of Nuclear Reactor Regulation

Enclosure:
Safety Evaluation

rcc: Dr. Avtar Singh
Electric Power Research Institute
3412 Hillview Avenue
Palo Alto, CA 94304-1395

Dr. Thomas C. Esselman, President
Altran Corporation
451 D Street
Boston, MA 02210

Mr. Kurt Cozens
Nuclear Energy Institute
17761 I Street NW, Suite 400
Washington, DC 20006-3708

<u>DISTRIBUTION</u>: ADAMS SPLB r/f GHammer WJensen BWetzel ACRS
JHannon BThomas JTatum SDinsmore GHolahan OGC

* See previous concurrence

DOCUMENT NAME: G:\SPLB\SECTION A - THOMAS\TATUM\GL 96-06 SE.WPD

OFFICE	SPLB:DSSA:NRR	SRXB:DSSA	SPSB:DSSA	EMEB:DE	ASC:SPLB	OGC
NAME	JTatum:bw	WJensen	SDinsmore	GHammer	BThomas	
DATE	02/27/02*	02/27/02*	02/28/02*	02/28/02*	03/04/02*	03/19/02

OFFICE	BC:SPLB					
NAME	JHannon					
DATE	04/03/02					

Enclosure

EVALUATION OF ELECTRIC POWER RESEARCH INSTITUTE

REPORT TR-113594, "RESOLUTION OF GENERIC LETTER 96-06

WATERHAMMER ISSUES," VOLUMES 1 AND 2

DATED DECEMBER 2000

1 INTRODUCTION

Generic Letter (GL) 96-06 required (among other things) that licensees evaluate containment air cooling systems to confirm that they are not vulnerable to waterhammer transients that might occur during a loss-of-coolant accident (LOCA) or a main steamline break (MSLB) event, concurrent with a loss of offsite power (LOOP). A LOOP during the postulated LOCA or MSLB would result in a temporary loss of pumping power to systems supplying cooling water to the air coolers. The heat that is released into containment during the event might cause the stagnant water in the cooling coils of the containment air coolers to boil and form steam. A waterhammer transient that exceeds the design limits of the cooling water system piping could occur when the containment air coolers are draining during the LOOP condition as hot steam comes in contact with cold water, or upon restoration of pumping power following the LOOP condition as cooling water is forced to flow into a steam pocket. Failure of cooling water systems that penetrate containment and remove heat from the containment air coolers could provide a pathway for radioactive gases to escape through the containment protective boundary to the environment. Failure of these cooling water systems could also result in a loss of heat sink for other safety-related components that are cooled by the failed cooling water system, as well as an unanalyzed increase in the amount of water that is discharged into the containment during the accident. If systems are found to be vulnerable to these conditions, licensees are expected to assess the operability of affected systems and take corrective action as appropriate.

Containment cooling systems are categorized as either open loop or closed loop systems. Open loop systems are typically found at fresh water sites. Closed loop systems are typically found at salt water sites. During a LOOP, the containment air coolers of open loop systems will typically drain, producing low-pressure voiding within the cooling coils without any additional heat being provided via a LOCA or MSLB. Closed loop systems typically do not drain during a LOOP and require additional heat from the containment atmosphere to produce voiding.

GL 96-06 did not prescribe how potential waterhammer events should be analyzed, and licensees were expected to use assumptions and methods that are appropriate and suitable for the plant-specific conditions involved. However, the GL suggested that licensees may find the information contained in NUREG/CR-5220, "Diagnosis of Condensation-Induced Waterhammer" (Ref. 1), to be informative and useful in evaluating potential waterhammer conditions. In order to assure that evaluations addressing the GL 96-06 waterhammer concerns were suitable and appropriate, responses to GL 96-06 were reviewed by the NRC and detailed requests for additional information (RAIs) were issued asking that licensees describe and justify the analytical methodology and assumptions that were used.

Waterhammer is a complex phenomenon, involving many variables that make it difficult to model and analyze. Bounding analytical methods use conservative assumptions and tend to yield conservative results. NUREG/CR-5220 estimates that these analyses can be conservative by a factor of 2 to 10, depending on the specific conditions involved. In order to address the RAIs that were issued, and to develop and justify a method that would be suitable for evaluating the waterhammer concerns discussed in GL 96-06, a group of utilities initiated a waterhammer testing and analysis program. By working as a group, licensees were able to minimize costs and avoid multiplication of effort in addressing the plant-specific RAIs that were issued. The scope of the program was designed and validated using a Phenomena Identification and Ranking Table (PIRT) assessment. The initiative was sponsored by 14 utilities, and the technical work was coordinated by the Electric Power Research Institute (EPRI) and performed by Altran Corporation. Independent program oversight and review was provided by a panel of industry experts, consisting of Dr. Peter Griffith of the Massachusetts Institute of Technology, Dr. Benjamin Wylie of the University of Michigan, and Dr. Fred Moody, an independent consultant. This evaluation will simply refer to EPRI as the organization responsible for completing this initiative. The NRC was also an active participant, monitoring and critiquing the work that was being performed by EPRI as the initiative progressed.

EPRI has completed its work on this initiative, and the results have been documented in EPRI Report TR-113594, “Resolution of Generic Letter 96-06 Waterhammer Issues,” dated December 2000. The report consists of two volumes; Volume 1 is the User’s Manual (UM), and Volume 2 is the Technical Basis Report (TBR). The UM establishes a methodology for participating utilities to use for evaluating the GL 96-06 waterhammer concerns, and the TBR provides the technical justification for the proposed methodology. The EPRI report was submitted for NRC review and approval by letter dated December 15, 2000. If approved, the EPRI report could be used by licensees in responding to the GL 96-06 plant-specific RAIs that were issued by the staff.

2 DISCUSSION

The testing and analysis program that was completed by EPRI investigated the two waterhammer phenomena that might occur in the low-pressure cooling water systems that are connected to the containment air coolers. These are column closure waterhammer, produced by the sudden start of a pump that causes water to flow into a partially voided section of piping; and condensation induced waterhammer, produced by unstable condensation in partially filled horizontal pipes.

2.1 Discussion of Column Closure Waterhammer (CCWH)

A CCWH, which results when two water columns join together within a pipe, can be evaluated by using the Joukowski equation for calculating the maximum pressure at column closure:

$$\Delta P = K \rho C (\Delta V)$$

In this equation when consistent units are used:

ΔP= the resulting pressure rise.

K= a dimensionless coefficient which is 0.5 for a column closure of liquid.

C= the velocity of sound in the medium.

ΔV= the velocity in the medium just prior to impact.

ρ= the density of the flowing liquid.

When the sonic velocity of cold water is used in the Joukowski equation, the resulting calculated pressure pulse is maximized. This methodology tends to provide results that are very conservative, with actual waterhammer loads being reduced by a factor of 2 to 10 from those predicted by the Joukowski equation due to reductions caused by air and steam cushioning, flexibility of the piping system, geometry of the water slug, frictional effects, and reductions that can occur in the length of the water slug (Ref. 1).

2.1.1 Air Release Due to System Depressurization

Small amounts of non-condensable gas bubbles suspended in the converging water columns will act to slow the speed of sound and have a direct effect on the resulting pressure rise. The solubility of air in water is proportional to the absolute pressure (Henry's law). When the pressure is reduced for water saturated with dissolved air, the excess air begins to leave the solution. Experiments by Zielke (Ref. 3) have shown that following a depressurization approximately 10 percent of the excess dissolved air contained in liquid water rapidly leaves solution, forming minute bubbles which dramatically reduce the speed of sound. The remainder of the excess dissolved air was found to leave solution more slowly depending on the presence of nucleation sites. Pressure reduction in containment cooling systems that result from the loss of pumping power in open cooling systems is expected to produce reductions in the speed of sound similar to that observed in the experiments. Reduction in the speed of sound will proportionally reduce the peak waterhammer pressure on impact.

2.1.2 Air Release Due to Boiling

If the containment atmosphere becomes heated as the result of MSLB or LOCA, the water contained in containment cooler units may boil, even in closed systems which do not experience a large pressure reduction on the loss of pumping power. Heating of water reduces the solubility of air. Boiling provides nucleation sites for the excess air, which cause the excess air to be stripped away with the steam.

To determine the air content in the void that might form within the low-pressure cooling water piping following a LOCA or MSLB at operating reactors, EPRI performed a series of tests. The test apparatus included a 5/8-inch ID copper tube that was 10 feet long to simulate one tube of a containment air cooler unit. The 5/8-inch tube was connected to a 2-inch vertical pipe to simulate a header. The 5/8-inch tube was sheaved in a 2-inch diameter steam jacket to simulate the containment environment during a LOCA or MSLB event. The tube was filled with water at approximately 70 °F. The tests were initiated by reducing the pressure within the copper tube to ½ atmospheric pressure to simulate loss of pumping power during a LOOP event. Heating by the containment atmosphere was simulated by supplying heated steam within the 2-inch diameter steam jacket. After 30 seconds, the test was terminated and water samples were collected. The oxygen content of the water was measured. This was compared to the original oxygen content. Since oxygen content should be proportional to air content, the difference should give a measure of the air evolved. In a first set of tests, only the copper test section was filled with water. EPRI determined that an excess of 50 percent of the original air in the test section came out of solution as the water was heated, boiled, and ejected from the test section.

In a second series of tests, the header pipe was filled with water. In these tests the water and steam from the test section were permitted to flow into the header. At the end of the test, EPRI measured the oxygen content in the header and in the water that flowed out of the header into an overflow tube. From these measurements, EPRI concluded that more than 24 percent of the air in a header to which fan cooler tubes are connected would be released if boiling occurred in a containment cooling unit during a LOCA or MSLB. In both series of tests, two temperatures of steam were used to vary the boiling rate. The air release fraction was found to be insensitive to the boiling rates that were used.

EPRI presented arguments that the test configuration was conservative in comparison to an actual containment air cooler unit in an operating plant. This is because in the test some of the water drained out of the test section without boiling, thus retaining much of its dissolved air. In an actual containment air cooler, the tube length is 3 to 4 times longer than the tube used in the test, which would permit more time for water in the tubes to boil. The water exiting the air cooler would be the hottest water in the air cooler and more likely to boil before draining into the header, compared to the test where the water was all the same temperature. Since a larger fraction of water in an actual air cooler would boil compared to the water in the test apparatus, a larger fraction than 50 percent of the air would be expected to be released.

2.1.3 Steam and Air Cushioning

Upon restoration of pumping power, the steam and air bubble located in the low-pressure cooling water piping for the containment air coolers will undergo compression and the steam will begin to condense. As the steam bubble condenses and begins to collapse, the air and steam contained in the void between two converging water columns will tend to cushion the resulting impact, thereby reducing the magnitude of the waterhammer pressure pulse.

CCWH tests were performed to measure the effects of air and steam cushioning. The effect of air cushioning was confirmed by performing experimental CCWH tests using water containing normal amounts of air (steam + air cushioning), and using de-aerated water (steam cushioning only). In both sets of tests, a steam bubble was formed in the test section by external heating and water was then accelerated into the steam bubble. Using de-aerated water resulted in waterhammer pressures that compared closely to the pressures predicted by the Joukowski equation, indicating that steam cushioning without the benefit of air was rather inconsequential. Using water with normal air content, the effect of steam and air cushioning together caused the resulting waterhammer pressures to be much less than predicted by the Joukowski equation.

The steam and air cushioning tests utilized a pipe section that was 2 inches in diameter and filled with water of normal air content. The test section was surrounded by an 8-inch diameter pipe section. Steam was admitted into the 8-inch diameter pipe section to cause the water in the 2-inch pipe to boil and form steam. A slug of water was then accelerated into the steam bubble, causing a waterhammer to occur. Various steam bubble lengths, dissolved air concentrations, and water column accelerations were investigated.

2.1.4 Correlation of CCWH Test Data

The data were correlated by two methods. The first method utilized the method of characteristics developed by B. Wylie (Ref. 4). The second method is a simplified calculational approach that was developed by Altran Corporation under contract to EPRI, which is referred to as the rigid body model.

2.1.4.1 Method of Characteristics (MOC)

The MOC allows the partial differential equations for momentum and continuity to be converted into ordinary differential equations. Pipelines are divided into equal length segments. The segment length is the distance that an acoustic wave will travel in one time interval. The MOC methodology is widely used for solving one dimensional, single phase, waterhammer problems. Wylie extended use of the MOC methodology to piping systems that have a discrete free-gas cavity, and this is the solution method used in the EPRI report. The method was benchmarked against test data from the CCWH tests. The tests had a known void size when the process of column closure was begun. The void was a mixture of steam and air which had left solution as a result of heating and boiling the water in the test section. As the columns converged, some of the steam was recondensed. The condensation rate was retarded by the presence of non-condensable air, resulting in a cushioning effect during column closure.

Although the initial dissolved air mass was measured for the CCWH tests, the final air mass was not. EPRI had to estimate the amount of air released based on the boiling time in the 2-inch test section. These estimates were refined by examining the waterhammer pressure pulse shapes. EPRI varied the heat transfer coefficient for condensing steam and the assumed air content until both the experimentally measured waterhammer pulse shapes and pulse magnitudes were reproduced. A constant heat transfer coefficient was derived that best correlated all of the CCWH test data. A heat transfer coefficient slightly larger in magnitude was proposed for plant evaluation purposes since a larger coefficient will produce a conservatively larger waterhammer pressure pulse.

2.1.4.2 Rigid Body Model (RBM)

The RBM methodology for waterhammer pressure pulse evaluation does not require a detailed noding of the piping system as does the MOC. Instead, a conservatively high waterhammer peak pressure pulse value is calculated using the Joukowski equation. A bounding pulse shape is calculated based on the time required for a pressure wave to travel to a reflecting surface and back. The calculated pulse magnitude and shape are then modified based on comparisons with the experimental data and nomographs that include the effects of steam and air cushioning. The nomographs were calculated by solving the differential equations for the acceleration of a water slug that is resisted by the compression of a gas bubble. The conservatively high heat transfer coefficient proposed for performing plant analyses from the MOC evaluations was used to account for the condensing of steam within the steam bubble. Information that is required for using of the nomographs are mass of air in the void, the frictional flow loss coefficient between the pump and the void, and the water slug length. The nomographs are provided in the UM. Table 5-2 in the UM provides analysis limits for use of the RBM. Applications lying outside these limits require plant specific analysis.

The CCWH test data indicated that the resulting waterhammer pulses were not rectangular in shape, but incrementally increasing in magnitude as the gas bubble was compressed. From this data, EPRI produced a correlation predicting the rate of increase for a pressure pulse using the RBM. Pressure pulse rise times were derived from a linearized treatment of the experimental pressure pulses. These rise times, in the form of a ramp, are applied to the peak pulses calculated using the RBM. The resulting pulse is trapezoidal or triangular in shape, depending on the geometry of the system. As a pressure pulse is transmitted through the piping system, the pulse will be reflected or attenuated by changes in piping geometry. Reflected pulses may affect the overall pressure in a positive or negative manner. EPRI provided a table and a nomograph to aid in determining the effect of reflected pulses.

The RBM was benchmarked against the MOC and found to be conservative. The difference between the two results is attributed to the treatment of reflected pressure pulses. The RBM was also compared to the experimental data from the CCWH experiments and was found to be conservative. The differences between measured and predicted values of pressure were attributed to the uncertainty in the amount of air present.

2.1.5 Scaling Considerations

All of the CCWH test data is from a 2-inch diameter test section. The diameter of the piping that supplies water to the containment air coolers in operating reactor plants is substantially larger than 2 inches. EPRI performed a scaling analysis showing that the condensing heat transfer coefficient was independent of the pipe flow area.

2.1.6 LOOP-Only Event

A CCWH in an open loop cooling water system that occurs during a LOOP-only event is expected to be more severe than one that occurs concurrently with a LOCA or MSLB. This is because the cooling water is not heated during the LOOP-only event. This results in much less steam and air being released into the void, which causes a reduction in air and steam cushioning, which causes the CCWH pressure to be higher.

Operating plants have conducted tests for LOOP, and some have experienced inadvertent LOOP events. These tests and events have resulted in CCWH occurrences in plants that have open loop containment air cooler cooling water systems. While minor piping support damage was noted in some instances, there were no piping failures.

One of these tests was conducted in November of 1991. The test was representative of a LOOP event with subsequent restart of the cooling water pumps. A peak pressure pulse of 205 psig was measured. The measured pulse is approximately ½ of that which would be obtained using the Joukowski equation without consideration of the non-condensable gas that would have come out of solution, and caused the resulting pressure peak to be reduced. The experience in operating plants tends to complement the analytical and experimental conclusions that have been reached, indicating that the release of non-condensable gas during system depressurization reduces the severity of CCWH.

2.1.7 Limitations and Restrictions Associated with CCWH Analyses

Use of either the MOC or RBM methodology for performing CCWH analyses of containment air cooler cooling water systems requires that licensees first perform an evaluation that is sufficient to obtain the necessary analytical inputs discussed in Section 2.2 of the UM (system design characteristics, worst-case conditions, steam bubble geometry, refill velocity, etc.). The following conditions must also be met in order for the analyses to remain within the scope of the test data:

- The calculated air mass must be greater than (60 mg)$(ID/2)^2$, where ID is the pipe inside diameter in inches at the location of the potential waterhammer.
- The calculated void temperature must be greater than 200 ^oF for the heat transfer coefficient derived by EPRI for steam and air cushioning to be valid.
- Additional limitations on use of the RBM are given in Table 5-2 of the UM. These limitations relate to water column size, void length, void and interface temperature, and initial closure velocity.

2.2 <u>Discussion of Condensation Induced Waterhammer (CIWH)</u>

This type of waterhammer might occur as containment cooling systems are drained during a LOOP condition, or during initiation of cooling water flow. CIWH typically occurs in horizontal pipe segments partially filled with cold water overlaid by steam that is supplied by a steam source. Condensation of steam on the surface of the water can cause tongues of water to be whipped up in a wave like manner. If steam condensation is vigorous enough, a water tongue can extend to the top of the pipe forming a plug. The steam bubble trapped between two plugs of cold water would experience a drop in pressure from continued condensation. The pressure difference then causes the two plugs to be driven together. CIWH occurs when the trapped steam bubble condenses and the plugs of water converge. Potential damage from this type of waterhammer is a function of the steam pressure that acts to drive the water plugs together. Piping damage from this type of waterhammer typically occurs in feedwater and other high pressure piping systems where steam pockets might form. In NUREG/CR 6519, “Screening Reactor Steam/Water Piping Systems for Water Hammer,” dated September 1997, Griffith reports that in most cases system pressure must be greater than 100 psia before any significant damage will occur due to CIWH (Ref. 2). Cooling water systems that are used to remove heat from containment air coolers usually operate well below this pressure threshold.

2.2.1 Test Results

EPRI conducted a series of tests in order to evaluate the potential severity of CIWH on low-pressure cooling water systems, such as those that provide cooling for the containment air coolers. The test section was 4 inches in diameter and approximately 22 feet in length, providing a long horizontal pipe section for CIWH to take place. Steam pressures were limited to 15 psig. Tests were initiated by simultaneously opening valves to permit steam to enter one end of the horizontal pipe and water to exit the other end. Horizontal stratified flow conditions were produced, and from this CIWH occurred. The resulting pressure pulses were recorded by pressure transducers located throughout the system. The waterhammer pressures were found to be relatively low (less than 200 psig). Those pulses having the highest peak pressures were found to have the shortest duration and consequently, the impulse loads were approximately constant for all of the CIWH pressure pulses that were generated. As a result of the testing and analyses that were completed, EPRI concluded that a CIWH in most low-pressure cooling water systems for the containment air coolers would not be severe enough to cause any significant damage. EPRI also concluded that the CCWH would typically be more severe in magnitude and duration than the CIWH, and generally would form the more limiting case.

2.2.2 Scaling Considerations

Cooling water systems supplying the containment air cooler units for actual plants are generally larger than the 4-inch diameter that were used in the EPRI tests. Based on the results of a scaling analysis, EPRI concluded that lower CIWH pressures would be expected for larger pipe sizes.

2.2.3 Limitations and Restrictions Associated with CIWH Analyses

The CCWH tests performed by EPRI produced much higher pressures and loadings than those of the CIWH tests. EPRI concluded that for plant conditions that are within the bounds of the test data, CCWH will be bounding and plant-specific CIWH analyses need not be performed. As specified Section 4.2.1 of the UM, this conclusion is applicable only in systems that meet the following conditions:

- The system pressure at the time of the postulated CIWH must be less than 20 psig.
- The system water has not been degassed.
- The piping has been shown by test, analysis, or operating experience to be able to withstand a CCWH following LOOP, LOOP with LOCA, or LOOP with MSLB, without significant degradation.

2.3 Advisory Committee for Reactor Safeguards (ACRS) Review and Comment

EPRI met with the ACRS Thermal-Hydraulic Phenomena Subcommittee to present and discuss EPRI Report TR-113594, Volumes 1 and 2, during the meetings that were held on November 17, 1999, January 16-17, 2001, and August 22-23, 2001. The ACRS discussed this matter with EPRI and the NRC staff during its 485th meeting on September 5-7, 2001, and completed its review of this matter during the 486th meeting of the ACRS on October 4-6, 2001. The results of the ACRS review was provided to Dr. William D. Travers in a letter dated October 23, 2001. The ACRS recommended that the EPRI methodology should not be approved until there is a better demonstration that it provides results that are bounding for realistic plant configurations and scenarios. The ACRS review focused on the prototypicality of the EPRI experiments, the adequacy of the scaling model, and the appropriateness of the condensation and air-release models. ACRS member Dr. Graham Wallis provided a detailed discussion of these areas in an attachment to the October 23, 2001, letter. The ACRS concluded that EPRI's conceptual model was oversimplified, and that it was not clear how the model could be applied to plant-specific scenarios and configurations. However, recognizing that the waterhammer concerns discussed in GL 96-06 may not be risk significant, the ACRS indicated that it would be supportive of risk-informed approaches for addressing the GL 96-06 waterhammer issue.

2.4 EPRI Response to the ACRS Comments and Discussion of Risk Considerations

By letter dated December 3, 2001, the NRC staff requested that EPRI respond to the comments contained in the October 23, 2001, ACRS letter, including an assessment of the risk significance of the GL 96-06 waterhammer issue. EPRI provided its response to the staff's request in a letter dated February 1, 2002.

2.4.1 Response to ACRS Comments

With respect to the ACRS comments that were raised, EPRI pointed out that many of the ACRS comments [discussed in the attachment to the ACRS letter] were focused on the complexities associated with plant-specific evaluation of heat transfer in the containment air coolers and the hydraulics of the voiding and draining process. EPRI clarified that details such as these were not included within the scope of the EPRI initiative. As discussed in the EPRI report (e.g., Figure 2-1 and Section 2.2 of the UM), these complexities must be evaluated on a plant-specific basis. Once these analyses have been completed, the EPRI report provides a methodology for determining waterhammer loads at the time of final refill and column closure following pump restart. The EPRI report also provides methods for calculating loads in pipe supports and stresses in piping.

2.4.2 Risk Considerations

Recognizing that the ACRS does not fully agree with the methodology being proposed for evaluating the GL 96-06 waterhammer issue, EPRI felt that consideration of the risk associated with the events and the results that would be achieved if the EPRI methodology is used may be an important factor. In responding to the staff's December 3, 2001 letter, EPRI proposed that if the EPRI methodology does not significantly increase the risk of unacceptable plant performance nor lead to an unacceptable risk to the plant, use of the EPRI methodology can be done safely without compromising the integrity or safety of the systems being evaluated. In order to assess the risk to the plant of using the proposed EPRI methodology, a review of the progression of events that could lead to an unacceptable condition was performed. The "unacceptable condition" was defined as a breach of the containment air cooler cooling water system boundary (i.e., pipe failure). EPRI outlined the following progression of events:

- Occurrence of a LOCA or MSLB

  From NUREG/CR-5750, the mean frequency of occurrence of a large-break LOCA for a PWR is listed as 5E(-6) per year, a medium LOCA is 4E(-5) per year, and a MSLB inside containment is 1E(-3) per year.

- Occurrence of a LOOP following a LOCA or MSLB

  NUREG/CR-6538 and subsequent NRC work indicates that the dependent probability of a LOOP event following a LOCA at a PWR is approximately 1.4E(-2) per demand.

- Occurrence of Simultaneous LOCA/LOOP Event

  The required design-basis consideration is for the simultaneous occurrences of a LOCA or MSLB and a LOOP. Combining the probabilities for occurrence of a LOCA or MSLB with the probability of a dependent LOOP yields a probability of a simultaneous occurrence of a LOCA or MSLB with LOOP of 1.4E(-5), or about 1E(-5) per year. With best estimate probabilities, this event likelihood of occurrence could be expected to be even lower.

- Void Formation

  Given a LOCA/LOOP event, a void will form in open loop cooling water systems with certainty. In a closed loop plant, void formation will depend on the specific plant characteristics and a void may or may not form.

- Pump Restart

  The cooling water pumps will restart with certainty and the velocity in the pipe, immediately prior to closing the void, will be defined by the pressure in the void, the piping geometry, and the pump characteristics. This velocity will not be higher than the rate at which the pumps, once restarted, can pump water. This is a plant specific analysis that can be conservatively performed.

- Column Closure

The water columns will refill the void and the velocity at closure cannot be larger than the largest calculated differential velocity for the upstream and downstream water columns.

- Maximum Waterhammer Pressure

  An upper bound on the waterhammer pressure can be calculated by the Joukowski relationship with the uncushioned closure velocity that corresponds to the pipe in which the closure will occur. Based on the tests that were performed by EPRI and others, it is unlikely that the Joukowski pressure will be attained due to the variations that can exist in void distribution just prior to final void closure. For example, at a velocity range of interest, the EPRI test data indicates that the maximum pressure attained was around 400 psig and the minimum was around 200 psig, with the theoretical maximum pressure (Joukowski) calculated to be around 775 psig. The EPRI methodology uses the highest calculated (Joukowski) pressure as the starting point for calculating the cushioned velocity, even though it is very likely that the pressure will be lower as seen in the tests that were conducted.

- Cushioned Waterhammer

  The EPRI methodology predicts (for open loop cooling water systems) a cushioned velocity that is on the order of 30 percent to 40 percent less than the maximum velocity that could be attained due to the cushioning effects of gas and steam in the void just prior to column closure. The cushioned velocity is expected to be on the order of 10 percent to 15 percent less for closed loop cooling water systems because less boiling and air release is expected to occur (i.e., closed-loop systems do not drain and therefore the saturation pressure should be higher than for open-loop systems). Consequently, the peak pressure from an actual waterhammer could be on the order of 30 percent to 40 percent less than what would be predicted by the Joukowski equation (10 percent to 15 percent less for closed-loop systems). The risk impact of the potentially higher (Joukowski) stress was considered in two ways.

  a. EPRI pointed out that the occurrence of waterhammer following a LOOP event has occurred many times, either during LOOP tests or following actual LOOP events that have occurred. The total number of LOOP-only events was estimated to be on the order of at least several hundred based on a review of available plant data. These occurrences have all been in open loop cooling water systems (closed loop systems do not drain during a LOOP), and are more severe than a waterhammer following a LOCA/LOOP event would be because the final column closure is not cushioned during a LOOP-only event. No piping failures have occurred in any of these events, which would indicate that the probability of pipe failure is on the order of 1E(-2) or less.

  b. Alternatively, EPRI estimated the probability of piping failure if the ASME Code limits were exceeded by 40 percent. For this evaluation, EPRI assumed that the ASME Code stresses in the pipe are at the faulted condition limit when the cushioned waterhammer occurred (i.e., includes the waterhammer stresses). The probability of A106, Gr. B piping failure was calculated based on an assumed stress distribution in the pipe that was 40 percent greater than the ASME Code faulted allowable. Based on the actual margins that are available in the ASME Code, EPRI estimated that the probability of pipe failure is on the order of 1E(-4) or less.

For the purposes of this risk assessment, EPRI used the more conservative value of 1E(-2) for the probability of pipe failure if the cushioned waterhammer pressure was exceeded.

Combining the probabilities from the event progression, 1E(-5) per year for the initiating event frequency and 1E(-2) for pipe failure, yields a probability of an unacceptable event that is on the order of 1E(-7) per year. EPRI concluded that this is below the threshold for significant risk to the plant.

2.5 Additional Considerations

Following preliminary review of the final version of the EPRI report, dated December 2000, the NRC staff requested additional information regarding the proposed methodology. EPRI responded to the staff's request in letters dated August 9, and September 17, 2001. In addition to minor editorial comments, EPRI provided the following additional information and clarifications:

- A comparison was provided of pressure rise times between the test configuration that included air in the steam bubble versus test configurations that did not include air in the steam bubble. EPRI concluded that the pressure rise times are similar when the closure velocities are similar.

- Additional air release testing was performed using test apparatus that more closely modeled the situation that would exist in the containment air coolers. The EPRI report was revised to describe the testing that was done and to reflect the test results that were obtained from these more recent tests.

- Additional information was provided concerning the characterization and validation of the pressure pulse as a trapezoid. The trapezoidal model was developed to reflect fundamental theory, and to capture the pulse magnitude, rise time, and duration in order to simplify the transient pressure response into a set of defined pressure-time (P-T) points for use in a structural calculation. The effectiveness of the trapezoidal model was evaluated by comparing the response of an ANSYS model with loading from the idealized trapezoids and loading with actual P-T histories to the measured force response from the tests. Most of the plotted points fell above the "predicted = measured" line (a favorable comparison), and those points that fell below the line were located close to the line and represented a small percentage of the total data. The comparison indicated that on average, the ANSYS analysis using the actual P-T loading was conservative by about 15 percent, while the ANSYS analysis using the idealized trapezoidal loading was conservative by about 30 percent. EPRI also explained that the pulse duration will change as the pressure magnitude is cushioned to satisfy conservation of momentum, and that there was no recommendation to increase the pressure pulse duration beyond this value. More detailed information about the pressure pulse can be found in Sections 9.2, 9.3, and 13.5 of the TBR.

EPRI also evaluated what effect increasing the assumed structural damping value from 0.1 percent (TBR Figures 13-7 and 13-8) to 2 percent would have on the comparison of calculated versus measured pipe support loads. The resulting dynamic load factors decreased by 1.9 percent to 7.7 percent with the increased damping. Based on a translation of these results to those presented in Figures 13-7 and 13-8 of the TBR, EPRI concluded that: a) the increased damping would not significantly impact the comparison that was made between calculated and measured forces, and b) the conclusion that the trapezoidal representation of the pulse is an appropriate modeling method remains valid.

- Additional justification was provided for using a single pressure pulse instead of multiple pulses. In essence, EPRI concluded that any subsequent pressure pulse after the initial pressure rise is caused by reflected waves passing through the system, and the reflected waves will be significantly smaller in magnitude than the initial pulse.

- EPRI clarified that the simplified method of attenuation described in TBR Section 12.4 is not provided for generic plant analysis, but it is simply used to show that the attenuation (which is cumulative) will quickly surpass any potential amplification due to fluid-structure interaction (FSI). The analysis is used as a basis for the recommendation that the potential amplification from FSI can be conservatively ignored.

- EPRI clarified that credit for air release will not be taken unless the cooling water is exposed to temperatures that are above the boiling point corresponding to the pressure. As an additional conservative measure, the TBR and UM will eliminate credit for air release unless the temperature of the containment air cooler tubes is at least 10 °F above the temperature at which the cooling water will boil.

- In extrapolating the 15 psig CIWH test data to include system pressures up to 20 psig, EPRI investigated the CIWH occurrence mechanism in detail and identified no aspects that would result in a change of the behavior of CIWH in a system that has a pressure that is only 5 psia higher than what was tested. Therefore EPRI believes that the conclusions stated in the TBR for CIWH are valid for system pressures up to 20 psig.

3 EVALUATION

As mentioned in Section 1 of this evaluation, the NRC staff was an active participant in the EPRI initiative, monitoring and critiquing the work that was being performed by EPRI. We considered the PIRT process to be appropriate and adequate for defining the scope of work that needed to be done, and found the outcome of the PIRT evaluation to be acceptable. Because waterhammer is a very complex phenomenon, we also considered EPRI's use of an expert panel to be appropriate and necessary in assuring the completeness and adequacy of the methodology that was being developed. We found the individual panel members to be recognized authorities in their areas of expertise, and well qualified to review the work that was being performed. On several occasions, we observed the work being performed by EPRI, including working level meetings, interaction with the expert panel members, and tests that were being performed. The work appeared to be well planned and orchestrated in all respects, and the individuals performing the work appeared to be very knowledgeable and conscientious in the conduct of these activities.

We have reviewed the information contained in the UM and TBR, as supplemented by letters dated July 10, August 9, September 17, 2001, and February 1, 2002, including interpretation and correlation of the test results, analytical modeling, assumptions, and conclusions that were reached. During our review of the EPRI report to determine whether or not use of the proposed methodology is adequately justified for use in evaluating GL 96-06 waterhammer events, we found the following areas to be of primary interest:

- CIWH Versus CCWH

  Based on the tests that were conducted and review of CIWH information that was available, EPRI determined that CIWH events in the low-pressure cooling water systems for the containment fan coolers will be bounded by CCWH for most situations. Section 4.2.1 of the UM lists the specific criteria that systems must satisfy in order to apply this conclusion. We agree that the information contained in Section 7 of the TBR adequately supports this conclusion and consequently, we focused our evaluation on the proposed methodology for analyzing CCWH events.

- Air Release Model

  During the event scenarios referred to in GL 96-06, air will most certainly be released from solution for any situation that involves the possibility of waterhammer. The testing that was done to determine the amount of air released from the horizontal tubes during boiling most closely modeled the cooling water system for containment air coolers that are located at the high points of the cooling water system, and would bound the case where the containment air coolers are located at a low point in the system. This is because more air would actually be released than what is assumed from the water that is draining back into the containment air cooler tubes from the vertical header and boils during the event. Another shortcoming of the test was that the water in the horizontal tubes mixed with the water in the vertical header, making it difficult to determine how much air was actually released from the water in the vertical header. In order to establish conservative results, EPRI chose the lower bound value of the air released from the water that spilled over into the overflow tube. As an additional measure of conservatism, the EPRI report will only allow credit for air cushioning if the water in the containment air coolers is exposed to containment air cooler tube temperatures that exceed the boiling point for the fluid conditions by at least 10 °F. While the accuracy of the test results can be questioned, we believe that the proposed methodology with respect to air release is conservative and acceptable for the specific application that is described in the UM.

- Scaling Considerations

  Section 7.6 of the TBR discusses the “segment scaling” approach that was used for the CIWH experiments, identifying and evaluating scale distortion phenomena. EPRI determined that both the waterhammer pressure rise and the absolute impact pressure in the smaller experimental pipes would be higher than expected in larger pipes, thus yielding conservative results. Section 8.3.6 of the TBR uses analytical methods to show that pipe diameter is not a relevant factor for scaling the CCWH test results. On the basis of these scaling evaluations, EPRI concluded that the proposed analytical method would be applicable to the larger-scale plant cooling water systems for the containment air coolers. EPRI's approach for addressing scaling considerations appeared to be reasonable for this particular application.

- Steam Condensation

  Sections 8 and 9 of the TBR discuss the MOC and RBM analytical methods, and describe how they were validated using the test results. The pressurization of the steam bubble due to the presence of air and the condensing of steam as the steam bubble is collapsing tend to cushion the waterhammer pressure pulse by slowing the closure velocity of the water column. Based on the test data and arbitrarily assuming the fluid surface area to be twice the available flow area, EPRI established a conservative condensing heat transfer coefficient for use in determining the steam condensation rate. The test data is well represented by the proposed methodology, and we believe that EPRI's approach is reasonable for this specific application.

- Pulse Shape

  In addition to lowering the peak waterhammer pressure, the steam and air cushioning effect results in a longer pressure pulse rise time in order to conserve momentum. Structural loading of the pipes and pipe supports is dependent on the slope of the rise, and a longer rise time results in reduced structural loading. For analytical purposes, EPRI modeled the waterhammer pressure pulse as a trapezoid. Section 9 of the TBR discusses the waterhammer pressure pulse rise times that were observed during the tests that were run, and establishes a method for predicting rise time that is inversely proportional to the water column impact closure velocity.

  The selection of a rise time defines the shape of the trapezoidal force-time pulse to be applied to a point in the piping system. The staff identified issues regarding the selection of rise times and the use of a single pulse to represent the loading function on the piping structure. While the rise time does exhibit an inverse relationship with closure velocity, the values selected to represent the test data do not appear to sufficiently bound all cases when considering the steepest part of the pressurization. Shorter rise times could result in additional structural response. In addition, the loading function for a waterhammer event is characteristically a series of pulses which eventually attenuate after several cycles. The consideration of additional pulses could also result in additional structural response due to additional energy input.

  To examine the effects of both varying rise times and additional pulses, the staff performed several parametric calculations using a single degree-of-freedom spring and mass model. Using this technique, it may be observed that for a repeating pulse input force at resonant or harmonic frequencies, significant additional energy may be input into the structure. However, it is also noted that actual waterhammer forcing functions have pulses which are not exactly repeating in magnitude or period, as evidenced by viewing plots of actual pressure histories. Therefore, it is expected that additional pulses can result in additional structural response, but not as much as the single degree-of-freedom model would predict. A comparison of the proposed analysis method with actual test data indicates that only a few of the analyzed loads did not bound the test loads, and that for most cases, the analysis method over predicted the actual test loads. Therefore, considering the margin available in the piping system when using the allowable stress for the piping material, the proposed rise times and single pulse methodology are acceptable for defining the forces on the piping due to a waterhammer event in the containment fan cooler service water system.

The work that was performed by EPRI was well focused and has substantially improved our knowledge and understanding of the waterhammer phenomenon, especially in low pressure fluid systems. We agree that the proposed EPRI methodology is generally well supported by the TBR and representative of the test results that were obtained. We also consider the guidance provided in the UM, including limitations and restrictions, to be an acceptable representation of the information developed in the TBR, and that use of the UM will assure proper application of the proposed methodology.

3.1 Risk Perspective

While the ACRS did not fully agree with the technical adequacy of the methodology that was proposed by EPRI, they indicated that a risk-informed approach could be a viable option. We would also agree that a risk-informed approach could be used to further justify the proposed EPRI methodology, given the convincing nature of the work that was done. In response to our request, EPRI provided its perspective on the risk associated with the GL 96-06 waterhammer issue. As discussed in Section 2 of this evaluation, EPRI concluded that the likelihood of an unacceptable GL 96-06 waterhammer event is on the order of 1E(-7) or less. EPRI's conclusion is based in part on plant experience with LOOP-only events. EPRI reasoned that LOOP-only events tend to bound the events of concern that are discussed in GL 96-06 (LOCA/MSLB with LOOP) for open-loop cooling water systems. Many LOOP-only events have occurred and no system failures have resulted. Based on this, EPRI concluded that the likelihood of pipe failure given a waterhammer event is on the order of 1E(-2) or less. We agree with EPRI's approach for evaluating risk, and concur with the risk perspective that was provided.

3.2 NRC Acceptance

A substantial amount of time and resources have been invested by EPRI and the NRC staff on completing this initiative. In order to address the concerns that were expressed by the ACRS, much more time and expenditure of resources would be required. However, given the following considerations, we do not believe that any further effort is warranted:

- The proposed methodology has been reviewed and endorsed by notable industry experts who are recognized authorities in their areas of expertise.
- The proposed methodology is consistent with the guidance provided in NUREG/CR-5220 (Ref. 1).
- Although uncertainties remain, the work that was completed by EPRI is very convincing and well supported by a substantial amount of test data and analytical information.
- The probability that a rupture will occur in the containment air cooler cooling water systems due to the waterhammer scenarios discussed in GL 96-06 is considered to be very low; on the order of 1E(-7) or less.

Therefore, we agree that adequate justification exists for using the proposed methodology in EPRI Report TR-113594, Volumes 1 and 2, for evaluating GL 96-06 waterhammer concerns and in responding to plant-specific RAIs that were issued. We agree that the limitations and restrictions established by EPRI, including clarifications provided by the supplementary information that was submitted, are sufficient to assure proper application of the proposed methodology. This includes the position that any potential pressure amplifications due to fluid/structure interaction (FSI) can be conservatively ignored, and that no pressure reductions due to FSI attenuations will be assumed (see EPRI letter dated August 9, 2001). Our approval of the proposed methodology is limited to use by licensees for addressing the GL 96-06 waterhammer issue, and our approval does not extend to any other regulatory application.

3.3 Licensee Responses to GL 96-06

Licensees who choose to use the methodology in TR-113594, Volumes 1 and 2, for addressing the GL 96-06 waterhammer issue, may do so by supplementing their response to include:

- Certification that the EPRI methodology, including clarifications, was properly applied, and that plant-specific risk considerations are consistent with the risk perspective that was provided in the EPRI letter dated February 1, 2002. If the uncushioned velocity and pressure are more than 40 percent greater than the cushioned values, also certify that the pipe failure probability assumption remains bounding. Any questions that were asked previously by the staff with respect to the GL 96-06 waterhammer issue should be disregarded.

- The additional information that was requested in RAIs that were issued by the NRC staff with respect to the GL 96-06 two-phase flow issue (as applicable).

- A brief summary of the results and conclusions that were reached with respect to the waterhammer and two-phase flow issues, including problems that were identified along with corrective actions that were taken. If corrective actions are planned but have not been completed, confirm that the affected systems remain operable and provide the schedule for completing any remaining corrective actions.

Licensees are reminded that their evaluations and responses to address the GL 96-06 issues may be subject to future NRC audit and inspection activities.

4 CONCLUSIONS

As discussed in Section 3 of this evaluation, we consider the use of EPRI Report TR-113594, Volumes 1 and 2, to be acceptable for performing evaluations to address the GL 96-06 waterhammer concerns. Licensees who choose to use this report may respond to the plant-specific RAIs that were issued as discussed in Section 3.3 of this evaluation. NRC approval of the EPRI methodology is limited to use by licensees for addressing the GL 96-06 waterhammer issue, and does not extend to any other regulatory applications.

5 REFERENCES

1. M. G. Izenson, P. H. Rothe and, G. B. Wallis, “Diagnosis of Condensation-Induced Waterhammer,” NUREG/CR-5220 Vol. 1, October 1988.

2. P. Griffith, “Screening Reactor Steam/Water Piping Systems for Water Hammer,” NUREG/CR-6519, Massachusetts Institute of Technology, September 1997.

3. W. Zielke, H-D Perko and A. Keller, “Gas Release in Transient Pipe Flow,” Proc. 6th International Conference on Pressure Surges, BHRA, Cambridge, England October 4-6, 1989.

4. E. B. Wylie and V. L. Streeter, “Fluid Transients in Systems,” Prentice-Hall, Inc., 1993.