When is a BWR like a Coca-Cola bottle?

Power uprates in boiling water reactors (BWRs) increase steam flow through the main steam line in proportion to the uprate. This increased flow had unexpected consequences at Quad Cities 1&2 BWRs in Illinois when they were uprated in 2002. The increased steam flow created an unexpected acoustic resonance, resulting in damage to the steam dryer. Although Quad Cities replaced both units' steam dryers and made other modifications to prevent further occurrence, greater understanding of the stresses imposed by a power uprate is needed to reduce the likelihood of future events. John Hosler of the USA's Electric Power Research Institute helped develop a report about steam dryer integrity demonstration methods (BWRVIP-194) currently being reviewed by the US Nuclear Regulatory Commission (NRC). He maintains that steam dryer problems are not always connected with upgrades.

John Hosler: What we've seen in the industry to date is occasional instances of stress corrosion cracking of steam dryers before and after uprates. Significant fatigue cracking, however, is rare. Where we've seen significant steam dryer issues, the primary cause has been acoustic resonance. The industry has not experienced any events comparable to those at Quad Cities, but the NRC now requires licensees to conduct detailed analysis and testing to demonstrate steam dryer integrity for uprates above 2%.

In an uprate, particularly in a BWR, the flow down the main steam lines increases proportionally to the power. This increased flow results in an increase in the turbulent flow loading, which goes up with the square of the velocity, so a 20% uprate can result in a 44% increase in turbulent flow loading on the steam dyer. As the flow proceeds down the main steam lines, it passes by standpipes that hold the safety relief valves. As the flow passes the entrance to the standpipes, it sheds vortexes off the upstream lip of the standpipe entrance. If the vortexes are shed at a frequency matching the quarter-wave standing acoustic frequency of the relief valve standpipe, a resonance is set up. It's like blowing over the top of a Coke bottle. If you blow slowly, nothing happens. If you blow faster, you get a tone; if you blow even faster, the tone goes away. There is a sweet spot that creates the tone. Similarly, when you increase power in a BWR by just the right amount, it's possible to create an analogous 'tone.' The acoustic pressures build up, get transmitted back up the main steam line to the vessel, where they impinge on the steam dryer. Over a period of time, these fluctuating pressures can lead to structural damage.

NEI: What are the general risk factors of acoustic resonances in BWRs?
JH: Acoustic resonance in main steam lines is primarily a function of steam flow and standpipe geometry. Based on the length and diameter of the main steam line standpipes, you can determine whether a resonant condition is expected at power uprate conditions. Such screening is recommended prior to any power uprate.

NEI: Does this mean that uprates require a steam dryer replacement?
JH: There are other reasons why the utility might want to replace a steam dryer. Increasing the flow rate changes the efficiency of moisture removal. You might want to install a more efficient steam dryer so that you get less moisture carrying through to the turbine blades. Several plants, such as Vermont Yankee and Hope Creek, have recently executed uprates without changing steam dryers. There is not a one-to-one correspondence between power uprates and steam dryer replacements.

NEI: What is the fix?
JH: There is no single fix, as it depends on multiple factors. At Quad Cities, devices to mitigate the resonance phenomenon, called acoustic side branches, were installed. These side branches change the standpipe frequency and contain a material that damps acoustic pressure. These devices have proven very effective in mitigating acoustic pressure loading within main steam lines and on the steam dryer.

NEI: How are jet pumps affected by resonances?
JH: Jet pump degradation can result from several potential flow-induced vibration phenomena. In jet pumps, the mixer portion contains an elbow leading to a nozzle, and because of the high velocity flow in the nozzle, fouling can occur that requires cleaning. Partly to facilitate such cleaning, jet pumps are composed of two major components; the upper part (mixer) can be removed. There is a slip joint there where the upper part fits into the lower part with a small annular gap. A wedge holds the mixer in.

Over the years, we have seen an increasing frequency and severity of wear of the wedge against the bracket (wedge wear) resulting from flow-induced vibration phenomena. There are three main causes of wedge wear. One is the general turbulence of water flowing through the pump, which results in a fretting action between the wedge and a bracket. The second relates to the pressure pulse created each time the recirculation pump blade passes; this excess pressure can cause additional vibration. The third, called slip joint leakage flow, is an effect that has been investigated most extensively in recent years. There is a 5-10mm radial gap at the slip joint. Pressure inside the pump is a little higher inside than out. Leakage flow can cause a hydroelastic instability. When the difference in pressure is enough, it causes an instability, a high-level vibration in the pump. That doesn't happen often...

NEI: Is the phenomena connected to uprates?
JH: In some ways. Most uprates don't result in a higher core flow, so flow wouldn't increase. But by putting more energy into the water that is fed in the core, you get more bubbling in the core, and there is more core resistance, and that is felt as back pressure. That theoretically increases the pressure in the jet pump, even if the flow didn't increase.

We currently have a full-scale low-flow test programme under way to study the slip joint leakage flow instability phenomena. A planned upgrade to the test rig will enable us to operate at prototypical flow rates to also investigate the effects of turbulent flow and pump vane passing pressure fluctuations on jet pump vibration. We're also working with the BWR fleet to collect data on the level of jet pump damage they've experienced, core loads, back pressures, etc. To date, most plants have not seen significant jet pump damage. In those that have, few have had uprates. It may be that different fuel types cause an increased core back pressure, pushing plants closer to the slip joint instability threshold. ■