ATTACHMENT

Letter Report No. 240-2

Review Of Arkansas Nuclear One (units 1 and 2) Waterhammer And Two-Phase Flow Analysis

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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 Water hammer and two-phase flow conditions. More specifically, the issues of concern are :[1]

> "(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). 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.
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> (2) Cooling water systems serving the containment air coolers may experience two-phase flow conditions during postulated LOCA and MSLB scenarios. The heat removal assumptions for design-basis accident scenarios were based on single-phase flow conditions. Corrective actions may be needed to satisfy design and operability requirements."

Entergy Operations, Inc. provided its assessment for the Arkansas Nuclear One (ANO), Units1 and 2 in a letter dated January 28, 1997. [2] Parts of the licensee's submittal addresses waterhammer and two-phase flow conditions. The licensee was requested to provide additional information in a letter dated April 14,1998.[3] The licensee's response was provided in a letter dated January 25,1999.[4]

Scientech, Inc. was requested (NRC-03-95-026, Task Order No. 240) to assist the NRC staff in reviewing the waterhammer and two-phase flow analyses that has been completed by the licensee for the ANO, Units 1 and 2 in response to GL 96-06. The objective of the review was to determine whether or not the analyses are adequate and conservative in all respects.

This letter report summarizes the results of the review that was performed and conclusions that were reached. Section 2 provides background information regarding the design characteristics of the cooling water systems in ANO-1 and ANO-2. The event considered for this evaluation is discussed in section 3. Section 4 and 5 provide the review results of the waterhammer and two-phase flow analyses, respectively. Section 6 provides a brief summary together with conclusions.

2. DESCRIPTION OF SERVICE WATER SYSTEMS IN ARKANSAS NUCLEAR ONE (ANO), UNITS 1 AND 2

The ANO-1 and ANO-2 service water systems are very similar. Both are dual purpose systems used for both normal and emergency cooling. However , for both units, the portion of the service water system supply to the fan coolers is in service only during emergency operation. During normal operation, the ANO-1 reactor building and ANO-2 containment are cooled by the chilled water system.[4]

The service water systems for both units are *open systems* which take suction from and discharge to Lake Dardanelle Reservoir. However, the ANO-2 service water system (SWS) discharge is switched to the emergency cooling pond by an engineered safety feature actuation system (ESFAS) signal. ANO-1 and 2 have very similar designs for their containment service water cooling coils (CSWCCs) and associated piping. CSWCC piping elevation is greater than thirty-two feet above Lake Dardanelle[2].

Prior to the issuance of Generic Letter 96-06, modifications were made to both units's cooling water systems to eliminate severe waterhammer . Air vacuum valves (AVVs) were added to outside- of- containment piping and "slow-refill" bypasses were added around the fan cooler service water inlet valves.[4] Failure modes and effects analysis was included in the modification packages prepared for the installation of the waterhammer mitigation system. Single failure could result in loss of redundancy but not loss of function for CSWCC heat removal. All common mode failure mechanisms were eliminated.[4] The following description of ANO-1 and 2 cooling water systems is from Reference 4:

> ***ANO-1*** The ANO-1 cooling water systems consist of service water, auxiliary cooling water (ACW) and the closed loop intermediate cooling water (ICW) systems. The service water system consists of two independent but interconnected loops that supply nuclear auxiliary components and the ICW heat exchangers. The service water pumps also supply the ACW system. Service water and ACW discharge to the Lake Dardanelle Reservoir . During an ANO-1 emergency, ACW is isolated as is service water to the ICW heat exchangers.
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> ***ANO-2*** The ANO-2 cooling water systems consist of service water, ACW and the closed loop component cooling water (CCW) systems. The service water system consists of two independent but interconnected loops that supply nuclear auxiliary components and the CCW heat exchangers. The service water pumps also supply the ACW system. Service water and ACW normally discharge to the Lake Dardanelle Reservoir. An ESFAS actuation automatically closes valves that allow service water discharge to the Lake Dardanelle Reservoir and open valves that direct service water to the emergency cooling pond. The ESFAS actuation also isolates the ACW and service water to the CCW heat exchangers.

3. SEQUENCES OF EVENTS CONSIDERED FOR EVALUATION

A LOCA with simultaneous initiation of a LOOP has been considered for this evaluation.

On a LOCA/LOOP scenario, loss of the service water pumps would be almost immediate, while circulation of the heated containment atmosphere would continue during fan coastdown in the containment fan coolers (CFC). The following expected key time parameters during the initial time period following the accident is from Reference 4.

Time	Description	
	ANO-1	**ANO-2**
0. sec	LOCA +LOOP	LOCA+ LOOP
16. sec	EDG accepts loads ACW and ICW valves begin to close SW crossover valves begin to close	EDG accepts loads ACW valve begin to close CCW isolation valves begin to close
19.5 sec		Service water pumps restart
21. sec		The swing service water pump starts (if it is aligned)
30. sec	Two service water pumps restart	
35.4 sec		CFC supply and return valves start opening (the return valve begins to open ~1.4 sec after the start of supply valve opening)
55. sec	CFC supply and return valves start opening (the return valve is assumed to begin opening 1. sec after the start of the supply valve opening)	

4. WATERHAMMER ANALYSIS

Prior to issuance of Generic Letter 96-06 the potential for severe waterhammers in all ANO cooling water systems was evaluated. The potential waterhammer initiator was a LOOP. When the service water pumps trip due to a LOOP, vapor voids form in high elevation piping. The collapse of these voids upon pump restart when emergency power becomes available results in waterhammer due to column rejoining. The LOOP scenario was modeled with and without a coincident LOCA. It should be noted that in the pre- Generic Letter 96-06 analysis, coil boiling due to fan coast down was not considered. Coil boiling was subsequently modeled and was described as a part of the licensee's response to a Request for Additional Information (RAI).[4]

The methodology used to evaluate waterhammer in these systems involved plant specific modeling using the Hydraulic Systems Transient Analysis (HSTA) computer program. HSTA is a generalized finite difference code developed by Bechtel Corporation and has been used extensively over the last 20 years for waterhammer design and diagnostic purposes in nuclear and non-nuclear piping systems.[4] The program uses Wylie and Streeter's well- known application of the Method of Characteristics (MOC)[6]. HSTA allows for large models containing as many as 18000 nodal points. The MOC is used to solve the hyperbolic partial differential equations (of continuity and momentum) to obtain the liquid velocity and pressure head at a known grid location. These flow variables are then utilized to generate the dynamic forcing functions on specified pipe run segments.

HSTA can model a complex piping system containing one or more of the several different types of flow devices (boundary conditions) present in the system. The HSTA hydraulic model for the piping network is composed of a set of pipes called "links", each of which is subdivided into two or more "nodes". At the beginning and end of each link is an identified boundary condition such as a valve, reservoir, pump, etc.,or a simple continuation.

The assumptions inherent in the HSTA computer program are:[4]

- One dimensional flow.
- Single phase compressible liquid with constant density.
- Velocity and head constant across the pipe cross-section.
- No heat transfer considered.
- Pipe wall is elastic. Sonic speed is constant in a link but can vary between links.
- Transient flow friction factor formulation same as that under steady flow.
- Liquid/vapor interface one-dimensional across the pipe cross section.

The HSTA code allows for the modeling of liquid (water) column separation when the pressure falls to the vapor pressure of the liquid. Two computational schemes are available. The first is a conventional scheme of generating a vapor pocket and tracking its size at each computational node where the system pressure tends to be lower than the vapor pressure. As it was pointed out in Reference 4, this commonly used methodology works well if the vapor pocket size is less than the distance between two adjacent nodes. For large vapor pocket sizes, the accuracy of results by this scheme is questionable.

The second HSTA computational scheme is "line filling" that treats the vapor pocket as bounded by two vapor /liquid interfaces. These liquid interfaces are tracked independently thus allowing for accurate representation of these pockets and their growth/collapse irrespective of the pocket size relative to the nodal distance. This method also allows the entire vapor pocket to effectively move along the piping system due to the independent motion of both the upstream and downstream interfaces.[4] This computationl scheme (which was used for the ANO models) is well suited for the analysis of column closure (water column rejoining) waterhammer.

As it is stated in the licensee's RAI response[4], the HSTA code has been validated by comparison with several experimental or tests data. For the line filling computational scheme, the HSTA validation efforts included comparisons against laboratory test data both from Europe and in the USA. One particular comparison mentioned is comparison against the subscale experimental results (from NUREG-0291[7]) of water reflooding upward in a closed end vertical pipe when the pressure in the pipe was reduced due to condensation. Using the line filling calculational scheme, the HSTA simulation resulted in very reasonable agreement with the measured data.

In the original configuration for ANO-1 and ANO-2 , when the service water pumps trip due to a LOOP, large open flow paths to the Lake Dardanelle Reservoir allow the service water system and ACW water to drain from high elevation piping. The collapse of vapor "voids" upon pump restart would have caused a series of waterhammers. These waterhammers could have been severe depending on the magnitude of the impact velocity and the compliance or non-compliance of the impacted object.[4]

An initial evaluation of potential waterhammer problems was performed which considered many cases (six cases for ANO-1 and two cases for ANO-2) that ranged from doing nothing to the final solution that modified system hardware and operating procedures as described below for each unit:[4]

> ***ANO-1*** The Reactor Building Service Water Cooling Coils (RBSWCCs) slow refill design change for ANO-1 closed the 10" inlet valves, maintained the outlet valves closed, and added a 1" normally open orificed bypass around each inlet valve containing a solenoid valve for containment isolation. The orifice is the solenoid valve port that has a 3/8" circular bore. During a LOOP, the drain down and refill is through the orifice bypass, which reduces the amount of draining and greatly reduces the recombining velocities. The solution for a coincident LOCA/LOOP event was a design change that makes this event identical in effect to a LOOP event by adding time delays on the inlet valves. The valves are not allowed to open until after the service water pumps are restarted and refill the RBSWCCs through the slow refill bypass. After the time delay, the inlet valves start to open. The outlet valves are interlocked with the inlet valves and do not open until the inlet valves are 10-25% open.

ANO-2 The CSWCCs slow refill design change for ANO-2 closed the 12" CSWCC inlet valves, maintained the outlet valves closed, and added a 1" normally open orificed bypass around each inlet valve containing a solenoid valve for containment isolation. The orifice is the solenoid valve port that has a 3/8" circular bore. During a LOOP, the drain down and refill will be through the orifice bypass, which reduces the amount of draining and greatly reduces the recombining velocities. The main inlet and outlet valves are not allowed to open until after the restarted service water pumps refill the CSWCCs through the slow refill bypass. The outlet valves are interlocked with the inlet valves and do not open until the inlet valves are 10-25% open.

For ANO-1 and ANO-2, the containment fan cooler water hammer concerns raised in Generic Letter 96-06 (i.e. fan coast down) were addressed by a combination of calculations. For the LOCA with coincident LOOP postulated accident, loss of the service water system pump pressure would be almost immediate while the containment cooling fans would coast down for a much longer time. The coast down or failure of a containment fan to trip would cause the cooling water to boil, thereby creating steam bubbles in the containment fan cooling coils.

A GOTHIC code analysis, performed by Numerical Applications, Inc., modeled the response of the service water to the pump trip transient and calculated the drain down (or the steam bubble size) following LOCA/LOOP in the ANO-1 for the slow refill configuration described above. The containment cooler fans force hot containment steam and gases over the coils containing service water. As the steam bubble develops, the water is displaced out through the 3/8" orifice. Instead of a large low-pressure void being created, a small high-pressure void is formed. The GOTHIC analysis demonstrated that in about 35 seconds, a steam bubble about 1.1 ft^3 in volume will be formed at the saturation pressure corresponding to the peak containment temperature of 284 °F (52.4 psia). The analysis indicated that for approximately 5 seconds, the (cooler) coils act as a heat sink, then pressure in the coil tubes rapidly rises to the saturation pressure. The GOTHIC analysis was used for both ANO-1 and ANO-2 due to virtually identical configurations.[4] A quasi-steady state hand calculation was also performed in which the time to start boiling was assumed as 5 seconds after LOCA/LOOP and the pressure in the fan cooler tubes was assumed to be the saturation pressure corresponding to the containment temperature. A steam volume of about 1.9 $ft^3$was obtained by hand calculation as compared to the GOTHIC calculated value of 1.1 ft^3 . For ANO-2, the hand calculation method was used with the added conservatism introduced by assuming that boiling starts two seconds after LOCA/LOOP.[4]

The result of the GOTHIC analyses were then used as input to new HSTA analyses performed by Bechtel Power Corporation[8,9]. For ANO-1, the analysis indicated that the water columns adjacent to the steam pocket impact at a maximum velocity of about 2.1 ft/s for Case 1 (two SWS pumps restarting) and 1.5 ft/s for Case 2 (one pump restating). These impacts take place at about 50 to 53 seconds after the pumps begin to start and they occur in the tube region. The maximum peak force was calculated to be about 2 kips. For each cooler, the CFC tubes were modeled as one lumped tube. The diameter of this equivalent tube is about the same as that of the cooler header pipe. Since the water column impact occurs in the tube, the pressure wave generated by this impact in the model travels into the system with very little reflection at the cooler header pipe. The conservatism in the results induced by this lumping were quantified and were reported to be about 17% of the calculated values. Thus the effective maximum impact velocity seen by the piping outside the tube region is about 0.4 ft/sec, and the maximum peak forces are effectively less than 500 lbf.[8] (It is noted that in Reference 4 , Page13, the results of the HSTA analysis for ANO-2 were reported incorrectly for ANO-1. Also, the supply and return valve data for the ANO-1 HSTA analysis reported in Table 1, sheet 7, Figure, are not consistent with the values discussed in the text, sheet 6.)

For ANO-2, the analysis results indicated that the effective maximum impact velocity seen by the piping outside the tube region is about 0.2 ft/s and the effective maximum peak forces are less than 220 lbf. in the CFC area.[9] Impacts take place at about 22 and 25 seconds after the service water pumps restart.

The impact velocity and force values (for both ANO-1 and ANO-2) were reported to be of the same order of magnitude as those previously calculated for waterhammers where fan coast down effects were not considered. Therefore, the conclusions of satisfactory structural integrity were assumed to be the same as for the previous analysis.

The following are the main conservatisms in the HSTA analyses [4]:

- The steam was considered to be a single bubble. Because the quantity of steam generated is small compared to the tube volume, it is most probable that the steam will be formed as distributed bubbles over the tube length. Thus the steam will exist in the water as a two-phase mixture. The presence of gas in water significantly reduces the sonic speed. In the HSTA analysis, the sonic velocity used is that of water with no gases present. This would result in a significantly conservative estimation of the surge pressure and waterhammer loads.

- The effect of air coming out of solution was ignored. It is likely that any air coming out of solution will cushion the steam bubble collapse and reduce the waterhammer loads.

It should be noted that the fluid/hydraulic forcing functions and structural analysis were performed in a de-coupled manner. In the ANO-1 and ANO-2 analyses, not only is the piping well supported but the forces calculated were quiet small. Significant pipe motion is not expected and therefore, fluid structure interactions effects were not considered.

5. TWO-PHASE FLOW ANALYSIS

The issue of two-phase flow in the containment air cooling system has also been evaluated for ANO-1 and ANO-2 . The concern is related to a potential reduction in containment cooling capacity due to reduced flow, caused by the increased friction of two-phase flow.

The ANO-1 fan cooler piping upstream and downstream of the fan cooler isolation valve does not have any orifices in the supply or return lines. There are globe valves downstream of the isolation valve in each 10-inch return line. The globe valves are used for back pressure purposes but are set fully open. The return line isolation valve is about 180 and 150 feet from the cooler tube outlets for loops I and II, respectively.[4] Based on the HSTA calculated velocities, it was determined that the return valves are almost 80% open by the time the hot water slug reaches them. At this opening position, the butterfly valves have small resistance and they are effectively fully open. Because these valves are located more than 25 feet below the top of the cooler piping and due to the pump head available (as observed from the HSTA output results), the water pressure was found to be higher than the saturation pressure at the maximum containment temperature. It has been further argued that the water temperature does not reach the maximum containment temperature (as was seen from the GOTHIC analysis) and there would be a temperature drop due to heat losses to the pipe wall as the water slug travels more than 150 feet. Based on the above evaluations, it was concluded that two-phase flow conditions do not exist at these minor flow restrictions.

The ANO-2 fan cooler piping has orifices in the return lines downstream of the isolation valves. The return line isolation valves are more than 144 feet from the outlets of the cooler tubes. Based on the HSTA calculated velocities for ANO-2, it was determined that the return valves are fully open by the time the hot water slug reaches them. The return isolation valves are about 30 feet below the top of the cooler and the orifices are about 42 feet below that. The orifices are almost full bore orifices (bore diameter is 11.25 inches and pipe diameter is 12 inches) with a flow resistance less than that of a full open butterfly valve. Therefore, two-phase flow across these devices was not expected. The results of hand calculations, performed under conservatively assumed conditions, was reported to indicate the possibility of some flashing for the short duration (few seconds) before the hot water slug reaches the main return header where it mixes with colder water. However , there is no mechanism to sustain two -phase flow that degrades the performance of the fan coolers. Therefore , it was concluded that two-phase flow is not a concern for the ANO-1 and ANO-2 containment fan cooler systems.

For ANO-1, the RBSWCCs are not needed to maintain containment peak pressure below its design limit. The RBSWCCs provide the long term cooling needed for an acceptable cooling profile for EQ components. Therefore, large margins have been added to the calculated refill time. These margins envelope all timing uncertainties. For ANO-2, the CSWCCs contribute a small but required amount of containment cooling to keep peak accident pressure below design. Therefore the timing uncertainties for ANO-2 have been more precisely defined. For conservatism, the void volume in the refill calculation was sized at twice its calculated volume.

It should also be noted that the supply and return valves to the containment fan coolers at ANO are not throttled and as such no erosion or cavitation induced vibrations are expected. These effects were, consequently, not considered in the ANO analysis.

6. SUMMARY AND CONCLUSIONS

The waterhammer and two-phase flow analysis that has been completed by the licensee for the Arkansas Nuclear One (units 1and 2) in response to GL96-06 has been reviewed. Prior to issuance of Generic Letter 96-06, the potential for severe waterhammers in all ANO cooling water systems was evaluated. The potential waterhammer initiator was a LOOP. Modifications were made to both units cooling water systems to eliminate severe waterhammer. Air vacuum valves (AVVs) were added to outside- of- containment piping and "slow-refill" bypasses were added around the fan cooler service water inlet valves.

The containment fan cooler water hammer concerns raised in Generic Letter 96-06 were addressed by a combination of calculations. A GOTHIC code analysis modeled the response of the service water to the pump trip transient and calculated the drain down and the steam pocket size following LOCA/LOOP in the ANO-1 RBSWCCs for the slow refill configuration. The GOTHIC analysis was used for both ANO-1 and ANO-2 due to virtually identical configurations. The results of the GOTHIC analysis were then used in the HSTA analyses. The methodology, especially use of the "line filling" computational scheme of the HSTA code, was found to be adequate and conservative for the evaluation of hydrodynamic loading due to column closure (water column rejoining) waterhammer.

The issue of two-phase flow in the containment air cooling system has also been evaluated. Significant flow throttling does not exist in either of the ANO-1 or ANO-2 fan cooler systems. The HSTA calculated velocities and hand calculations under conservatively assumed conditions were used for these evaluations. It is agreed with the licensee's conclusion that two-phase flow is not a concern for ANO-1 and ANO-2 containment fan cooler systems.

7. 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. Entergy Operations Inc., "Arkansas Nuclear One-Units 1 and 2, 120-Day Response To Generic Letter 96-06," 0CAN019702, January 28, 1997.

3. Nuclear Regulatory Commission (NRC), " Request for Additional Information Pertaining to Generic Letter (GL) 96-06, Assurance of Equipment Operability and Containment Integrity During Design-Basis Accident Conditions," Letter from William Reckley to C. Randy Hutchinson, April 14,1998.

4. Entergy Operations Inc., "Arkansas Nuclear One- Units 1 and 2, Additional Information pertaining to Generic Letter 96-06", 0CAN019903, January 25, 1999.
5. Izenson, M.G.,P.H. Rothe and G.B. Wallis, " Diagnosis of Condensation- Induced Waterhammer," NUREG/CR-5220, October 1998.
6. Wylie, E. Benjamin and Victor L. Streeter, *fluid Transients*, FEB Press, Ann Arbor Michigan, 1982.
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8. Bechtel, "SWS Containment Fan Cooler Water Hammer Analysis", ANO Unit1, CALC NO: 97-E-0034-01, October 17, 1997.
9. Bechtel, "SWS Containment Fan Cooler Water Hammer Analysis", ANO Unit2, CALC NO: 97-E-0034-02, November 24, 1997.