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1. Introduction

This white paper provides a brief overview of Boiling Water Reactor (BWR) steam dryer design; the fatigue failures that occurred at the Quad Cities (QC) nuclear power plants and their root causes; a history of BWR Extended Power Uprates (EPUs) in the USA; and a discussion of steam dryer modifications/replacements, alternating stress mechanisms on steam dryers, and structural integrity evaluations (static and alternating stress).

2. Steam Dryers, Past EPU Evaluations, and Fatigue Failures

In BWR nuclear power plants, the heat generated by the reactor fuel boils water in the reactor pressure vessel (RPV). Steam rises from the boiling water and travels vertically through tube banks, called steam separators, to remove moisture. Above the steam separator, a perforated hooded structure, called the steam dryer (see images in Figure 1), further removes moisture from the steam. The steam exits the dryer and collects at the top of the RPV, then flows through four main steam lines (MSLs) to turbines which generate electricity. Although steam dryers in BWR nuclear power plants are not classified as safety-related components, the steam dryer must maintain its structural integrity to prevent loose parts from adversely affecting components with safety-related functions. For more details on BWR plant operation, see the U.S. Nuclear Regulatory Commission (NRC) BWR Reactor Concepts Manual (available on the NRC public website).

2.1 Quad Cities Steam Dryer and MSL Valve Failures

By June 2004, the NRC had approved EPU operation for 11 BWR nuclear power plants, with uprates ranging from 6.3% for Monticello in 1998 to 20% for Clinton in 2002. Seven of the 11 nuclear power plants have experienced no major problems related to their steam dryers or MSL components under EPU operating conditions. However, four plants - QC Units 1 and 2 (QC1 and QC2) and Dresden Units 2 and 3, with uprates in the range of 17 to 18% - experienced significant increases in flow-induced fluctuating loading and vibration in the MSLs and within the RPV. The increased fluctuating loading and vibration damaged the steam dryers and valves in those nuclear power plants.

In 2004, the NRC issued a summary of steam dryer degradation that had occurred up to that time [NRC, 2004]. General Electric Hitachi (GEH), the BWR designer, issued a Services Information Letter (SIL) and a supplement to owners of BWR plants [GEH, 2006], which recommended more frequent visual inspections of steam dryers and provided specific inspection locations. Images of steam dryer failures from the SIL are replicated in Figure 2, and summarized here.

Figure 1. Top – Cutaway of BWR RPV and steam dryer (left), and curved hood dryer (right); Bottom: schematic of typical original BWR steam dryer: assembly (left), single panel (right). From [Hambric, et. al., 2006 and US NRC Reactor Concepts Manual]

In June 2002, a large cover plate on the outside of the original QC2 steam dryer broke, and pieces of the plate were carried by the steam through the MSLs. Before and after the failure, increased moisture content in the MSL steam was identified, indicating that cracks and/or holes had occurred in the steam dryer that were allowing wet steam to flow directly into the MSLs. High cycle fatigue was identified as the cause of the QC2 steam dryer failure, and Exelon, the QC licensee, installed thicker cover plates and used stronger welds to repair the steam dryer. However, in May 2003, moisture carryover in the MSL steam at QC2 increased significantly again, and the licensee shut down the plant in June 2003 so the steam dryer could be inspected. The inspection found large cracks through the walls of the outer bank of the QC2 steam dryer. Also, several braces and tie bars on the top of the steam dryer had cracked.

In October 2003, the moisture content in the MSL steam of QC1 began to increase. In November 2003, the licensee shut down QC1 for a steam dryer inspection. Among the findings, the QC1 steam dryer inspection revealed that a portion of the outer bank hood had broken loose (about 16 cm x 23 cm x 1.3 cm).

The QC licensee initially addressed the cracking and structural failures by installing stronger and more robust steam dryers in each unit. The QC2 replacement steam dryer was instrumented to provide measured data to validate proposed steam dryer loading models (described in section 3). At QC1 and QC2, the MSLs were also instrumented in an attempt to quantify steam dryer loading via remote measurements. The steam dryer and MSL data were used, along with structural finite element models, to ensure that the stress levels for the QC1 and QC2 steam dryers were within acceptable limits. These measurement and analysis procedures have evolved over several more recent EPU applications and are described in general terms in this white paper.

Although the steam dryer degradation was being addressed, valves in the MSLs at QC1 and QC2 continued to experience significant vibration as a result of acoustic resonance at the EPU conditions. In November 2003, an electromatic relief valve (ERV) on a QC1 MSL, along with several MSL support clamps and tie-back supports, failed. In January 2006, several ERVs in the QC1 and QC2 plants were found to be significantly degraded due to damage induced by strong loading fluctuations and vibrations. Although, as noted above, steam dryers do not perform safety-related functions, safety relief valves in MSLs at BWR nuclear power plants are responsible for relieving reactor overpressure and must remain functional.

There are many sources of alternating stress in BWR steam dryers [Hambric et. al., 2006]. The root cause of the QC steam dryer fatigue failures was the coupling of a shear-layer instability mode resulting from flow over standpipes on MSL valves combined with acoustic resonances within those standpipes. The resulting alternating loads at the flow-excited resonance frequencies were extremely high. These resonances are well understood [Ziada and Lafon, 2014; Baldwin and Simmons, 1986; and Ruggles, 2009].

Following the relief valve degradation at QC1 and QC2, the licensee initiated a program to minimize the acoustic resonance loading on the steam dryers and MSL components. This program resulted in the installation of Acoustic Side Branches (ASBs) on the MSL valve

standpipes in QC1 and QC2 as well as in Dresden Units 1 and 2 [DeBoo, et al., 2007]. The ASBs shifted the acoustic resonance frequencies and eliminated the feedback with the shear layer instability. As a result, the acoustic resonance loads and vibration on the steam dryer and MSL valves were essentially eliminated. Since the installation of the ASBs, no adverse flow effects have occurred in the steam dryers or MSL valves at QC1 or QC2, or Dresden Units 1 and 2.

Over the years since the first QC steam dryer failure, the NRC has issued several information notices that described BWR steam dryer failures and monitoring programs [NRC 2002, 2003, 2004, and 2013].

Figure 2. Schematic and photos of cracks and subsequent loose parts in original QC dryers (from GEH SIL 644, 2006).

2.2 Current NRC Steam Dryer Structural Integrity Requirements

Following the QC steam dryer failures, the NRC has required that BWR nuclear power plant licensees requesting power uprates evaluate their existing or replacement steam dryers for structural integrity, including high cycle fatigue life. Licensees typically apply the fatigue limits in American Society of Mechanical Engineers (ASME) *Boiler and Pressure Vessel Code* (BPV Code), Section III, Subsection NG. For Austenitic stainless steels at temperatures up to 425 °C (850 °F), typical of BWR steam dryers, the high cycle fatigue limit at 10^{11} cycles is provided in Figure I-9.2 and Table I-9.2 of the ASME BPV Code. Earlier versions of the ASME fatigue limits included multiple curves (A, B, and C), to account for mean stress from various sources, such as gravity loading or residual stresses caused during manufacturing. The multiple fatigue curves have been eliminated; current practice is to use a single value, independent of mean and/or residual stress.

In addition to the fatigue assessment, nuclear reactor structural components are designed to satisfy the ASME BPV Code stress limits for normal operation (Service Level A), upset conditions (Service Level B), emergency conditions (Service Level C), and faulted conditions (Service Level D). Loads due to gravity, thermal expansion, pressure differences, and transients (including seismic events and sudden valve closures) are evaluated. Each service level includes several loading combinations to ensure that worst-case conditions are considered. These loading conditions are typically evaluated with static stress analyses, with multipliers to account for dynamic amplification where necessary.

Service Level A, B, C, D and fatigue evaluations are performed for steam dryer structural components, and for the welds that connect the individual components. Typically, alternating stresses in welds are the most limiting because the welds proceed along joints where stresses are magnified. Fatigue strength reduction factors (FSRFs) are applied, depending on the type of weld (partial penetration, full penetration, fillet, etc.) and local geometry. Weld quality reduction factors are applied to the nominal Code service level stress limits, depending on the extent of nondestructive examination of the welds.

Licensees of several US BWR plants have been granted EPU license amendments subsequent to the QC steam dryer failures. Some licensees have reinforced their steam dryers to withstand the increased dynamic loads resulting from the higher flow at EPU conditions. Others have replaced their steam dryers with new heavier, stronger models. Many of the new steam dryers have been instrumented with surface strain gages, accelerometers, and pressure transducers for further validation of the estimated loading on the steam dryer, and benchmarking of the applied structural response analysis method. Table 1 summarizes the US BWRs that have been granted power uprates since 2005. The BWR designs range from GE BWR/3 to GE BWR/6. Each reactor design uses a different steam dryer, as shown in the schematic provided in GE SIL 644, and replicated in Figure 3. Not shown in Figure 3 is the current GEH dryer design for the BWR/6, which is based on the curved hood design, but with stronger welds and thicker plating. Two plants have replaced their original GE dryers with hexagonal 'Nordic' steam dryers, used previously in Norway and Sweden.

Plant	Plant Design/Containment	Original License	EPU granted	Original Steam Dryer type	Modifications/ Replacement
Dresden 2/3	BWR3/Mark I	1970	2004	GE Square hood	Replaced with GE stiffened slanted hood, ASBs installed
Monticello (MNGP)	BWR3/Mark I	1971	2014	GE Square hood	Replaced with Westinghouse 3 ring octagonal 'Nordic' dryer
Quad Cities 1/2 (QC)	BWR3/Mark I	1972	2004	GE Square hood	Replaced with GE stiffened slanted hood, QC2 dryer instrumented, ASBs installed
Vermont Yankee (VY)	BWR4/Mark I	1972	2006	GE Square hood	Modified original dryer
Browns Ferry 1,2,3 (BFN)	BWR4/Mark I	1973	Pending	GE Slanted hood	Replaced with GE stiffened curved hood, BFN3 dryer instrumented
Peach Bottom 2,3 (PBAPS)	BWR4/Mark I	1973	2014	GE Slanted hood	Replaced with Westinghouse 3 ring octagonal 'Nordic' dryer, PB2 dryer instrumented
Hope Creek (HCGS)	BWR4/Mark I	1986	2008	GE Curved hood	Modified original dryer, in-air damping measured on spare HC original dryer
Susquehanna 1,2 (SSES)	BWR4/Mark II	1983/1985	2009	GE Curved hood	Replaced with GE stiffened curved hood, instrumented
Laguna Verde 1,2 (LV)	BWR5/Mark II	1990/1995	2014/2015	GE Curved hood	Modified original dryers
Nine Mile Point (NMP2)	BWR5/Mark II	1987	2011	GE Curved hood	Modified original dryer following discovery of nonconservative dryer loading errors
Grand Gulf (GGNS)	BWR6/Mark III	1984	2012	GE Curved hood	Replaced with GE stiffened curved hood, instrumented

Table 1. US BWR EPU Summary.

Figure 3. Cross-sectional views of steam dryer hood regions (taken from GE SIL 644). The RPV walls and MSL inlets are to the left of the figure.

3. Steam Dryer Loading

In general, a BWR nuclear power plant licensee may demonstrate that its steam dryer meets the ASME BPV Code stress limits based on simple static finite element (FE) structural analysis. However, alternating stresses induced by (a) turbulent steam flow, (b) flow-induced resonances in valve standpipes, (c) flow-excitation of acoustic waves within the RPV, (d) structural loading caused by strong tones at Reactor Recirculation Pump (RRP) vane passing frequencies (VPFs), and (e) pulsations from boiling water along the steam dryer skirt, are not easily estimated. Vendors and contractors have developed different approaches for estimating peak alternating stress in BWR steam dryers based on measurements of in-plant pressures, vibrations, and strains.

With the instrumentation installed on the QC2 replacement steam dryer, Exelon measured the surface pressures on the steam dryer at several locations (see photograph of the instrumented QC2 replacement dryer in Figure 4). Samples of the surface pressure spectra are shown in Figure 5 for the steam dryer hood and skirt. The spectra are Fast Fourier Transforms (FFTs) of the measured pressure time histories, and reveal several strong loading peaks.

Below about 60 Hz, low frequency ‘humps’ are evident in the spectra. In particular, the skirt pressures have strong peaks that are associated with acoustic resonances of the steam within the RPV that surrounds the steam dryer. However, the strong tones near 150 Hz caused the fatigue failure of the original QC steam dryers. These tones are associated with flow over valve standpipe openings which ‘locked in’ to acoustic resonances of the steam within the standpipes.

Figure 4. Instrumented QC2 replacement steam dryer with pressure transducers on the hood (top) and skirt (bottom). From source material previously published in [NUREG/CP-0152, Hambric et. al, 2006].

Figure 5. Example of steam dryer surface pressure spectra, left – hood; right – skirt. From source material previously published in [NUREG/CP-0152, Hambric et. al, 2006].

Low frequency sources within the RPV

The flow through a steam dryer and within the RPV is highly non-uniform, generating strong, large-scale turbulent vortices. This turbulence excites large-scale acoustic cavity modes within the RPV. Ohtsuka [2006] discusses typical RPV acoustic modes for an advanced BWR design. The cavity acoustic modes oscillate against the steam dryer walls, causing strong low frequency excitation. Typical flow velocities and examples of these modes are shown in Figure 6, taken from a compressible computational fluid dynamics (CFD) calculation for a US BWR nuclear power plant. The modal amplitudes, and, therefore, the steam dryer loads, are particularly strong in the narrow annulus between the steam dryer skirt and RPV wall, causing the strong peaks in the skirt pressure spectra shown in Figure 5.

As the turbulent steam enters the MSLs from the RPV, it contracts through a sudden mean flow gradient. The mean flow gradient depends on the difference in the slower steam velocity upstream of the MSLs and the faster flow within the MSLs. As a result of the flow gradient, strong acoustic pulsations emanate from each MSL inlet, and back-propagate onto the steam dryer surface, sometimes amplified by the internal RPV cavity modes. The sound waves also travel down the MSLs, where they may be measured by external strain gage arrays.

MSL valve resonance

The steam flow velocity increases significantly within the MSLs to 50-70 meters per second (m/s) depending on the mass flow and the MSL cross-sectional area. Although the safety relief valves and other valves in the MSLs may be over 40 feet from the RPV, shear layer instability modes can occur over the valve standpipe openings at certain flow rates. In some cases, these modes couple with and are significantly amplified by fundamental acoustic resonances in the valve standpipes (see [Baldwin and Simmons, 1986; Ruggles, 2009; Ziada and Lafon, 2014] for details on this mechanism). The acoustic waves that emanate from this 'lock-in' condition are extremely strong, and propagate back along the MSL steam column, and radiate acoustic waves into the RPV steam volume. These waves impinge on the steam dryer surfaces, particularly on the outer hood regions adjacent to the MSL inlets, causing vibration and alternating stresses. In the original QC dryers, these stresses were higher than the material fatigue limits, and the steam dryers cracked and eventually failed.

Figure 6. Typical flow rates within an RPV (top) and low-order RPV steam volume acoustic resonances (bottom); analyses of a BWR nuclear power plant using FLUENT compressible flow CFD analysis. From source material previously published in [NUREG/CP-0152, Hambric et. al, 2006].

Steam dryer loading inferred from MSL strain gage array measurements

The acoustic waves within the MSLs at low frequencies propagate only along the axis of the piping. These ‘planar waves’ pulsate against the MSL walls in phase around the circumference, generating fluctuating structural hoop strains. The strains may be measured directly using arrays of external strain gages. The gages are oriented circumferentially, and several are used around the MSL circumference, as shown in Figure 7. The gages are summed coherently, thereby filtering out strains caused by beam-like bending, or cross-sectional ovaling motion (common near elbows). Strain-to-pressure conversion factors are applied, based on the pipe cross-sectional properties, and the steam impedance. Szasz, Fujikawa, and DeBoo summarize and demonstrate the MSL strain gage acoustic measurement methodology [2006]. Variations on this method have been used in many US BWR nuclear power plants.

The strain gage arrays not only measure acoustic waves emanated by valve resonances, but also measure sound waves related to acoustic pressures within the RPV. If two MSL strain gage arrays are installed, the direction of acoustic sound propagation may be inferred along with the wave amplitudes. Waves traveling toward the RPV are generally caused by flow over valve standpipes, and waves traveling away from the RPV are evidence of sound within the RPV, along with waves reflected from the impedance discontinuity at the MSL inlet. In either case, the wave amplitudes may be used to infer equivalent acoustic sources at the MSL inlets, which may be applied to acoustic models of the RPV steam volume. This ‘remote sensing’ method therefore may be used to estimate all acoustic loads on a steam dryer.

Inferring MSL acoustic waves requires a simple one-dimensional (1D) acoustic plane wave model of the steam ‘columns’ within the MSLs. A methodology called ‘Acoustic Circuit Modeling’ (ACM) developed by Continuum Dynamics Incorporated (CDI) has been used to analyze several US BWR nuclear power plants, as has an updated tool called ACE (Acoustic Circuit Enhanced), developed by Westinghouse [Forsyth and Longoni, 2010]. GEH uses a procedure called Plant Based Load Evaluation (PBLE). In all of these approaches, the ‘acoustic circuits’ within the MSLs are modeled using simple analytic formulas of the acoustic wave equation, and the propagating wave amplitudes are computed using the well-known Two Microphone Method (TMM) [Seybert, 1977, 1988; Abom and Boden, 1988]. Assumed mass density, sound speed, and damping are applied to the models, along with the measured MSL acoustic pressures at two locations.

Figure 7. MSL strain gage arrays (left) and typical individual and summed 'hoop' strain, from QC2. From source material previously published in [NUREG/CP-0152, Hambric et. al, 2006].

RPV Steam Volume Acoustic Modeling

While the acoustic waves in the MSLs are 1D, acoustic waves in the RPV steam volume are three-dimensional (3D). Numerical methods have been used to model the sound waves propagating throughout the RPV steam volume and impinging on the outer and inner surfaces of steam dryers. Speed of sound and mass density are assumed, and are sometimes different within and outside the steam dryer. Based on the sound speeds, wavelengths are estimated at the upper limit of the frequency range of interest. The wavelengths are used to specify minimum mesh density, which must use at least six subdivisions to represent an acoustic wavelength. Acoustic damping within the steam must also be modeled. The damping within steam may be estimated using guidance from various sources [Karplus, 1961; Petr, 2004]. The 3D RPV models are coupled to the MSL 1D models at the MSL inlets, thus enforcing continuity of particle velocity. The fluctuating pressures and particle velocities at the MSL inlets drive the 3D RPV model, and steam dryer loading is computed.

RRP VPF loading

Centrifugal RRP's generate strong tonal excitation, both structure-borne and fluid-borne, at their VPFs, which is the product of the shaft rotational rate and the number of impeller vanes. When multiple RRP's operate, the tones usually occur at slightly different frequencies, causing 'beating' of the signals. The beating leads to constructive interference between the tones, and much higher loading amplitudes.

There is no direct physical connection between the RRP and the steam dryer in a BWR nuclear power plant. However, the VPF tones are strong enough to propagate throughout the reactor coolant system (RCS) and impact the steam dryer. In one BWR nuclear power plant, steam dryer fatigue cracking was linked to strong VPF tones. To account for the loads induced by VPF tones, some licensees have inferred the alternating stresses using on-dryer strain gage and accelerometer measurements. Other licensees have measured the vibration amplitudes of operating pumps and estimated, using engineering structural analyses, the transmission of vibration through the RCS to the steam dryer mounts. The transmitted loads are then applied to the steam dryers at the mounts, and alternating stresses are computed.

For RRP with Variable Frequency Drives (VFDs), the drive frequency and VPF vary over a fuel cycle, with the frequencies typically increasing later in the cycle to increase core flow rate to account for reduced fuel rod thermal output. For RRP with VFDs, the full range of possible frequencies and load amplitudes needs to be considered. In that the RRP VPF loads are not correlated with load related to steam flow, their contributions to alternating stresses are typically included via the Square Root of the Sum of the Squares (SRSS) method.

4. Steam Dryer Structural Modeling and Stresses

FE modeling approach

Steam dryer structural vibrations and alternating stresses are computed using FE analysis. Models are typically constructed with shell elements which include both bending and in-plane (membrane) effects. Solid elements may be used to represent thick sections, and need to be properly coupled with shells to ensure that all moments are properly transferred. Structural material properties are based on operating temperature and pressure conditions; elastic moduli are lower than at room temperature. Vibration damping of 1% of critical damping is typically applied to steam dryer models. For time-domain analysis methods, Rayleigh damping may be applied. In that Rayleigh damping varies with frequency, the lower and upper anchor frequencies are chosen to bracket any limiting load frequencies. The damping between the anchor frequencies is less than 1%, which is conservative.

Convergence of the structural FE modeling is typically demonstrated using mesh discretization studies of selected critical sections. In particular, convergence of stress concentration regions is shown. To reduce calculation time, bias corrections have been applied to models that are not fully converged. The bias corrections are based on convergence studies of model sections.

Some structural regions may need detailed submodeling, usually with models constructed entirely of solid elements. Boundary conditions from the global shell model are applied along the edges of the solid submodel, along with the external loads. Submodeling may lead to higher or lower stresses, depending on the application.

For the global shell model, FSRFs are applied to welds, in accordance with ASME BPV Code, Section III, Subsection NG. Most new steam dryers have only full penetration welds, in

order to avoid the higher FSRFs associated with partial penetration and fillet welds. Per Subsection NG, the allowable stress limits for Service Levels A, B, C, and D sometimes are reduced by applying weld quality factors, when the welds are not sufficiently inspected to ensure high quality. For high quality welds, no reduction is required.

FE structural analyses

FE structural analyses are performed to determine the stress in the steam dryer. The loading over a steam dryer is computed using an acoustic model, and is mapped to the nodes and elements of the steam dryer FE structural model. The acoustic and structural model meshes rarely align, requiring interpolation of the loading onto the structural model. Some commercial FE software, such as ANSYS, have automated load mapping capabilities. The mapped and original loading are compared to ensure that there are minimal errors in the load mapping process.

Comparisons of measured and simulated steam dryer structural response have shown that the simulated resonance frequencies are generally accurate to within $\pm 10\%$. Because the most important steam dryer loads are tonal (at valve flow-induced resonance frequencies or RRP VPF), several analyses are performed to assess the worst-case alignment of these loads and steam dryer resonances. The time histories of the steam dryer loading are compressed and expanded to span the $\pm 10\%$ resonance frequency uncertainty. Based on the assumed 1% vibration damping, it is reasonable to subdivide the $\pm 10\%$ span into increments of 2.5%. Therefore, the steam dryer stresses are computed for nine load cases, and the highest stresses are compared to allowable fatigue limits.

End-to-end benchmarking

The overall steam dryer alternating stress calculations rely on several components, each of which has its own bias error and uncertainty. These include, for example, instrumentation and measurements, acoustic modeling, and structural modeling. Rather than attempting to quantify all of the individual bias errors and uncertainties and combine them, it is more appropriate for a licensee to perform end-to-end benchmarking, based on vibration and strain measurements on a steam dryer in an operating BWR nuclear power plant. The simulated and measured vibrations and strains are compared, and end-to-end bias errors and uncertainties are computed, sometimes over subregions of the steam dryer. The bias errors and uncertainties are applied to the simulated vibration and strains, and again compared to measured levels to demonstrate the corrected simulations are bounding and conservative. These bias errors and uncertainties may be applied to steam dryers in other BWR nuclear power plants, with the measured steam dryer serving as a valid prototype as discussed in NRC Regulatory Guide 1.20, "Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Startup Testing."

Alternating stress ratios

To evaluate the stress margin availability for a BWR steam dryer, Alternating Stress Ratios (ASRs) are computed at all highly stressed regions. At a minimum, the five most highly stressed locations on the upper steam dryer, and the five most highly stressed locations on the lower steam dryer are evaluated. The ASRs are based on the high cycle fatigue limit of the steam dryer material, which is 13,600 pounds per square inch (psi) for Type 304

Austenitic stainless steel. The Minimum Alternating Stress Ratio (MASR) needs to be greater than unity. In cases where MSL data are used to evaluate the loading on the steam dryer, an MASR of 2.0 is typically considered to be appropriate.

Inspections

The BWR nuclear industry has developed guidance for visual inspection of steam dryers during refueling outages based on their design and operating conditions. The BWR nuclear power plant licensee evaluates all indications found in the steam dryer for disposition by repair or leave as-is until the next inspection. Repairs may include welding, crack growth prevention, or partial or full panel replacement.

5. Summary and Conclusions

This white paper describes the general methods used by nuclear power plant licensees to assess the alternating stresses in steam dryers in operating BWR nuclear power plants. In-plant measurements, either of on-dryer pressures, structural response, and/or MSL internal acoustic pressures, are combined with numerical models of the acoustic waves in the steam within the RPV and MSLs to compute steam dryer loading. The loading is applied to steam dryer structural FE models to compute alternating stresses, which are compared to material fatigue limits. End-to-end benchmarking may be used to compute bias error and uncertainty corrections. These procedures have been used successfully by many BWR nuclear power plant licensees to provide reasonable assurance of the structural integrity of their existing or replacement steam dryers. Following application of these evaluation procedures, no significant fatigue cracking has been observed in steam dryers in BWR nuclear power plants that have been granted power uprates by the NRC.

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