APPLICATION OF ACOUSTIC METHODOLOGY FOR EVALUATION OF SUBMERGED STRUCTURES ON THE MARK III LARGE PASSIVE ECCS SUCTION STRAINER

Prepared By: Gordon K. Ashley, II

Reviewed By: Alcuin J. Schneider

ISSUE

On May 6, 1996, the Nuclear Regulatory Commission (NRC) issued Bulletin 96-03, *Potential Plugging of Emergency Core Cooling Suction Strainers by Debris in Boiling Water Reactors.* This bulletin requires boiling water reactor (BWR) licensees to take actions that will ensure that the emergency core cooling systems (ECCS) retain their capability to perform their safety functions following a loss of coolant accident (LOCA).

NRC Bulletin 96-03 was issued based on a series of events at operating BWRs and subsequent analysis of the events by the Boiling Water Reactor Owners Group (BWROG) and the NRC. In July of 1992, an event involving plugging of two suction strainers in the containment vessel spray system occurred at Barsebäck Unit 2, a Swedish BWR. The strainers were partially plugged by mineral wool insulation dislodged by steam released from a pilot-operated relief valve. Two separate events involving clogging of ECCS suction strainers occurred at the Perry Nuclear Power Plant in 1993. In the first event, debris in the suppression pool clogged the suction strainers for the Residual Heat Removal (RHR) system. The same strainers were clogged by a combination of glass fibers from drywell cooling unit filters that had inadvertently dropped into the suppression pool and corrosion products that accumulated on the glass fibers. A fourth event occurred at the Limerick Nuclear Generating Station in 1995 when both suction strainers in the "A" loop of the suppression pool cooling subsystem were clogged by a combination of fibrous materials and sludge.

Analyses of these events indicated that blockage of ECCS suction strainers could result in insufficient net positive suction head (NPSH) for the ECCS pumps. This could lead to failure to meet the requirements for providing adequate core cooling following an accident and long term cooling capability following a LOCA to remove decay heat and ensure that the core temperature is maintained at acceptably low values. These requirements are specified in Section 50.46 of Title 10 of the Code of Federal Regulations.

RESOLUTION APPROACH

Cleveland Electric Illuminating (CEI) Company and Entergy Inc., the owners and operators of the Perry Nuclear Power Plant, the Grand Gulf Nuclear Station, and River Bend Station, initiated a cooperative effort to evaluate ECCS suction strainer plugging and develop a common approach to resolving the issue. All three plants are BWR6/Mark III containment plants with substantially similar designs. Responses to Bulletin 96-03 to be submitted in early November, will provide a summary of the program undertaken by CEI and Entergy, the conceptual design they have jointly developed for a new ECCS suction strainer, and a description of a test program to validate the conceptual design.

CEI and Entergy initially completed a detailed evaluation of options to resolve the ECCS suction strainer plugging issue. The utilities considered replacement of current insulation in the drywell with reflective metal insulation and, if necessary, installation of new ECCS suction strainers to provide sufficient capacity to cope with corrosion products and non-insulation debris produced as a result of postulated accidents. In addition, the utilities evaluated installation of three types of strainers without replacement of existing insulation: (1) active strainers with gravity self-cleaning capability, (2) continuous backwash strainers and, (3) large passive strainers. Following a careful analysis of technical issues, costs, and potential schedules for implementing each option, the utilities determined that installation of a large passive strainer represented the best overall option for resolution of the issue based on data available at the time. A key factor contributing to the selection of the large passive strainer option was its ability to minimize sensitivity of the design to uncertainties associated with the design bases. In particular, the large passive strainer design is less sensitive to uncertainties regarding quantities of debris and corrosion products present during routine plant operation, debris generation as a result of the LOCA, and effects of long term head loss during the extended period of operation after the accident to provide long term cooling of the containment. This option is also superior with regards to the impact of installation and reliable operation over the life of the plant.

Following selection of the large passive strainer option, CEI and Entergy initiated a design and testing program to develop a conceptual design for the strainer. The effort has focused on establishing the appropriate design basis, selecting the best conceptual approach, investigating design loads, developing preliminary support designs and evaluating potential constraints on fabrication and installation.

ACOUSTIC METHODOLOGY APPLICATION

Components or structures located in the Mark III containment pressure suppression pool must be designed to withstand dynamic loads including seismic loads, post-LOCA hydrodynamic loads, and Safety Relief Valve (SRV) hydrodynamic loads. The large toroidal passive strainer has been designed to withstand applicable combinations of these loads. The conceptual design locates the proposed strainer on the suppression pool floor and as close to the containment wall as possible to minimize the impact of postulated dynamic loads.

The calculational methodology for determining appropriate combinations of seismic and hydrodynamic loads acting on the conceptual design is specified in the GESSAR II document. The critical load combinations calculated using the GESSAR II methodology include significant upward loads on the strainer that would tend to lift the strainer off the floor of the suppression pool. For example, the SRV air bubble load produces large uplift loads. Although the condensation oscillation load case was determined to be non-critical, it also contains a vertical uplift component. These uplift loads complicate design of an appropriate restraint system for the passive strainer. Accordingly, the Mark III Owners have elected to use acoustic theory to reanalyze loads produced by certain hydrodynamic phenomena to provide a more realistic definition of the loads. This methodology has previously been used to analyze hydrodynamic loads produced in both the Mark III containment and the Mark II containment.

The acoustic chugging methodology (either the Mark II Improved Chugging Methodology or the SciEnTec Acoustic Chugging Methodology) properly consists of (1) a source function, (2) a transfer function, and (3) fluid-structure interaction (FSI). The complete and proper solution of the acoustic wave equation provides the transfer function that incorporates the FSI. For the solution to be proper, it must incorporate the correct boundary conditions. These boundary conditions are (1) the pressure field vanishes at the water surface and (2) the water velocity normal to the fluid-structure boundary must equal the local velocity of the structure boundary. The free surface boundary condition requires that the total pressure response is equal to the sum of the acoustic pressure field, the over pressure, and the hydrostatic pressure. The normal velocity boundary condition couples the fluid to the boundary and provides for interaction. How this is incorporated into the transfer function is explained in complete detail in the documents describing the acoustic theory.[1,2,17] The representation of FSI by the acoustic theory has been demonstrated to be correct via comparison with the results from a finite element computer model for the 4TCO test facility, for a typical Mark II containment, and from comparison with test data. The source function used in conjunction with the acoustic methodology is generally extracted from prototypical test data that reflects a specific containment geometry. Consequently, data from Mark II will not suffice for Mark III. Instead appropriate source functions will be created using conditions imposed by the GESSAR II. These conditions consist of bounding the suppression pool boundary pressure response, both by amplitude and power by frequency.

What references support NRC approval for application of the acoustic methodology? The acoustic theory of safety relief valve (SRV) quencher discharge and unstable steam condensation was developed in 1976 for Task A.16 Phase II of the Mark II Owners Group Long-Term Program.[1] The purpose of Task A.16 was to provide an improved chugging load definition methodology resulting in more realistic loads and to answer NRC concerns about fluid-structure interaction. This methodology constitutes the Improved Chugging Methodology for the Mark II program and was documented in a report issued by the General Electric Corporation.[2]

During August 1981, the NRC issued a report reviewing the calculation methodology for the LOCA-related suppression pool hydrodynamic loads in Mark II-type BWR facilities.[3] With this report, the NRC concluded Generic Technical Activity A-8, "Mark II Containment Pool Dynamic Loads," that had been designated as an

"Unresolved Safety Issue" pursuant to Section 210 of the Energy Reorganization Act of 1974. In their report the NRC specifically reviewed the acoustic methodology and found that it met the requirements of General Design Criterion 16 in Appendix A to 10 CFR Part 50. In their report, the NRC stated that, "On the basis of large-scale tests conducted in 1979, the Mark II Owners developed improved condensation oscillation and chugging loads for the suppression pool boundary and lateral loads for the containment downcomers. The staff has reviewed these loads and concluded that, with a few specified changes, these loads provide conservative loading conditions."[4] In addition to other hydrodynamic suppression pool loads, the NRC report then describes in detail, without the mathematical formalism, the Mark II Improved Chugging Methodology.[5]

In July 1980, the Mark II lead-plant owners proposed using a simplified approach (which they believed was bounding) to deal with the new data from the 4TCO facility for assessment of their containments.[6] However, this simplified interim approach was not accepted as a substitute for the load specification developed through the generic improved-chugging load task.[7] Accordingly, each of the lead Mark II owners were required to evaluate their plant containment using the acoustic methodology.[8]

Where has the acoustic methodology been used? Following its acceptance by the NRC, the acoustic methodology was used to compute the suppression pool boundary hydrodynamic loads in Boiling Water Reactor (BWR) facilities with the Mark II pressure suppression containment design. Of the ten Mark II-type BWR containments (units), six elected to utilize the acoustic methodology directly, three chose to use an interim bounding loads approach in order to support their start-up schedule, and one containment used an equivalent method based upon a finite element model coupled with a harmonic analysis of the chugging test data. Specifically included among those containments using the acoustic methodology were the PECO Energy Company Limerick Generating Station (LGS) Units 1 and 2, and the Pennsylvania Power & Light (PP&L) Company Susquehanna Steam Electric Station (SSES) Units 1 and 2. In addition to computing suppression-pool boundary loads, these four units (LGS Units 1 and 2 and SSES Units 1 and 2) used the acoustic methodology to determine the submerged structure loads due to unstable steam condensation (chugging and condensation oscillation) for all submerged structures in the suppression pools. This included all the components of the Emergency Core Cooling System (ECCS)[9] suction strainers and associated piping, safety relief valve discharge lines, downcomers, support columns, and the downcomer bracing network.

In May 1982, Mr. John Humphrey, a former lead systems engineer at the General Electric Company raised concerns that focused, in part, on the lack of final load definition for the potential occurrence of condensation oscillation resulting from high steam mass flux discharge into the suppression pool through the RHR heat exchanger relief valve discharge lines. The initial Mark III CIOG response was that any RHR condensation oscillation loads would be bounded by other design-controlling phenomena. The NRC requested[10] that the CIOG provide additional confirmatory analyses quantifying the potential RHR condensation oscillation loads in order to demonstrate that they would be bounded by other phenomena. Potential flow theory, which was utilized to evaluate the Mark III hydrodynamic loads via a method of images solution, could not be used because it would have produced unrealistic RHR condensation oscillation loads that exceeded those other design controlling phenomena. This is because a method of images solution to the potential flow equation is inappropriate,[11] overly conservative, and because of the proximity of the suppression pool wall to the RHR discharge point.

Because of this excessive conservatism inherent in the original Mark III design basis methodology, the Mark III Containment Issues Owners Group (CIOG)[12] elected to use the acoustic methodology for the assessment of Mark III RHR condensation oscillation.[13] This assessment demonstrated that both the suppression pool boundary and submerged structure loads due to RHR condensation oscillation were bounded by the design basis suppression pool boundary loads caused by SRV quencher discharge.

The acoustic theory was used to assess the effect of RHR condensation oscillation in each of the Mark III containments.[13] This required the calculation of plant-unique suppression pool boundary loads for each of the four CIOG containment designs.[14] In addition, an assessment of the submerged structure loads resulting from RHR condensation oscillation was performed by calculating the radial and tangential force densities for a cylindrical structure in each of the CIOG containments.[15]

In 1996 the acoustic theory of SRV quencher discharge and unstable steam condensation was re-developed from first principles. As a consequence, the *POWER-ACM v1.0* microcomputer program was developed for SciEnTec utilizing a new formulation for the Improved Chugging Methodology. This is referred to as the SciEnTec Acoustic Chugging Methodology (SACM). By a comparison of the mathematical development for the SACM and the Improved Chugging Methodology, it was demonstrated that the theoretical basis for each methodology is the same except for differences in nomenclature. This comparison was documented via a formal SciEnTec calculation.[16] In addition, the *POWER-ACM v1.0* code was compared with the software that was developed at Bechtel using the Mark II Improved Chugging Methodology and also found to be the same except for improvements in the mathematical algorithms.[17] A series of benchmark test problems was run by *POWER-ACM v1.0* for software verification.[18] The computed results were found to be the same as those calculated by the Improved Chugging Methodology software to within the numerical precision of the computer platforms employed.[19]

Why is the acoustic theory applicable for Mark III ECCS submerg.:I structure loads? The Mark II Improved Chugging Methodology or its equivalent, the SciEnTec Acoustic Chugging Methodology, is applicable to the calculation of the Mark III ECCS submerged structure loads for the following reasons:

(1) The acoustic theory has been approved by the NRC and is the standard against which all other approaches are to be evaluated. As the Mark III suppression pool is quite similar in geometry to the Mark II suppression pool, it is expected that acoustic theory will apply in Mark III as well.[20] Consequently, the acoustic transfer function (which incorporates fluid-structure interaction) shall be utilized. However, determination of the sources is unique to containment type and test data for other containments will not be used in generating submerged structure loads for Mark III ECCS strainer design.

(2) This methodology was used for the design evaluation of chugging and condensation oscillation suppression pool hydrodynamic loads, including submerged structure loads, for Mark II-type BWR containm.:nts and forms part of the licensing documentation (UFSAR) _ specifically for the LGS and SSES containments.

(3) This same acoustic methodology was used to calculate Mark III suppression pool boundary responses as well as submerged structure loads in order to answer questions raised regarding the so-called Humphrey cor.cerns. Presentations were made to the NRC using the acoustic methodology to demonstrate that these concerns were ill founded. The regulatory agencies concurred with this conclusion. In order for the NRC to concur, two conditions must have been fulfilled. The first condition is that both the RHR condensation oscillation suppression pool and submerged structure loads were bounded by an existing hydrodynamic load definition. Such a load definition is provided by the design basis methodology for RHR quencher discharge that is described in the Mark III GESSAR II. This first condition is necessary but it is not sufficient. It is necessary because if the RHR condensation oscillation loads were not bounded, it would have been necessary to re-evaluate the containment and all associated equipment for RHR loads. The second condition required was that the acoustic methodology must conservatively and accurately represent the true suppression pool boundary and submerged structure loads generated by RHR condensation oscillation. Were this second condition not fulfilled, this Humphrey

concern could not have been satisfactorily resolved because the calculated acoustic load would not be confidently viewed as representing the actual conditions that might occur. This second condition is therefore necessary but, like the first, it is also not sufficient. However, together these two conditions are both necessary and sufficient for resolution of this Humphrey concern. Consequently, the satisfactory resolution of the Humphrey concerns regarding possible condensation oscillation loads from steam discharges through the RHR heat exchanger relief valve discharge logically implies that these two conditions were accepted. The acoustic methodology is therefore an acceptable approach for assessing the submerged structure loads for the Mark III ECCS strainer.

(4) Another consideration is that adequate conservatism is incorporated into the acoustic methodology. This is realized via the proper development of source functions. Normally, source functions are developed such that they would bound or envelope the measured pressure response data used to specify the hydrodynamic loads. For Mark III ECCS applications, it has been proposed that an effective source be used that will match the design basis suppression pool boundary pressure response rather than test data. Because this design basis load is conservative, source functions generated from this load will consequently also be conservative.

References:

[1] G. K. Ashley II, N. M. Howard, E. Rabin, *An Approach to Chugging*, Task A.16 Phase 2, Mark II Improved Chugging Methodology, Rev. 1, Bechtel Power Corporation, San Francisco Power Division, August 1980, (Proprietary).

[2] G. K. Ashley II, N. M. Howard, E. Rabin, *Mark II Improved Chugging Methodology*, NEDE-24822-P Class III General Electric Company, May 1980; This document was prepared for the Mark II Utility Owners' Group by Bechtel Power Corporation under contract with General Electric Company, (Proprietary).

[3] C. Anderson, *Mark II Containment Program Load Evaluation and Acceptance Criteria*, Generic Technical Activity A-8, NUREG-0808, U. S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, Washington D.C., August, 1981.

[4] Anderson, *NUREG-0808*, loc., cit., p. iii.

[5] Anderson, *NUREG-0808*, loc. cit., Section 2.2.2, p. 2-20, et. seq..

[6] C. Anderson, *Mark II Containment Program Lead Plant Program Load Evaluation and Acceptance Criteria*, Generic Technical Activity A-8, NUREG-0487, Supplement No. 2, U.S. Nuclear Regulatory Commission, Office of Nuclear Reactor Regulation, February 1981.

[7] Anderson, *NUREG-0808*, loc. cit., p. 2-21.

[8] Ibid.

[9] For Mark II-type BWR containments, the Residual Heat Removal (RHR), Core Spray (CS), High Pressure Core Injection (HPCI), and Reactor Core Isolation Cooling (RCIC) systems are collectively referred to as the ECCS.

[10] NRC memorandum to A. Schwencer and W. Butler from D. Houston and J. Kudrick, 13 Mary 1982, Docket Numbers 50-416/417.

[11] "The method of images is restricted to boundaries which are composed of straight lines in two dimensions or planes in three dimensions. ... This limitation on the image method may be expected from an elementary knowledge of geometric optics, for it is well known that the only mirror for which the image of a point source is itself a point is the plane mirror. Of course this does not mean that the image method cannot be applied to other shapes, rather it can be applied only approximately." (Philip M. Morse and Herman Feshbach, *Methods of Theoretical Physics*, McGraw-Hill Book Company, Inc., 1953, New York, p. 820.)

[12] The Mark III Containment Issues Owners Group (CIOG) consists of Grand Gulf Nuclear Station (GGNS), Perry Nuclear Power Plant (PNPP), River Bend Station (RBS), and Clinton Power Station (CPS).

[13] G. K. Ashley II and T. S. Leong, *An Approach to Chugging, Assessment of RHR Steam Discharge Condensation Oscillation in Mark III Containments*, Prepared for the Mark III Containment Issues Owners' Group, Job 16031, Bechtel Power Corporation, San Francisco Power Division, Nuclear Engineering Staff, March 1984, (Proprietary).

[14] Ashley and Leong, loc. cit., p. 5-1, et. seq..

[15] Ashley and Leong, loc. cit., p. 5-12, et. seq..

[16] G. K. Ashley II, "Theoretical Basis for the SciEnTec Acoustic Chugging Methodology," SciEnTec Engineering Calculation SEC-96-01, Science and Engineering Technology, Inc., Los Altos, CA, July 1996.

[17] Ibid.

[18] G. K. Ashley II, "Verification of the SciEnTec *POWER-ACM v1.0* Microcomputer Software," SciEnTec Engineering Calculation SEC-96-02, Science and Engineering Technology, Inc., Los Altos, CA, July 1996.

[19] Ibid.

[20] Acoustic theory applies in all water filled tanks. This fact has been implicitly acknowledged by the NRC when they accepted potential flow methodology for both Mark II and Mark III containments. The potential

flow theory is a special case of the acoustic theory for zero frequency or steady conditions. It is possible to analytically solve the potential flow equation in both cylindrical and annular geometry via an eigenmode expansion. When this eigenmode solution is compared with the method of images solution, a significant load reduction is observed. The eigenmode solution is both appropriate and complete while the method of images solution is neither. This is the origin of this load reduction.