April 3, 2008

MEMORANDUM TO:	Vonna L. Ordaz Assistant for Operations Office of the Executive Director for Operations
THRU:	Michael E. Mayfield, Director **/RA/** Division of Engineering Office of New Reactors
FROM:	Anthony H. Hsia, Chief **/RA/** Engineering Mechanics Branch 1 Division of Engineering Office of New Reactors
	Jennifer Dixon-Herrity, Chief **/RA/** Engineering Mechanics Branch 2 Division of Engineering Office of New Reactors
SUBJECT:	PROCEEDINGS OF THE 16TH ANNUAL INTERNATIONAL CONFERENCE ON NUCLEAR ENGINEERING

This memorandum conveys the enclosed technical paper, which Messrs. C.I. Wu, P.Y. Chen, P. Sekerak, and T. Scarbrough, of the Office of New Reactors, prepared for the International Conference on Nuclear Engineering meeting in Orlando, FL. The enclosed presentation paper is also available in the Agencywide Documents Access and Management System (ADAMS), under Document Accession No. ML080920356. Details regarding the meeting are as follows:

Meeting:	International Conference on Nuclear Engineering (ICONE ’08)
Place:	Orlando, FL
Date:	May 11 - 15, 2008
Presentation:	“Potential Adverse Flow Effects at Nuclear Power Plants”
Presentor:	Mr. Patrick Sekerak

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POTENTIAL ADVERSE FLOW EFFECTS AT NUCLEAR POWER PLANTS

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ABSTRACT

In recent years, the nuclear industry experienced adverse flow effects that caused structural damage to safety-related and nonsafety-related components as a result of flow-induced acoustic resonance in both Boiling Water Reactor (BWR) and Pressurized Water Reactor plants. In particular, fatigue failures and cracks in steam dryers occurred in certain BWR plants during the extended power uprate operation with generation of loose parts that can adversely affect safety-related components within the reactor vessel and the reactor coolant system. The acoustic resonance occurs when the main steam line flow exceeds a critical value such that the vortices over the cavity of the closed side branch pipe are excited by the acoustic modes of the stagnant fluid in the branch. The occurrence of this phenomenon is highly dependent on plant-specific operating conditions and the piping as-built configuration. The U.S. nuclear industry has initiated extensive activities to address this phenomenon in BWR plants. The staff of the U.S. Nuclear Regulatory Commission (NRC) has been monitoring generic industry activities, as well as reviewing the evaluation of potential adverse flow effects that might result from power uprates at current operating plants, and during the design certification and licensing of new reactors. This paper discusses operating experience with adverse flow effects at nuclear power plants from the acoustic resonance phenomenon, industry actions to address and resolve the phenomenon, and NRC staff review activities related to this issue.

1. BACKGROUND

The nuclear industry in the United States (U.S.) has recently experienced adverse flow effects that caused structural damage to safety-related and nonsafety-related components as a result of flow-induced acoustic resonance in both Boiling Water Reactor (BWR) and Pressurized Water Reactor (PWR) plants. In particular, fatigue failures and cracks in steam dryers occurred in certain BWR plants during the extended power uprate (EPU) operation with generation of loose parts that can adversely affect safety-related components within the reactor vessel and the reactor coolant system (RCS). The acoustic resonance occurs when the main steam line (MSL) flow exceeds a critical value such that the vortices over the cavity of the closed side branch pipe are excited by the acoustic modes of the stagnant fluid in the branch. The occurrence of this phenomenon is highly dependent on plant-specific operating conditions and the piping as-built configuration. The U.S. nuclear industry has initiated extensive activities to address this phenomenon in BWR plants. The staff of the U.S. Nuclear Regulatory Commission (NRC) has been monitoring generic industry activities, as well as reviewing the evaluation of potential adverse flow effects that might result from power uprates at current operating plants, and during the design certification and licensing of new reactors.

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[1] This paper was prepared by staff of the U.S. Nuclear Regulatory Commission. It may present information that does not currently represent an agreed-upon NRC staff position. NRC has neither approved nor disapproved the technical content.

2. ACOUSTIC AND HYDRODYNAMIC EXCITATIONS LOADINGS

The vortex shedding phenomenon and its effects on structures submerged in sub-sonic fluid flow streams has long been recognized as an important design consideration. The generation of vortex street wakes and the resulting oscillating pressure waves can produce flow-induced vibration responses in elastic structures with potentially destructive effects on the integrity of a wide range of engineered structures including bridges, refinery towers, offshore oil rigs, process piping components, instrument wells, and heat exchanger internals.

Recent operating experience at U.S. BWR nuclear power plants subjected to increased steam flow rates resulting from EPU operation has revealed fatigue-related degradation of main steam system (MSS) components. Certain isolated combinations of steam system physical arrangements and steam flow velocities have produced flow-excited acoustic pressure wave resonances of sufficient magnitude to cause material fatigue failures in BWR components. These acoustic pressure loads originated within the MSS piping from coincidence of fluid shear wave vortex shedding frequencies with acoustic natural frequencies of stagnant fluid column in branch line connections leading to closed safety relief valves. Previous experiments by Ziada and Shine [1] indicated that the pulsation amplitudes generated by this type of acoustic resonance can be several times higher than the dynamic head in the main process pipe. Figure 1 shows a schematic of a branch standing wave excited by the vortex shedding generated at the EPU flow condition. The resulting large amplitude, high frequency (e.g., >100 Hz) vibrations can cause severe noise and/or vibration problems. This acoustic resonance condition has been identified as a contributory factor initiating localized structural failures in components such as electromatic relief valves (ERVs) and reactor pressure vessel (RPV) steam dryers. Subsequent plant shutdowns were required in order to conduct necessary repairs.

Acoustic and fluid-dynamic excitation causing amplified pressure fluctuations acting on BWR steam dryers can be initiated from several sources within the RPV and the MSS. Steam flowing through and around the dryer within the RPV steam dome volume is subject to turbulent buffeting (i.e., vortex shedding). The resulting steam flow turbulence induces random, oscillating pressures on the dryer surfaces, with the magnitude of the pressures increasing with flow speed as the steam is forced around the dryer and exits the RPV at the MSL nozzles. The turbulent flow also excites large-scale, low frequency (e.g., <100 Hz) acoustic modes in the RPV steam volume. These low frequency acoustic pressure waves, in turn, oscillate against the dryer outer surfaces. Significant acoustic disturbances in the MSS piping downstream of the RPV can propagate through the steam flow upstream and downstream, and radiate pressure waves at higher frequencies (e.g., >100 Hz) back into the RPV steam volume. The radiated pressure waves impinge on the dryer surfaces and can be amplified by acoustic modes in the RPV [2].

Studies to determine the contributions of the various sources of amplified pressure fluctuations affecting BWR steam dryers have included analyses by acoustic circuit and computational fluid dynamics models, scale model tests, and installation of instrumentation on a replacement steam dryer and associated MSS piping. Results of these studies indicate that one significant loading mechanism contributing to steam dryer fatigue damage is the high frequency acoustic coupling between the RPV and the MSS steam volumes. This load mechanism results from the acoustic feedback from energy sources in the MSS, such as closed branch lines, which at certain frequencies, couple with and amplify the turbulent buffeting within the RPV steam volume. The acoustic feedback loading mechanism is highly dependent upon a combination of design conditions, such as MSS configuration (including localized piping design details), main and branch piping diameter ratios, closed branch pipe lengths, RPV internals geometry, and steam flow velocities in the MSS and the RPV steam volumes. Certain combinations of these physical characteristics may result in strong acoustic coupling with amplified pressure oscillations on components, while other combinations of MSS geometries and fluid flow velocities may result in minimal amplification of structural loading due to the absence of acoustic resonance.

Monitoring of MSS acoustic pressures through the use of instrumentation, such as strain gages and pressure transducers, suitably located on MSS piping and prototype RPV internals is important during power ascension at both new nuclear power plants and operating nuclear plants planning power uprates. Appropriate use of instrumentation is a reliable method for detection of the onset of amplified acoustic resonance within MSS acoustic energy sources, which could lead to the acoustic feedback loading mechanism and potential initiation of component degradation [3].

3. OPERATING EXPERIENCE AND INDUSTRY ACTIONS

Operating experience during EPU operation has shown that higher MSL flow can create an acoustic resonance in the steam lines as the flow passes over branch lines. At specific BWR nuclear power plants, this acoustic resonance has created pressure waves that have impacted the steam dryer with sufficient force to cause the stresses in the steam dryer to exceed the material fatigue limits. The acoustic resonance has also caused excessive vibration that has damaged MSL components, such as relief valves and piping.

In June 2002, the cover plate for the steam dryer in Quad Cities (QC) Unit 2 failed following 90 days of operation at EPU conditions. The licensee repaired the steam dryer and returned the unit to EPU operation. About one year later in June 2003, the steam dryer at QC Unit 2 experienced failures of its hood, internal braces, and tie bars. The licensee repaired the steam dryer in QC Unit 2 and again returned the unit to EPU operation. In March 2004 during a refueling outage, the licensee found damage to steam dryer gussets as well as damage to steam dryer welds.

In November 2003, the steam dryer in QC Unit 1 experienced severe cracking following about one year of EPU operation. A 6 by 9 inch piece of the outer bank vertical plate of the steam dryer had broken loose. Damage also was found to an ERV, MSL supports, and the actuator for a high pressure coolant injection motor-operated valve.

As a result of the QC steam dryer failures during EPU operation, the licensee installed new steam dryers in QC Units 1 and 2 with an improved design in May 2005 that are stronger and more streamlined than the original dryers. The licensee placed pressure, strain, and acceleration instrumentation on the Unit 2 steam dryer to determine steam dryer loading directly. The licensee also installed strain gages on the MSLs in QC Units 1 and 2 to measure pressure fluctuations as input to its analysis to calculate steam dryer loading.

Following the return to EPU operation of QC Units 1 and 2 in mid-2005, the actuators for several ERVs in the MSLs in both units experienced severe degradation that was identified in late 2005 and early 2006. As a result of the continuing degradation of plant components from acoustic-generated pressure fluctuations and MSL vibrations, the licensee performed modifications to the inlet lines for the ERVs and main steam safety valves at QC Units 1 and 2. This modification, referred to as an Acoustic Side Branch (ASB) shown in Figure 2, was designed to reduce the MSL pressure fluctuations from acoustic resonance. During subsequent power ascension to EPU conditions, the licensee used MSL instrumentation to determine that the pressure fluctuations were reduced to pre-EPU levels at QC Units 1 and 2.

The original steam dryers in Dresden Units 2 and 3 were similar to the original QC steam dryers. The Dresden steam dryers were subsequently modified to increase their structural capability. The licensee initially operated the Dresden units at EPU conditions for several years without significant damage. However, due to the discovery of steam dryer damage at Dresden in 2005 and 2006, the licensee replaced the Dresden steam dryers with the improved design installed as replacements at Quad Cities.

After a detailed review of the Vermont Yankee EPU request, the NRC determined that the licensee's analysis of potential adverse flow effects for EPU operation was acceptable. In early 2006, the NRC approved EPU operation for Vermont Yankee with specific license conditions and a regulatory commitment for monitoring plant instrumentation during power ascension. The licensee did not identify any severe pressure fluctuations using MSL instrumentation upon EPU power ascension. During a subsequent refueling outage in May 2007, the licensee found indications in the steam dryer that were primarily the result of stress corrosion cracking. The licensee justified continued EPU operation with the dryer indications to be re-inspected in the future.

The licensees for Browns Ferry Units 1, 2 and 3, Hope Creek, and Susquehanna Units 1 and 2 nuclear power plants have proposed license amendments to operate at EPU conditions. Due to the complexity of acoustic resonance phenomena, the scale model testing and the acoustic analysis to address this issue are quite involved and require significant resources. EPU applicants have made substantial improvements in the assumptions and evaluations of potential adverse flow effects. As a result of its analyses, the Susquehanna licensee is replacing the steam dryers in its two units.

In May 2005, the BWR Vessel and Internals Project (BWRVIP) submitted BWRVIP-139, "BWR Vessel and Internals Project, Steam Dryer Inspection and Flaw Evaluation Guidelines." In November 2006, the NRC staff held a public meeting to discuss improvements to the Boiling Water Reactor Owners' Group (BWROG) guidance in NEDO-33159, Revision 0, "Extended Power Uprate (EPU) Lessons Learned and Recommendations." The BWROG prepared Revision 1 to NEDO-33159 in January 2007. Additionally, GE Hitachi and the BWRVIP have notified the staff of their plans to develop separate topical reports that address steam dryer integrated evaluation methodologies.

With respect to PWR operating experience, a shutdown cooling (SDC) isolation valve in the Palo Verde Unit 1 nuclear power plant underwent significant vibration in the Spring of 2001 following restart from a refueling outage when the valve actuator (MOV-651) was vibrating at one inch per second (ips) near 24 Hz. The high vibration occurred on the first SDC isolation valve (UV-0651) off the reactor coolant system (RCS) hot leg. Prior to this incident, the Unit 1 Train A SDC suction line had experienced high vibrations resulting in leaks from suction line drain piping and the failure of the SDC valve. The vibration amplitude increased following the replacement of the steam generators in the Fall 2005 outage. The licensee's hypothesis for vibration condition was the development of pressure pulsations in the suction line resulting from coupling between the fundamental (one-quarter wave length) acoustic frequency of the SDC suction line and the shear layer instability (vortex shedding) due to RCS flow over the SDC suction nozzle. The licensee implemented a modification to decouple the acoustic frequency from shedding modes and pipe modes by relocating the isolation valve toward the RCS. This modification eliminated the acoustic resonance and greatly reduced the vibrations.

4. NRC OVERVIEW AND ACTIONS

The recognition of acoustic resonance as causing adverse flow effects is relatively new to the U.S. nuclear industry. In response, the NRC staff has been performing more detailed reviews and inspections of plant performance and power uprate license amendment requests with respect to adverse flow effects on plant structures, systems, and components. The NRC staff has also been updating its standard review plans and regulatory guidance to incorporate the evaluation of potential adverse flow effects at operating plants requesting power uprates, and in design certification and license applications for new reactors.

The NRC regulations in Appendix A to Part 50 of Title 10 of the *Code of Federal Regulations* (10 CFR Part 50, Appendix A) include General Design Criteria 1, 2, 4, and 10, which require that structures and components important to safety be constructed and tested to quality standards commensurate with the importance of the safety functions performed and designed with appropriate margins to withstand effects of anticipated operational occurrences and normal operation, natural phenomena like earthquakes, postulated accidents including loss-of-coolant accidents, and events and conditions outside the nuclear power unit. Section 55a in 10 CFR Part 50 incorporates by reference the American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel Code* regarding design and inspection requirements for plant components within the scope of the Code. The NRC regulations in 10 CFR Part 52 reference portions of 10 CFR Part 50 for implementation by applicants for design certifications and combined licenses (COLs) of new reactors.

NRC Standard Review Plan (SRP) Section 3.9.5, "Reactor Pressure Vessel Internals," describes the staff review of reactor pressure vessel internals, including structural and mechanical elements inside the reactor vessel.

One of the specific areas of review is the basis for the design of the reactor internals, including potential adverse flow effects of flow-excited vibrations and acoustic resonances. The analytical or experimental methods for determining the loading conditions and their validation are reviewed along with the random uncertainties and bias errors. Guidance for staff review of the consideration of potential adverse flow effects by applicants for power uprates, and design certifications or operating licenses, is provided in Appendix A to SRP Section 3.9.5. The review of dynamic analyses, input forcing functions, and response to loadings (including those due to adverse flow effects) is addressed in SRP Section 3.9.2, “Dynamic Testing and Analyses of Systems, Structures, and Components.”

With respect to regulatory guidance, the NRC staff revised Regulatory Guide (RG) 1.20, “Comprehensive Vibration Assessment Program for Reactor Internals during Preoperational and Initial Startup Testing,” in March 2007 to incorporate guidance for the consideration of potential adverse flow effects in nuclear power plants. The staff included lessons learned from the evaluation of steam dryer failures at BWR nuclear power plants. The staff also provided information on potential adverse flow effects outside of the reactor vessel for consideration by applicants and licensees of BWR and PWR plants. In addition, the staff included guidance for COL applicants on the consideration of potential adverse flow effects for new nuclear power plants in RG 1.206 (June 2007), “Combined License Applications for Nuclear Power Plants (LWR Edition).”

The NRC staff will continue to monitor industry activities on a generic and plant-specific basis for appropriate consideration of potential adverse flow effects in current operating nuclear power plants requesting power uprates, and in the review of design certifications and operating licenses for new nuclear power plants.

5. CONCLUSIONS

The evaluation of potential adverse flow effects in nuclear power plant systems is important for (1) nuclear power plants being designed, constructed, and initially operated, and (2) current nuclear plants considering operation at EPU conditions. These evaluations need to ensure that adverse effects of hydraulic loadings and acoustic resonance are avoided not only for reactor internals (including the steam dryer in BWR plants), but also for other plant components (such as MSL safety relief valves). The staff reviews the consideration of potential adverse flow effects on plant systems by applicants for a design certification of a new reactor or an operating license for a nuclear power plant, and licensees of operating BWR or PWR nuclear power plant proposing a power uprate license amendment. The U.S. nuclear industry is continuing its efforts to address potential adverse flow effects at nuclear power plants.

6. REFERENCES

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2. Hambric, S.A., Mulcahy, T.M., Shah, V.N., et. al., “Flow-Induced Vibration Effects on Nuclear Power Plant Components Due to Main Steam Line Valve Singing, Proceedings of the Ninth NRC/ASME Symposium on Valves, Pumps and Inservice Testing, NUREG/CP-0152, Vol. 6, pp. 3B:49-3B:69, July 2006.

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4. NRC Information Notice 2002-26, Failure of Steam Dryer Cover Plate After a Recent Power Uprate, September 11, 2002 and Supplement 2, Additional Flow-Induced Vibration Failures after a Recent Power Uprate, January 9, 2004.

5. GE Nuclear Energy Services Information Letter (SIL) No. 644, BWR/3 steam dryer failure, August 21, 2002, and Revision 1, BWR Steam Dryer Integrity, November 9, 2004.

6. NUREG – 0800, Standard Review Plan (SRP) for the Review of Safety Analysis Reports for Nuclear Power Plants,” March 2007, U.S. Nuclear Regulatory Commission, Washington, DC.

7. Regulatory Guide 1.206, “Combined License Applications for Nuclear Power Plants (LWR Edition).,” June 2007, U.S. Nuclear Regulatory Commission, Washington, DC.

8. Regulatory Guide 1.68.1, “Preoperational and Initial Startup Testing of Feedwater and Condensate Systems for Boiling-Water Reactor Power Plants (Rev. 1, ML070260029),” March 2007, U.S. Nuclear Regulatory Commission, Washington, DC.

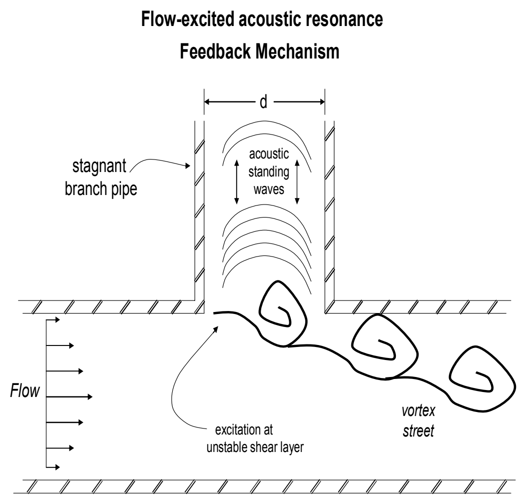

Figure 1 - Vortex shedding frequency excites acoustic standing wave in the stagnant branch pipe to cause the acoustic pressure fluctuation and the increased component vibrations.

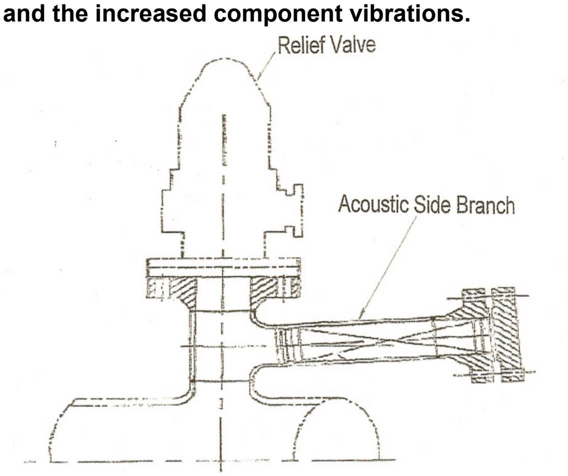

Figure 2 - Acoustic Side Branch (ASB) modification increases the effective length of the standing pipe decreasing the frequency of the acoustic standing wave that reduces the pressure oscillation and the component vibration when the vortex shedding and the standing wave frequencies are no longer coupled.