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Document Control Desk
U.S. Nuclear Regulatory Commission
11555 Rockville Pike
Rockville, MD 20852

Attention: Mr. Jim Tatum

SUBJECT: Response to ACRS Comments (letter dated 10/23/01) on the EPRI Report on Resolution of NRC GL96-06 Waterhammer Issues

Dear Mr. Tatum:

EPRI has reviewed the input from the ACRS Thermal Hydraulics Subcommittee and Full Committee relative to Generic Letter 96-06 waterhammer issues as provided in the subject letter. We would like to provide some additional information on the specific issues that are raised in the ACRS letter, and we would also like to provide, as suggested in the letter, a perspective on the risk associated with the use of the methods recommended by the EPRI reports.

ACRS Comments

Many of the ACRS comments address the complexity associated with plant-specific evaluation of heat transfer in the fan coolers and the hydraulics of the voiding and draining process. The application of the EPRI work to plant-specific scenarios and configurations depends upon the plant-specific definition and subsequent evaluation of the plant-specific scenarios and configurations. Although the plants are generally similar in the design and performance of these systems, the plant specific differences require that individual, plant specific analyses be performed to evaluate the behavior of the fan cooler, the draining characteristics, and several other system related parameters. These specific plant calculations must be performed and reviewed on a plant-by-plant basis. The scope of the EPRI Technical Basis Report (TBR) was to provide methodology for evaluation of waterhammer loads at the time of final refill and column closure following pump restart.

The EPRI User's Manual (UM) provided plant specific analysis steps in Figure 2-1 and describes the application in Section 2.2. The following text that was extracted from the User's Manual describes the requirement for plant specific evaluation for heat transfer in the fan cooler, system voiding, and system refill.

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Model System Hydraulics: The flow, pressure, and potential paths for water to move and voids to form in the service water system should be determined for the duration of the transient. This will specifically include the time from the loss of power to the time of closure of the void. The system hydraulic model should include the following sub-tasks.

a) **Determine Fan Cooler Unit Performance:** The heat transfer across the coolers and the contribution this heat makes to the generation of steam voids should be determined. This effort should be performed on an individual plant basis – specific guidance is not provided in this User's Manual.

b) **Determine System Voiding:** Using the FCU heat input, piping elevation and system resistances, the system pressure and voiding should be determined. This effort should be performed on an individual plant basis – specific guidance is not provided in this User's Manual.

c) **Determine System Refill**: The flow rates and velocities of the refilling water should be determined from the pump curves and system hydraulic model. Determine anticipated location(s) of closure. This effort should be performed on an individual plant basis – specific guidance is not provided in this User's Manual.

On some issues, such as consideration of single active failure, guidance was provided in the User's Manual to assist in the development of a plant specific analysis.

Once the specific plant analysis was complete, the EPRI User's Manual and Technical Basis Report (TBR) would then be used to provide methodology for the determination of waterhammer loads at the time of final refill and column closure following pump restart. Limitations of application of the EPRI methodology to a specific plant were also provided. In Section 5.3.2 of the User's Manual, for example, limitations on column length, void length, water velocity, gas content, and void and interface temperature were provided. If these limits are not met by the results of the specific plant analysis, the results presented in the EPRI User's Manual are not applicable.

This is a complex problem that requires the analysis of system hydraulics, fan cooler boiling, void formation, and steam and gas behavior within the system. The EPRI project does not provide this analysis for the plants nor does it recommend methods to perform this analysis. These issues are the responsibility of the plant analysts.

The User's Manual provides guidance for the calculation of waterhammer characteristics after the pumps restart and final closure of the columns occurs. This is where cushioning for steam and other non-condensables in the void is calculated. The User's Manual also provides a basis for determining some of the final closure input (such as the amount of gas release) and methods for applying these dynamic pressures to a piping system to calculate loads in the pipe supports and stresses in the piping.

Risk Consideration

Given that we have not come to a conclusion with the ACRS on the conservatism of the technical approach presented in the User's Manual and the Technical Basis Report, a consideration of the risk associated with the events and the results that will be achieved if the report methods are used may be important. If the methods proposed in the EPRI Reports do not significantly increase the risk of unacceptable plant performance nor lead to an unacceptable risk to the plant, it is proposed that the methods of the EPRI report may be safely implemented without compromising the integrity or safety of the piping for plant application.

In order to assess the risk to the plant of application of the EPRI method, a review of the "progression" of events that could lead to an unacceptable condition should be performed. For the purposes of this evaluation, the "unacceptable condition" following a LOOP/LOCA event will be defined as a breach of the service water system pressure boundary. The events are as follows:

1. **Occurrence of a LOCA or MSLB** – The probabilities of occurrence of LOCA and MSLB events are provided in NUREG/CR-5750. From that document, the mean frequency of occurrence of a large LOCA is $5\cdot10^{-6}$/year, a medium LOCA is $4\cdot10^{-5}$/year, and a MSLB is $1\cdot10^{-3}$/year. The LOCA probabilities are represented in NUREG/CR-5750 as "reasonable but conservative" estimates of the frequency of occurrence.

2. **Occurrence of a LOOP following a LOCA or MSLB** – Studies provided in NUREG/CR-6538 and subsequent NRC work indicate that the dependent probability of a Loss of Offsite Power event following a LOCA event is approximately $1.4\cdot10^{-2}$/demand.

3. **Occurrence of a Simultaneous LOCA/LOOP Event** – The required design basis consideration is for the simultaneous occurrence of a LOCA or MSLB and a LOOP. The frequency of the combined event depends upon the probability of the LOCA and the MSLB and the dependent probability of the LOOP given that the LOCA has occurred. Using the values defined in each of the NUREGs referenced above gives a probability of the combined event on the order of $1.5\cdot10^{-5}$/year. For our purposes here, the value of probability of the design basis event (LOCA or MSLB occurring simultaneously with a LOOP) will be taken as 10^{-5}/year. With best estimate probabilities, this event likelihood of occurrence could be expected to be even lower.

4. **Void Formation** - If we have a LOCA/LOOP event, a void will form in an open loop plant with certainty. In a closed loop plant, void formation will depend on the specific plant characteristics and a void may or may not form. If a void does not form, a waterhammer will not occur.

5. **Pump Restart** – The pumps will restart with certainty and the velocity of the fluid 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 uncushioned closure velocity can be

reliably calculated. This velocity will not be higher than the rate at which the pumps, once restarted, can pump water. The calculation of the water velocity prior to closure is a plant specific analysis that can be conservatively performed.

6. **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.

7. **Maximum Waterhammer Pressure** - An upper bound on the water hammer pressure can be calculated by the Joukowski relationship with the uncushioned closure velocity that corresponds to the pipe in which the closure will occur. The waterhammer pressure cannot be larger. With a probability of one, the waterhammer pressure will be equal to or less than the Joukowski pressure. The actual waterhammer pressure that will occur is stochastic and will have a wide variation. This variation is due to variations in the void distribution in the system immediately prior to final closure. This variation appears in all the integral system level experiments. The variation in the test data has been reviewed and, in the velocity range of interest, it varies from 50% to 100% of the maximum (for example, in the Configuration 2a tests, at a velocity of approximately 25 feet per second, the maximum pressure measured from the test was approximately 400 psig, the minimum pressure was approximately 200 psig, the Joukowski pressure for this velocity of closure is 775 psig -- see Figure 10-9 in the TBR). The variation in the test data that has been seen as part of the EPRI project is typical of many other waterhammer tests that have been previously performed and it indicates that it is unlikely that the Joukowski pressure will be attained given the scatter in the results of measured waterhammers compared to those predicted. It is assumed in the EPRI reports that the largest (Joukowski) pressure is attained for the calculated cushioned velocity, although it is very likely that the pressure less than the maximum seen in a test will be experienced.

8. **Cushioned Waterhammer** - With the cushioning that is predicted to occur due to gas and steam, the cushioned velocity will be on the order of approximately 30% to 40% lower than the maximum velocity (see User's Manual appendix – this depends on many parameters, including the amount of gas and steam). For closed loop plants, this value may be only 10-15%. The waterhammer that is predicted, then, will be on the order of 30% to 40% less than the pressure calculated by Joukowski, as the relationship between pressure and velocity is linear. If the cushioning did not occur, the waterhammer pressure and the stresses in the piping would be equivalent to the uncushioned waterhammer that would not have the 30% to 40% adjustment. There are two ways to consider the impact of this potentially higher stress:

   - The first is to consider actual plant performance. The occurrence of the waterhammer following a LOOP event – either simulated in a test or real – is known to have occurred many times in the industry. The waterhammer following a LOOP-only event is not cushioned by gas and steam in the void. The total number of occurrences of LOOP-only events are estimated to be on the order of at least several hundred, based on a review of the available plant data. These occurrences have all been in open loop plants and are more severe than a waterhammer that would occur following a LOOP/LOCA event.

Without any cushioning, the LOOP waterhammer is more severe than that following a LOOP/LOCA. No piping failures have occurred in any of these events. This would indicate that the probability of failure for a more severe waterhammer (an uncushioned waterhammer) is of the order of 10^{-2} or lower.

- The other method is to take the ASME Code limits and to calculate the probability of failure if the code limits were to be exceeded by approximately 40%. For the purpose of this evaluation, it will be assumed that the piping system is designed so that all the ASME code stresses in the piping were at the faulted condition limit when the cushioned waterhammer occurred – that is, the EPRI methodology is used and that the pipe was designed up to the code acceptable limit for that load. To determine probability of failure, an assumed stress distribution is used around a stress that is 40% larger than the faulted allowable ($2.4S_h$) and compared to the actual tested material strengths for A106-Gr B piping. Based on the actual margins available in the ASME code (see NUREG/CR-2137), the probability of the stress exceeding the strength can be shown to be on the order of 10^{-4} or less.

For the purpose of continuing the "event progression", a probability of failure in the pipe if the cushioned waterhammer were exceeded will be taken to be on the order of 10^{-2}. It is probably much less likely.

9. **Likelihood of an Unacceptable Event** - Given the low probability (10^{-5}/year) of the initiating events and the low probability (10^{-2}) of piping failure, the use of the methodology in the User's Manual and the Technical Basis Report will lead to a likelihood of an unacceptable event that is on the order of 10^{-7}. Again, for the purposes of this evaluation, the "unacceptable event" following a LOOP/LOCA event is taken as a breach of the service water system pressure boundary. The probability of 10^{-7} for this event is below the threshold for significant risk to the plant. Use of the methods in the User's Manual, therefore, will not compromise the safety of the plant for the systems within the bound provided in the User's Manual and Technical Basis Report. The methodology should be accepted as recommended in the report.

The most important consideration in the behavior of the waterhammer following pump restart is that there is an upper bound on the waterhammer pressure that can be attained -- the waterhammer without cushioning -- and that the waterhammer without cushioning has occurred many times in simulated LOOP events. The methods proposed in the EPRI TBR use the physics of gas compression to calculate a reduced closure velocity and waterhammer magnitude. The change in risk introduced by the use of these methods is not significant and the methods do not lead to an unacceptable plant risk following a LOOP/LOCA event. Hence, from the Risk-informed perspective, the methods proposed in the submitted EPRI TBR and UM are adequate for plant-specific application for resolution of the Generic Letter 96-06 issues.

The methods provided in NUREG 5220 were considered acceptable for conservatively analyzing waterhammer events. The NUREG uses the Joukowski relationship with the uncushioned velocity. NUREG-5220 acknowledges that the calculated results using their methods could be 2-10 times higher than reality. All seem to agree that if a void forms following a LOOP/LOCA event, it will have non-condensable gas and some steam in it, and that some cushioning will occur. The emphasis of the work that was performed by EPRI is to define the amount of cushioning that would be expected. The cushioning calculated will provide, in general, between zero and approximately 40% velocity reduction and subsequent pressure reduction. The risk discussion of this letter shows that given the low probability of the events, the limited energy available from this event, and the low probability of pipe failure, that the methodology proposed in the User's Manual is reasonable for those cases that fit within the parameters of the User's Manual and Technical Basis Report.

We hope the information provided herein is helpful. If you have any questions on the enclosed information or the general subject it addresses, please call me at 919-546-7959 or Avtar Singh at 650-855-2384.

Sincerely,

Avtar Singh for

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Carolina Power & Light Company
Chairman, EPRI Waterhammer Project Utility Advisory Group