Acoustic Resonance in Nuclear Boiling Water Reactors

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Introduction

- Some nuclear power plants with boiling water reactors (BWRs) have experienced significant acoustic resonance in their reactor and steam systems.
- In some cases, acoustic resonance has resulted in damage to plant components in reactor pressure vessel (RPV) and steam lines.
- As a result, nuclear power plant applicants and licensees evaluate potential adverse flow effects during initial plant design and startup of new reactors, and for power uprates of operating reactors.

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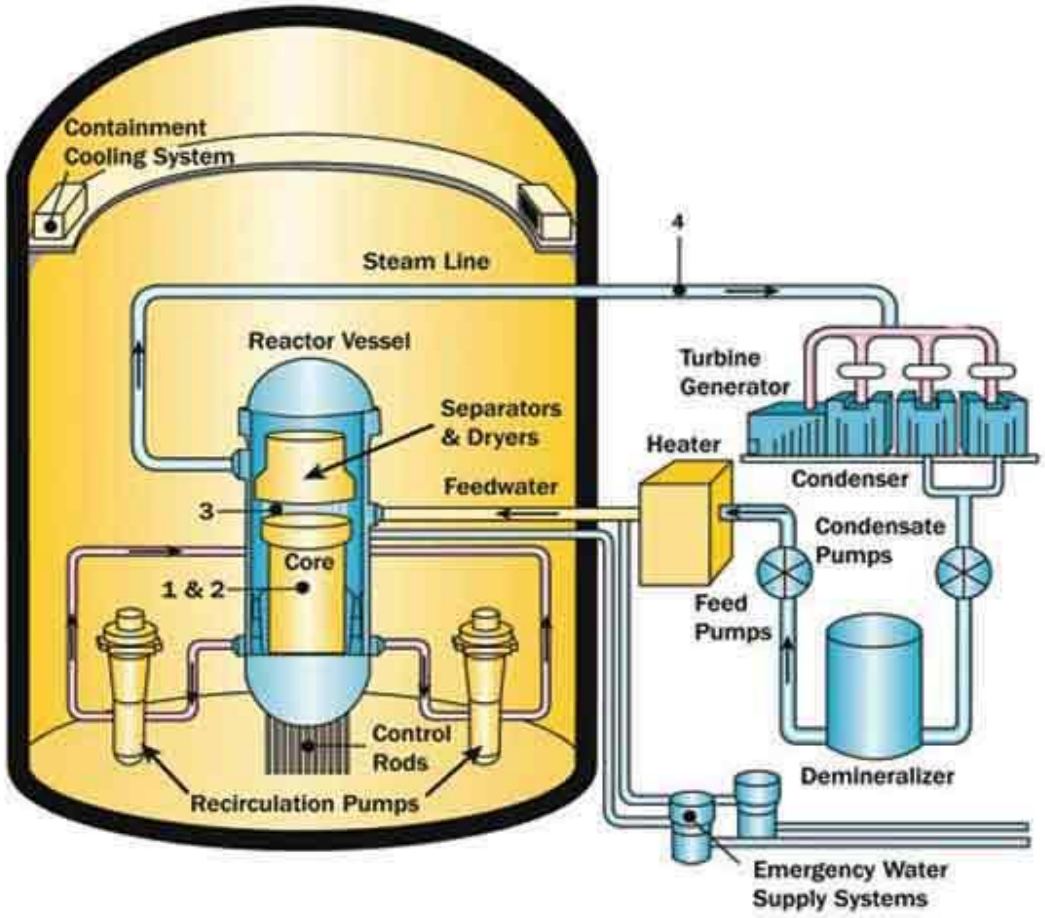
Boiling Water Reactor



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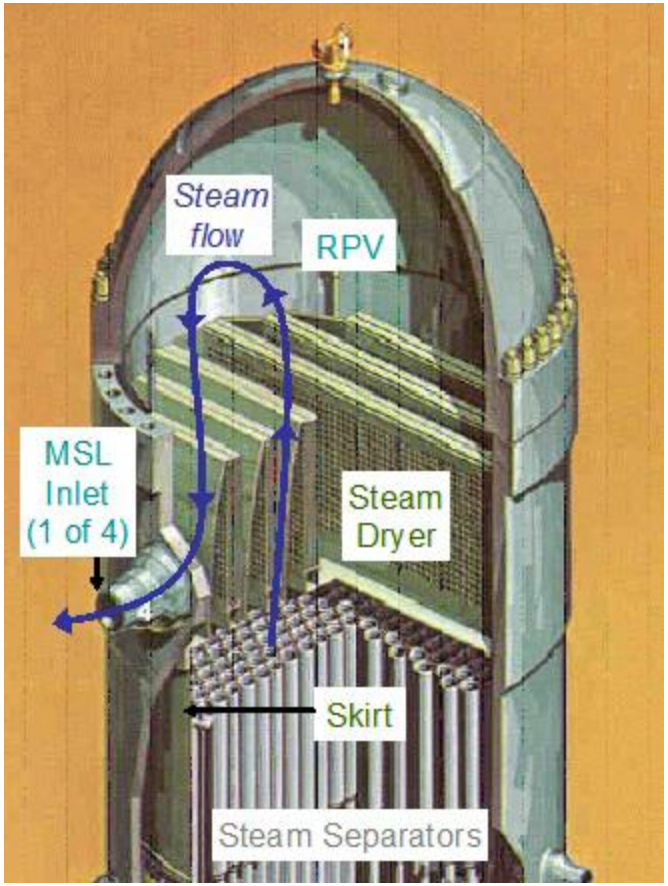
Boiling Water Reactor Pressure Vessel



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Acoustic Resonance

- Turbulent steam flow in RPV can excite large-scale, low-frequency acoustic modes
- Steam flow over safety valves (SVs), safety relief valves (SRVs), and other branch lines can couple with high-frequency acoustic mode of branch steam column
- Pressure fluctuations with low and high frequencies in RPV and steam lines can impact steam dryer
- Acoustic resonance has caused severe vibration of steam line components

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Strouhal Analysis

- Strouhal number can be defined as fD/U, where f is frequency at which shear layer oscillates, D is side-branch opening diameter, and U is steady flow speed of shear layer
- Strouhal numbers can vary with pipe diameter ratio, distance from upstream elbows, and acoustic damping
- Strouhal number chart developed by Ziada and Shine to predict critical flow velocity at which acoustic resonances may be initiated

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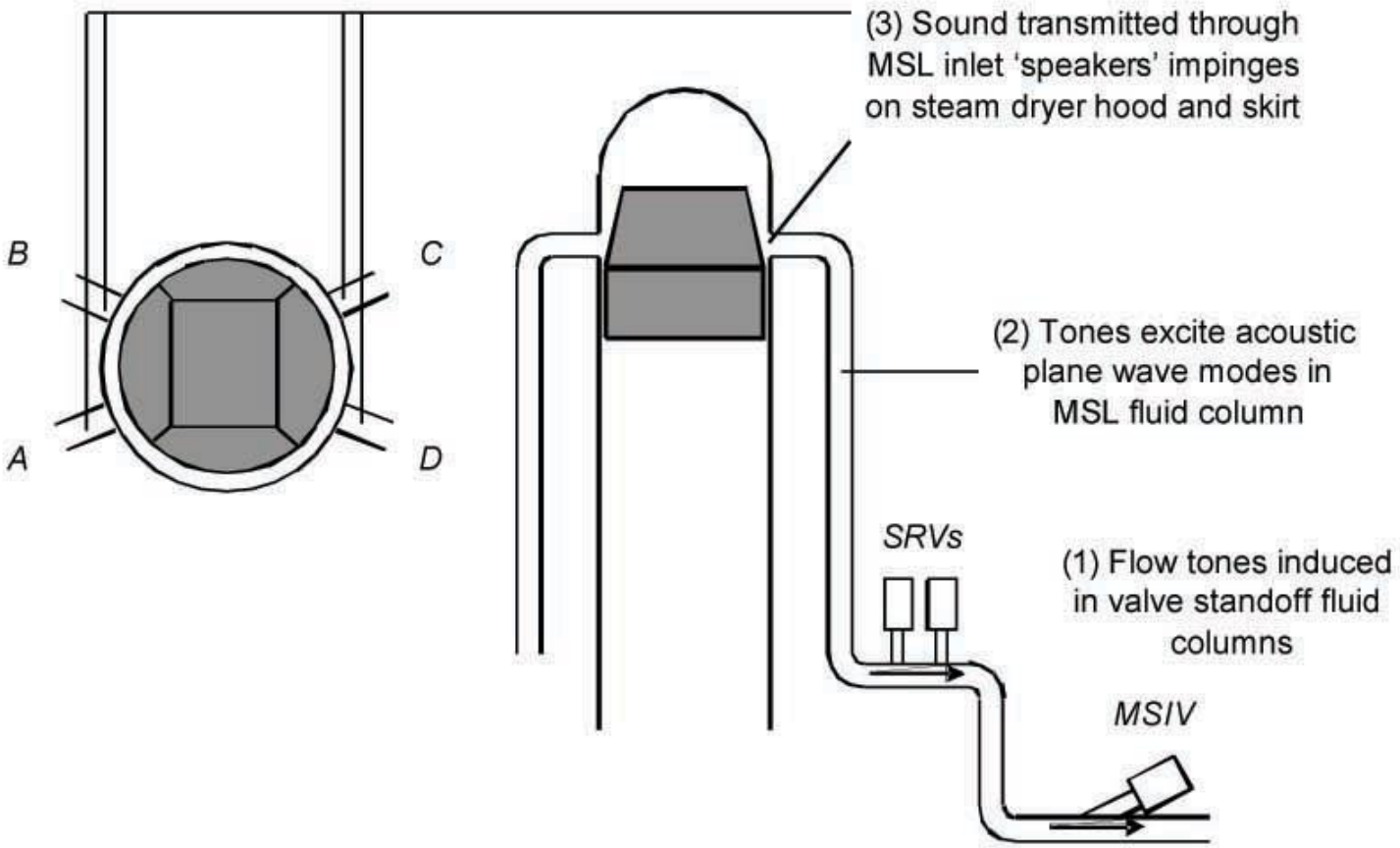
Valve Tone Excitation in BWR Steam Lines



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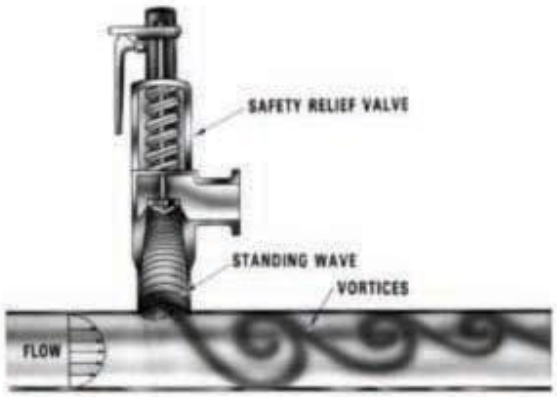
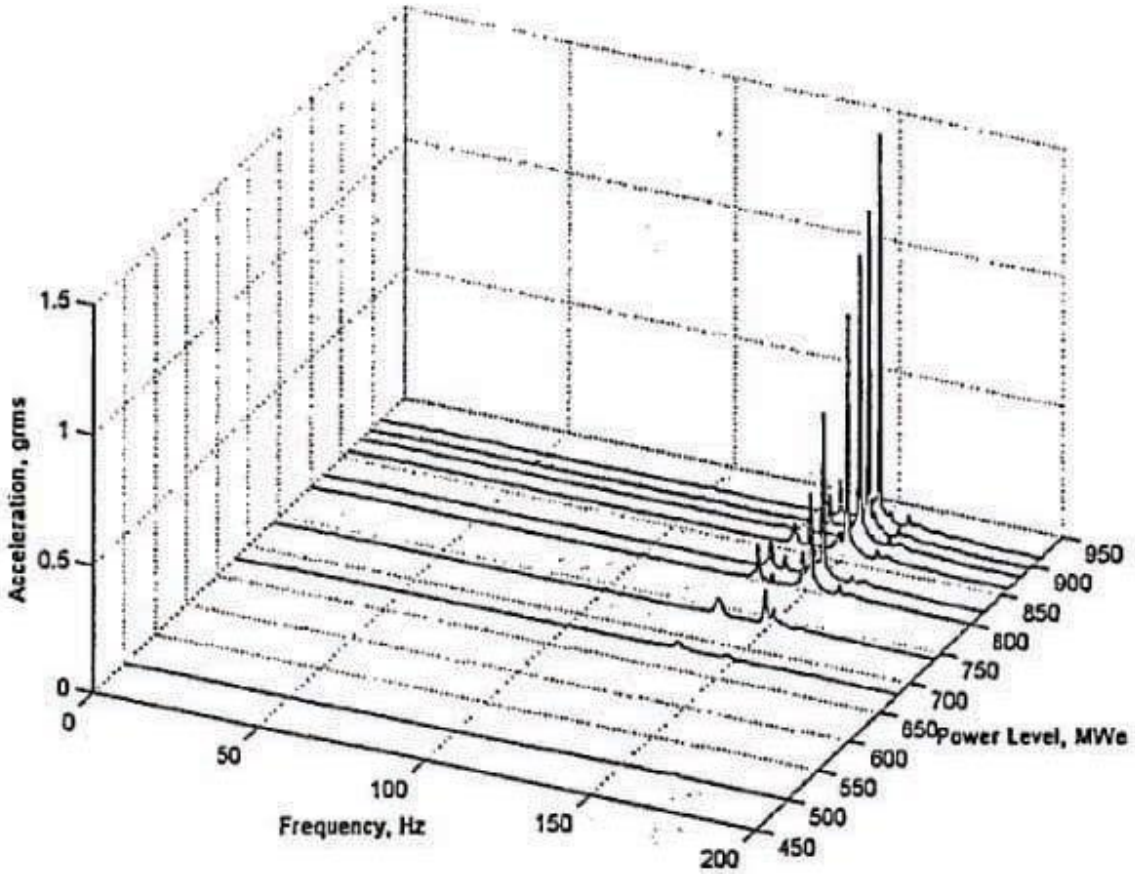
"Singing" Safety Relief Valve





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U.S. BWR Unit 2 Steam Dryer Experience

- In June 2002, steam dryer cover plate failed after 90 days of power uprate operation (117% original power).
- In June 2003, steam dryer hood failed after additional 300 days of power uprate operation.
- In March 2004, steam dryer cracked after additional 8 months of power uprate operation.

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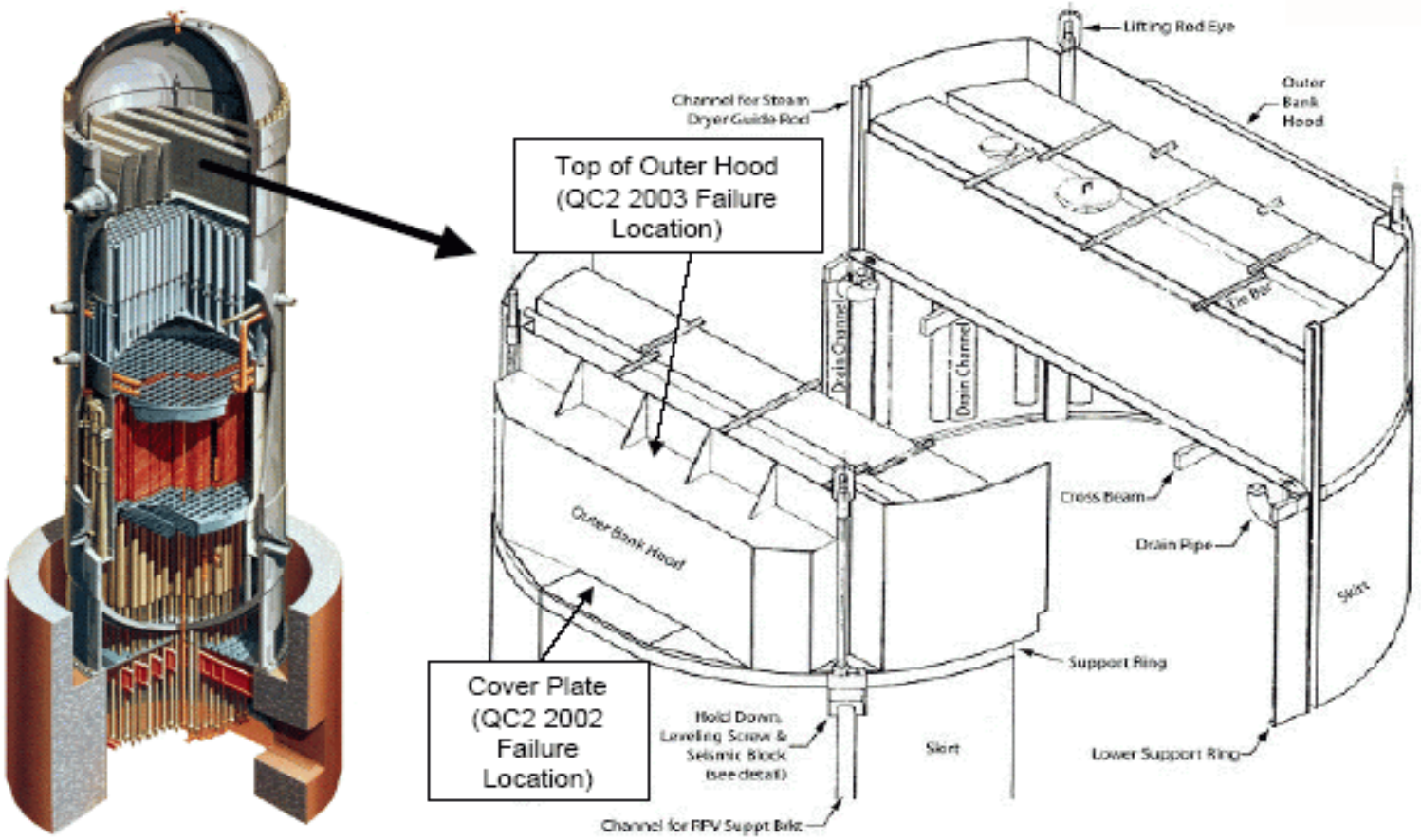
BWR Unit 2 Steam Dryer Failures (2002 and 2003)



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U.S. BWR Unit 1 Steam Dryer Experience

- In November 2003, steam dryer hood failed after 1 year of power uprate operation (117% original power).
- 6x9 inch plate of steam dryer outer bank lost in reactor coolant and steam system
- Damage also found to steam line components

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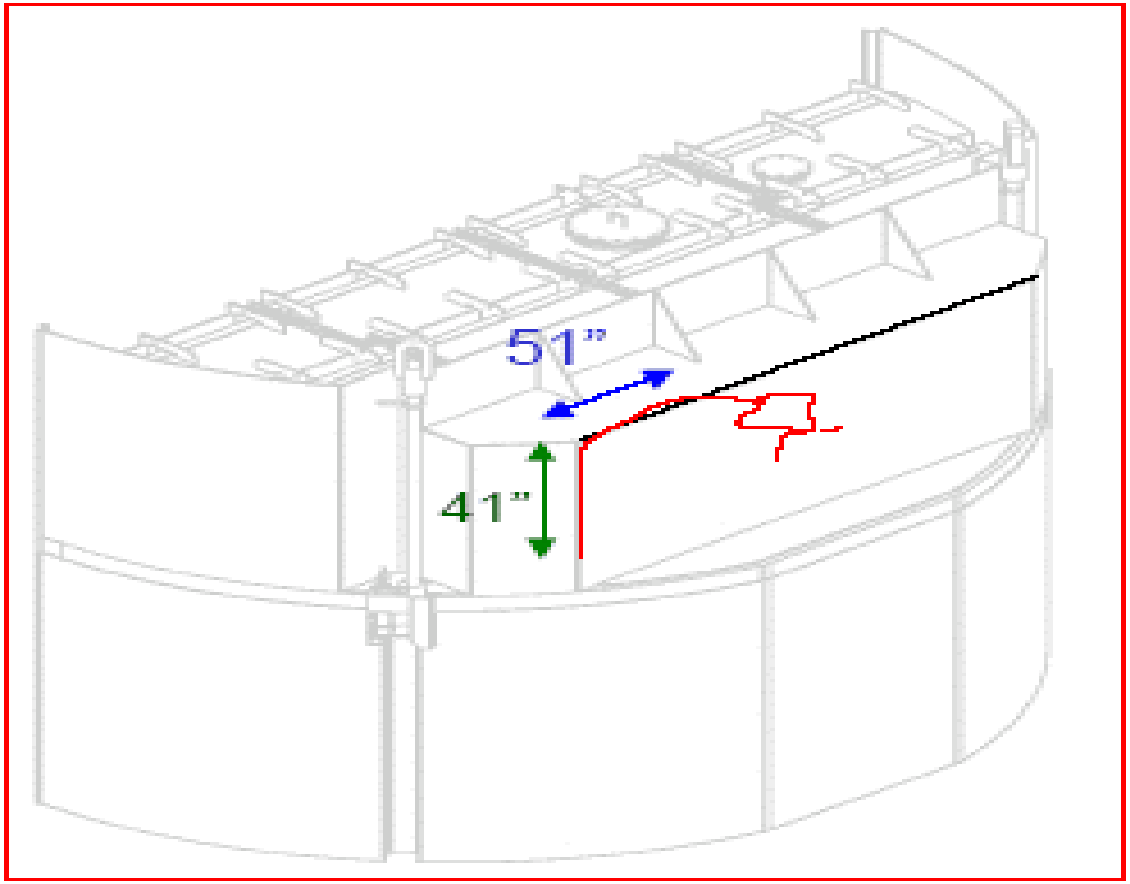
BWR Unit 1 Steam Dryer Failure (Nov. 2003)



270° Side

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Example BWR Steam Dryer Replacement

- In Spring 2005, BWR Units 1 and 2 steam dryers replaced with improved design
- Unit 2 steam dryer instrumented with pressure sensors, strain gages, and accelerometers
- BWR steam lines instrumented with strain gages to calculate pressure load on Unit 1 steam dryer based on Unit 2 benchmark
- Highest pressure load of 0.65 psi^2/Hz (168 dB) on steam dryer during BWR power uprate operation

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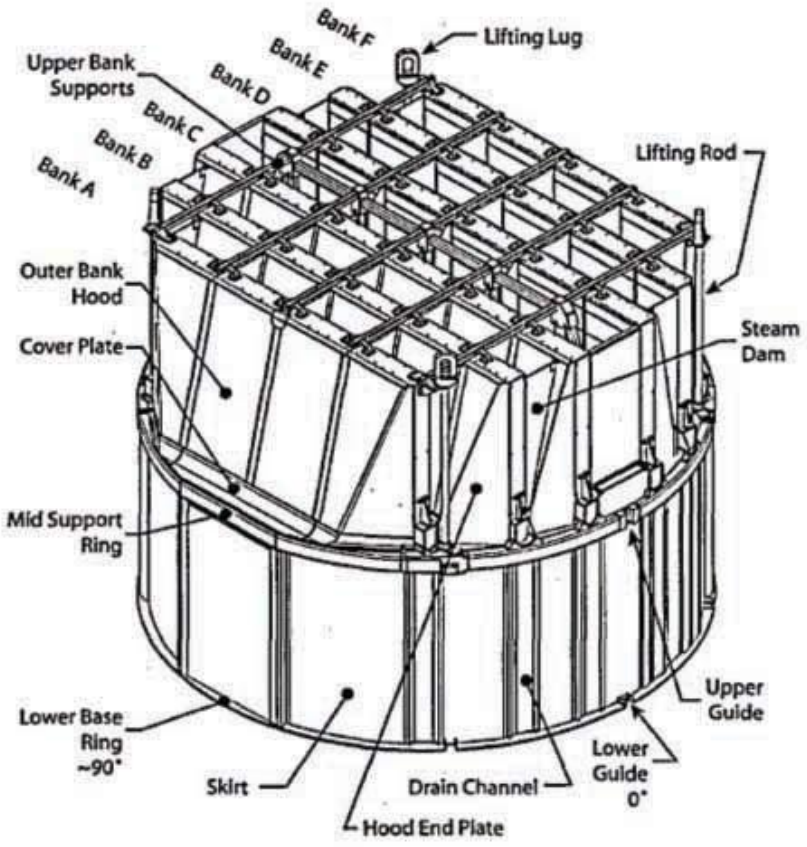
BWR Unit 2 Replacement Steam Dryer



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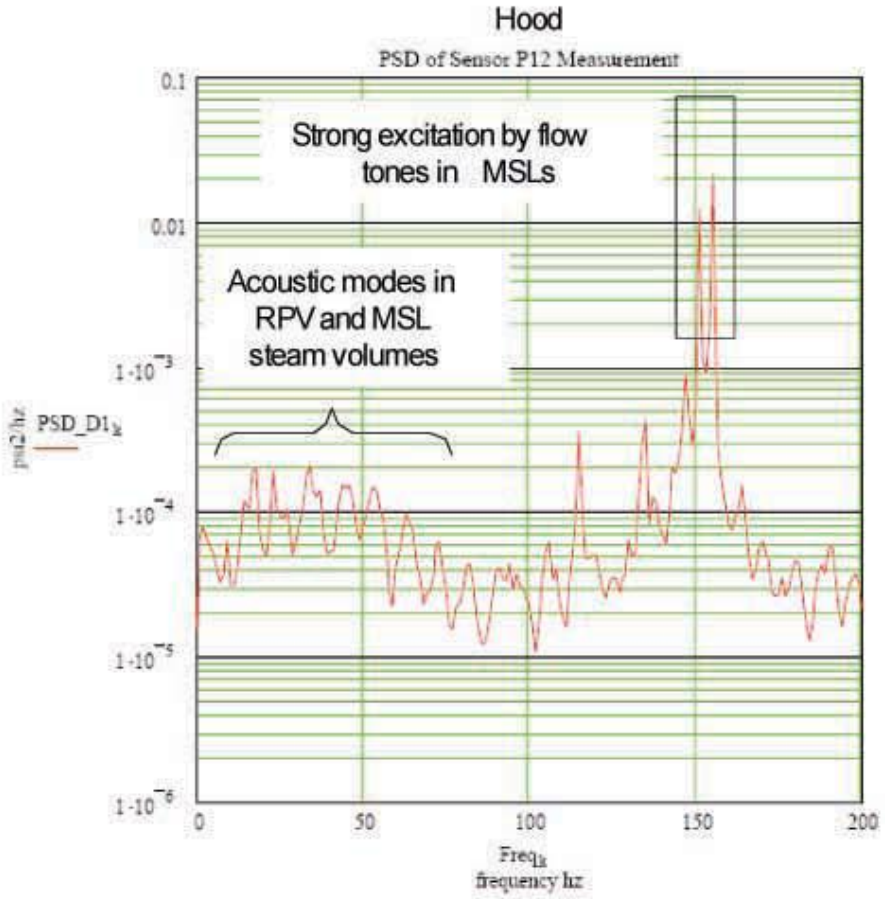
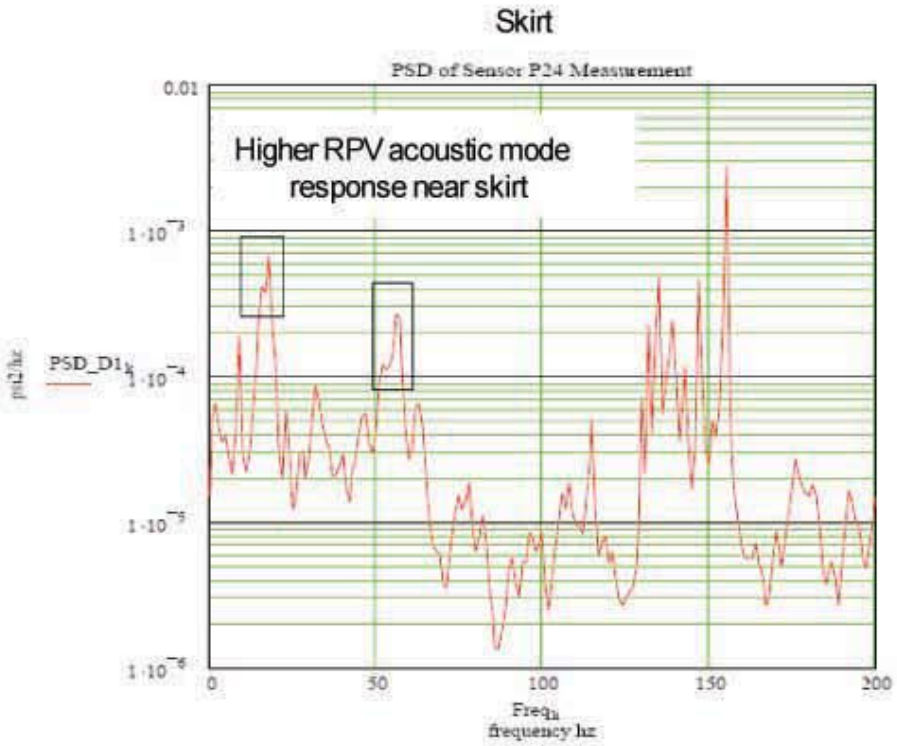
BWR Unit 2 Steam Dryer Pressure Spectral Densities (790 MWe Original Licensed Power Level)





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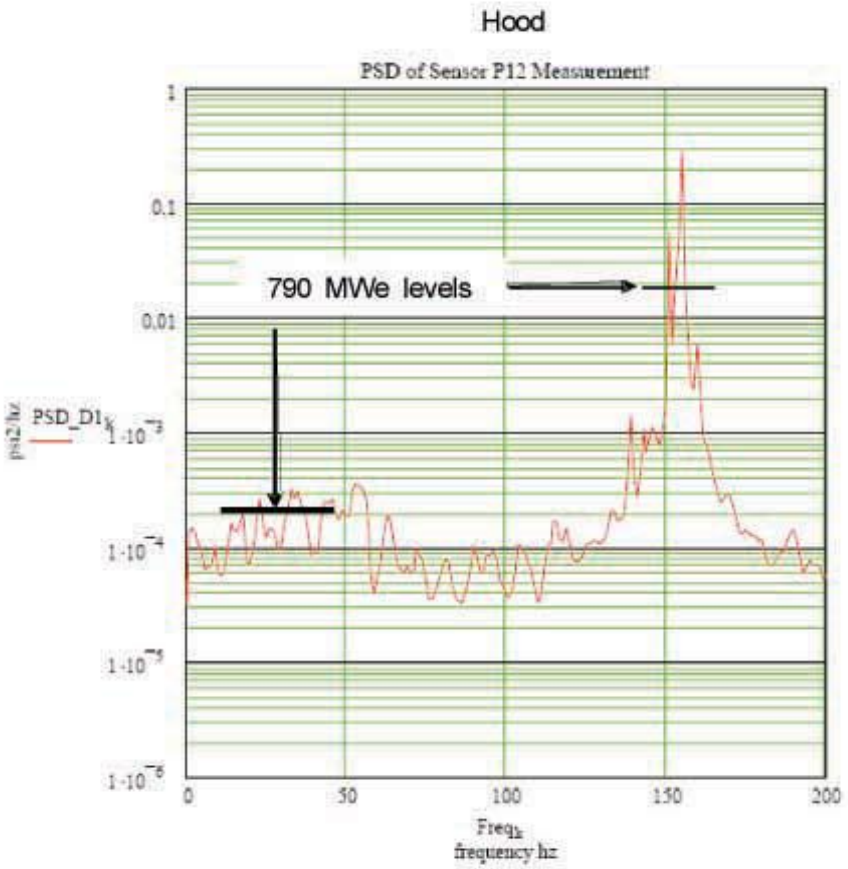
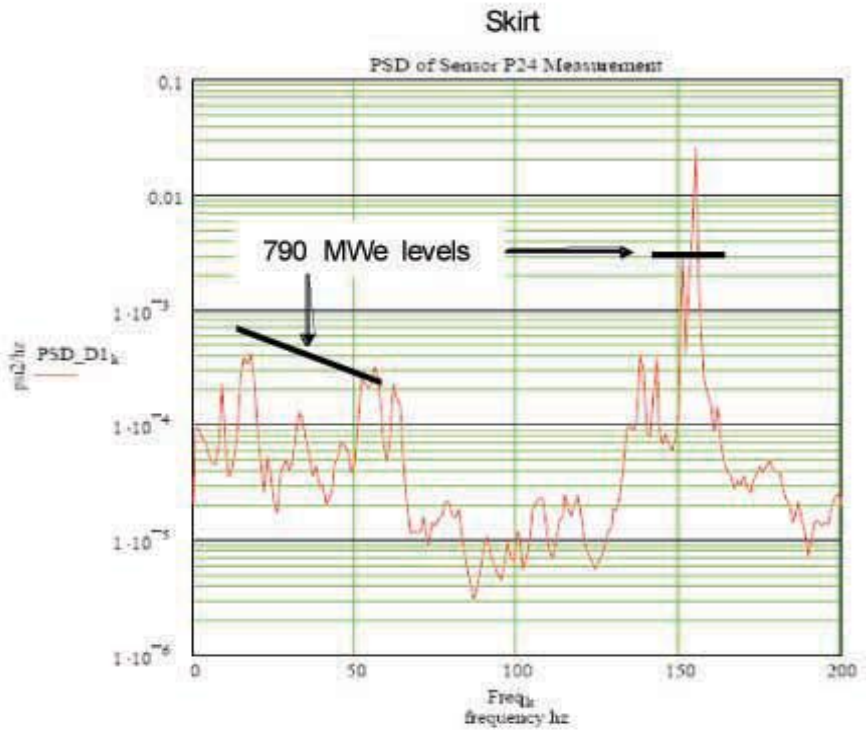
BWR Unit 2 Steam Dryer Pressure Spectral Densities (930 MWe Power Uprate Power Level)





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Safety Relief Valve Damage

- In late 2005, SRV in BWR Unit 2 experienced short circuiting
- Unit 2 reduced power for inspection with broken SRV actuator parts found
- Both BWR units shut down for inspection with damage found to several SRVs
- SRV damage caused by severe vibration from acoustic resonance
- As a result, licensee initiated program to eliminate acoustic resonance from BWR steam lines

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BWR Acoustic Resonance Elimination

- Analysis indicated that SV and SRV branch line length could not be reduced sufficiently to cause acoustic resonance to occur at steam velocity beyond operating conditions
- Licensee installed deadleg T-connection pipe in SV and SRV branch lines to effectively lengthen branch line and cause acoustic resonance to occur at lower steam velocity with reduced pressure fluctuations
- Upon reactor restart, measurements indicated significant acoustic resonance sources eliminated

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Acoustic Resonance Lessons Learned

- NRC Regulatory Guide 1.20 revised to provide guidance on potential adverse flow effects
- Operating BWRs proposing power uprate and new BWR applications evaluate potential adverse flow effects from acoustic resonance
- Vendors have developed proprietary methods using data from replacement steam dryers and steam lines to determine pressure load and stress on steam dryers
- BWR licensees monitor steam dryer and steam line data during power ascension and implement steam dryer inspection program during refueling outages

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References

- S.A. Hambric, et al., “Flow-Induced Vibration Effects on Nuclear Power Plant Components Due to Main Steam Line Valve Singing,” U.S. NRC NUREG/CP-0152, Volume 6, Proceedings of the Ninth NRC/ASME Symposium on Valves, Pumps and Inservice Testing, 2006.
- G. DeBoo, et al., “Identification of Quad Cites Main Steam Line Acoustic Sources and Vibration Reduction,” 2007 ASME Pressure Vessels and Piping Division Conference, Proceedings of PVP2007, July 2007.
- S. Ziada, “Flow-Excited Acoustic Resonance in Industry,” Institute of Thermomechanics, Flow Induced Vibration, Zolotarev & Horacek, eds., Prague, 2008.