Enclosure 8

MFN 13-091

GE Hitachi Nuclear Energy, "ESBWR Steam Dryer – Plant Based Load Evaluation Methodology – PBLE01 Model Description," NEDO-33408, Rev. 5, Class I (Non-Proprietary), December 2013

Public Version

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GE Hitachi Nuclear Energy

NEDO-33408
Revision 5
December 2013

Non-Proprietary Information-Class I (Public)

ESBWR STEAM DRYER -
PLANT BASED LOAD EVALUATION METHODOLOGY
PBLE01 Model Description

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Summary of Changes
NEDE-33408P, Revision 5

Changes from Revision 4 to Revision 5	
Page / Section	**Description of Changes**
Title Page	Updated document to reflect the new revision. Updated document headers.
1.0	Description of overall analysis process deleted and replaced with a reference to the full description contained in NEDE-33313P.
4.5.4	Revised to describe Figures G-14 through G-25 showing low frequency comparison of peak measured sensor amplitude to peak adjusted sensor amplitudes. Addressed LF response/sensors.
5.0	Deleted reference to PBLE01 "Method 1". Terminology no longer used to describe the method.
6.0	Updated Reference [14] and added Reference [15].
Appendix G	Added new figures, Figure G-14 through G-25 showing low frequency comparison of peak measured sensor amplitude to peak adjusted sensor amplitudes

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Acronyms and Abbreviations

ABWR	Advanced Boiling Water Reactor
AG	Accelerometer Gauge
ASME	American Society of Mechanical Engineers
BWR	Boiling Water Reactor
CAD	Computer-Aided Design
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
COL	Combined License
EPU	Extended Power Uprate
ESBWR	Economic Simplified Boiling Water Reactor
FE / FEM	Finite Elements / Finite Element Method / Finite Element Model
FIV	Flow Induced Vibration
FRF	Frequency Response Function
FSAR	Final Safety Analysis Report
GDC	General Design Criteria
GEH	GE Hitachi Nuclear Energy
GGNS	Grand Gulf Nuclear Station
HF	High Frequency
Hz	Hertz
LF	Low Frequency
MASR	Minimum Alternating Stress Ratio
MSL	Main Steam Line
NRC	Nuclear Regulatory Commission
PBLE	Plant Based Load Evaluation
PLTP	Previous Licensed Thermal Power
PSD	Power Spectral Density

PT	Pressure Transducer
PWR	Pressurized Water Reactor
RG	Regulatory Guide
RMS	Root Mean Square
RPV	Reactor Pressure Vessel
SF	Singularity Factor
SG	Strain Gauge
SRF	Stress Reduction Factor
SRV	Safety / Relief Valve
3D	Three Dimensional

Abstract

A methodology, termed Plant Based Load Evaluation (PBLE01), is presented for defining the fluctuating loads that are imposed upon the Economic Simplified Boiling Water Reactor (ESBWR) reactor steam dryer. The PBLE01 load definition can be applied to a structural finite element model of the steam dryer in order to determine the steam dryer alternating stresses. The overall ESBWR steam dryer methodology is applied to an operating BWR replacement steam dryer as an example of the successful implementation of the methodology.

1.0 INTRODUCTION

As a result of steam dryer issues at operating Boiling Water Reactors (BWRs), the US Nuclear Regulatory Commission (NRC) has issued revised guidance concerning the evaluation of steam dryers [1]. Analysis must show that the dryer will maintain its structural integrity during plant operation due to acoustic and hydrodynamic fluctuating pressure loads. This demonstration of steam dryer structural integrity comes in three steps:

(1) Predict the fluctuating pressure loads on the dryer,

(2) Use these fluctuating pressure loads in a structural analysis to qualify the steam dryer design, and

(3) Implement a startup test program for confirming the steam dryer design analysis results as the plant performs power ascension.

The PBLE (Plant Based Load Evaluation) is an analytical tool developed by GEH to perform the prediction of fluctuating pressure loads on the steam dryer. This report provides the theoretical basis of Version 01 of the PBLE method (PBLE01) that will be applied for determining the fluctuating loads on the ESBWR steam dryer, describes the PBLE01 analytical model, determines the biases and uncertainties of the PBLE01 formulation, and describes the application of the PBLE01 method to the evaluation of the ESBWR steam dryer.

This report also provides an example implementation of the FIV analysis methodology. The overall structural evaluation and power ascension testing for the ESBWR steam dryer is described in Section 1.0 of Engineering Report, NEDE-33313P (Reference 14). The overall finite element stress analyses are supported by NEDE-33312P (Reference 15), which describes the development of the ESBWR steam dryer design load definition for the FIV analyses.

2.0 MODEL DESCRIPTION

2.1 Overview

[[

]]

Figure 1. PBLE01 Process Flow

The PBLE01 can be [[

]]

This is the methodology to be used in the ESBWR evaluation and is described in this report. [[

]]

The PBLE01 is built on the commercial software packages Matlab [2] and Sysnoise [3]. Matlab is a software package designed for engineering computations. The general architecture of the PBLE01 scripts makes use of the Matlab programming language and graphical interface.

The vessel acoustic response is calculated with Sysnoise. Sysnoise is a program for modeling acoustic wave behavior in fluids, using implementations of the finite element and boundary element methods. In the PBLE01 context, Sysnoise calculates how sound waves propagate through a FEM model of the RPV dome steam volumes. This 3D acoustic model is described in detail in Section 2.2 below. Alternate FE programs as described in Appendix D can also be used.

2.2 Dome Acoustic Model

2.2.1 Sysnoise Modeling Principles

Sysnoise [3] models acoustics as a wave-phenomenon. The modeling is carried out in the frequency domain, thus using the so-called Helmholtz form of the wave equation (see e.g. [5] and [10]). [[

]]

The following system of equations is solved:

$$(1) \quad \left[K + i\omega C - \omega^2 M\right]\{p\} = \{F_A\}$$

Where F_A is the vector of nodal acoustic forces, proportional to the normal velocity boundary conditions imposed on the faces of the mesh. The stiffness *[K]*, damping *[C]* and mass *[M]* matrices are computed at each frequency. The system of equations is thus set up and solved to obtain the pressure distribution *{p}*. The velocity field is obtained by differentiation of the pressure field at the Gauss points of the elements and then extrapolation and averaging at the nodes.

2.2.2 Geometry Modeling

The dome FE mesh (Figure 2) comprises all RPV steam volumes [[
]]

In all GEH BWRs, there are two steam zones with different steam qualities, upstream and downstream of the dryer. [[

]]

[[

]]

Figure 2. Modeled steam region (left) and details of typical vessel meshes (right)

Figure 3. (Figure Deleted)

[[

]]

[[

]]

Figure 4. [[

]]

[[ ]]

Table 1 First Ten RPV modes

Mode No.	Modal Frequency (Hz)
1	[[
2	
3	
4	
5	
6	
7	
8	
9	
10	]]

2.2.3 Finite Element Model

[[

]]

[[

]]

Figure 5. [[ ]]

[[

]]

[[

]]

Figure 6. [[ ]]

[[

]]

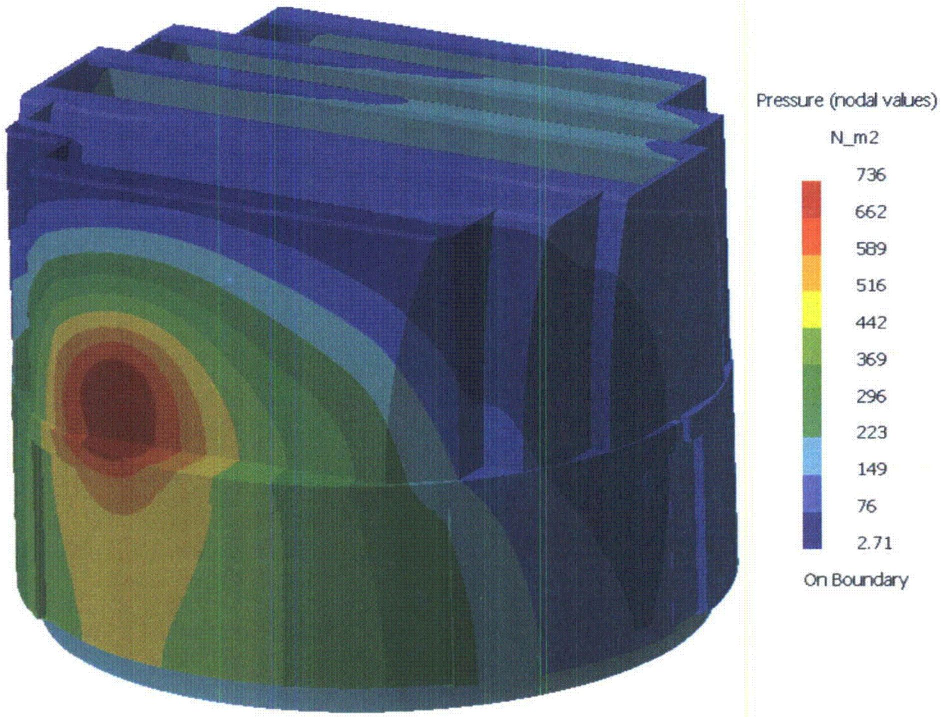

Figure 7. Pressure amplitudes on dryer at 15 Hz (Forced Response)
View of CD side

2.2.4 Fluid Properties and Boundary Conditions

[[

]]

Steam and water properties including impedance boundary conditions are described in detail in Section 2.4.

[[

]]

Figure 8. Vessel passive boundary conditions

2.3 PBLE01 from [[ ]]

2.3.1 Solution Formulation

The pressure at any dryer point P [[

]]

These considerations make the PBLE01 from in-vessel pressures a quite powerful tool.

2.3.2 Singularity Factor

The Singularity Factor (SF) is a tool to understand the mathematical limitations in PBLE01. It is calculated as: [[

]]

[[

]]

Figure 9. [[ ]]

2.4 Steam and Water Acoustic Properties

This section describes all steam and water characteristic properties used in PBLE01 models:

[[

]]

Dry steam properties, including speed of sound and density, are readily known from standard steam tables published by the International Association for the Properties of Water and Steam [6]. Petr [7] developed the [[

]] by Karplus [8].

2.4.1 [[ ]]

The following summary follows the description given in [7], Section 2. The variable nomenclature for this section is in Table 2.

[[

]]

Table 2 [[ ]]

[[	
	]]

[[

]]

[[

]]

Figure 10. [[ ]]

2.4.2 Steam-water interface

[[

]]

[[

]]

Figure 11. Steam-Water Interfaces

Table 3 Impedances in a Typical BWR RPV Environment

[[				
				]]

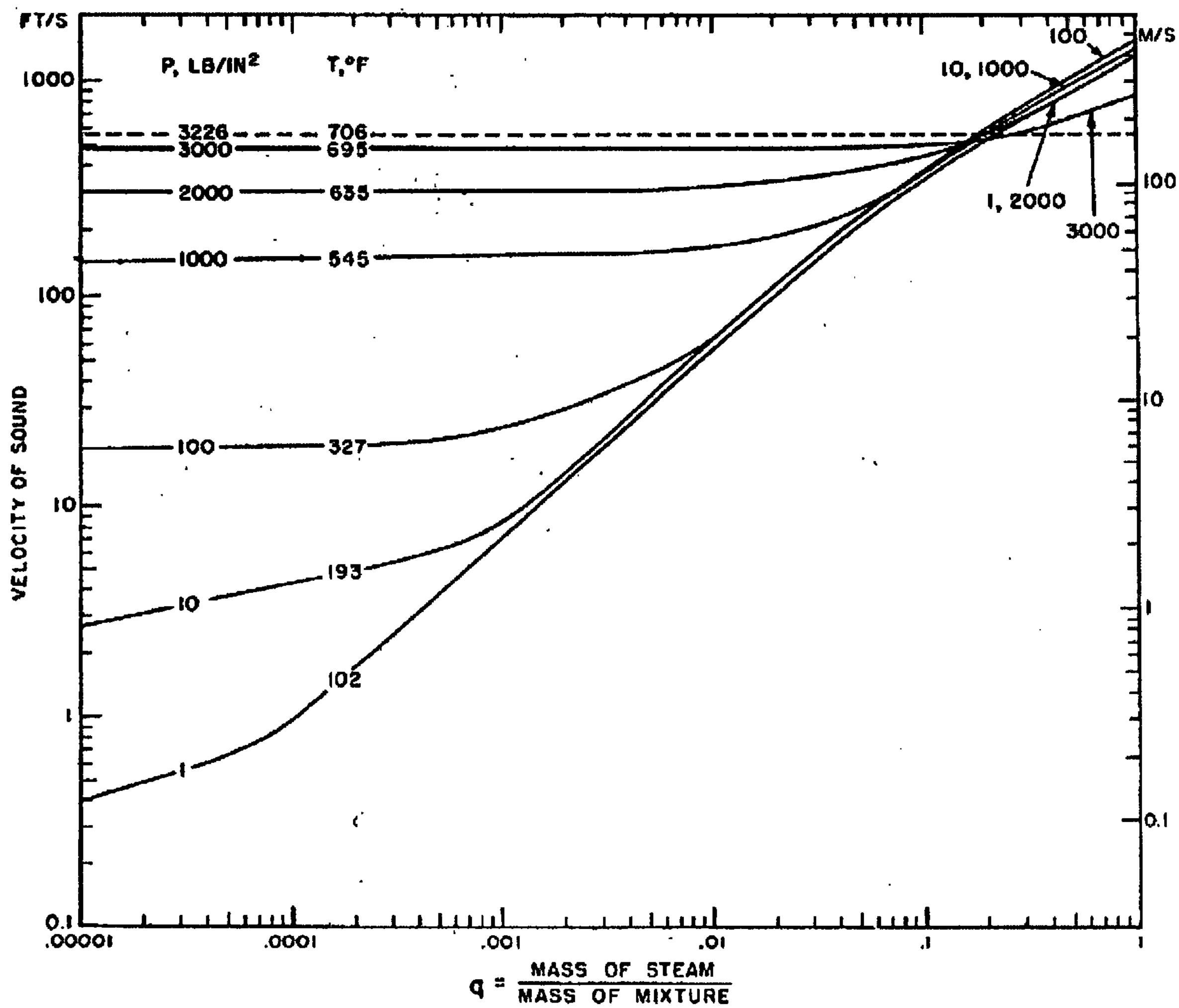

Figure 12. Speed of Sound in [[ ]] (Fig. 5 in Karplus [8])

The solution that was adopted for the PBLE01 is to model [[

]]

2.4.3 [[ ]]

[[

]]

[[

]]

Figure 13. [[ ]]

3.0 MODEL QUALIFICATION: BWR PLANT VALIDATION

The Grand Gulf Nuclear Station (GGNS) replacement steam dryer, installed in 2012, was instrumented with a significant number of on-dryer pressure sensors. This section presents the steam dryer fluctuating load definitions obtained with the PBLE01 method at GGNS for two power levels, one at the GGNS Previous Licensed Thermal Power (PLTP) level and at Extended Power Uprate (EPU) conditions.

3.1 Procedure for GGNS PBLE01 Validation

A three-dimensional GGNS acoustic FEM, shown in Figure 2, representing the steam dryer and the steam dome region of the reactor pressure vessel (RPV) above the reactor steam separator tubes and the liquid water interfaces was used to generate acoustic loads. The model was developed with the mesh requirement of [[ ]]

[[

]]

To monitor the steam dryer pressure loads, the GGNS steam dryer was instrumented with 15 pressure transducers (PTs). The location of the pressure transducers is described in Appendix A. [[ ]] The regional layout of the GGNS PT sensors is also shown in Appendix A. The layout was selected to be well distributed to capture the pressure response over the entire dryer. The regional locations were also selected to avoid pressure nodes in the acoustic harmonic response for frequencies that contribute most heavily to loading in the dryer components with the highest stress. [[ ]]

During the GGNS startup, test data was obtained at various power levels during approximately steady state conditions. The data samples taken were at least [[ ]] seconds long.

[[

]]

Figure 14. [[ ]]

The [[ ]] data was then used with the acoustic model described above and the methodology defined in Section 2.3.1 to predict loads on the steam dryer.

3.2 GGNS PBLE01 Validation at PLTP

Steady state data was obtained at PLTP conditions during the GGNS startup. The [[ ]] data was then used to define acoustic loads on the steam Appendix B shows the comparison between the PBLE01 predicted pressure loads and the measured pressures for each of the on-dryer pressure sensors at PLTP condition. During the power ascension from PLTP to EPU conditions, [[

]]

3.3 GGNS PBLE01 Validation at EPU

Steady state data was obtained at EPU conditions during the GGNS startup. The [[ ]] data was then used to define acoustic loads on the steam dryer. Appendix C shows the comparison between the PBLE01 predicted pressure loads and the measured pressures for each of the on-dryer pressure sensors at EPU condition. During the power ascension from PLTP to EPU conditions, [[

]]

3.4 GGNS PBLE01 Validation Conclusions

The PBLE01 [[ ]] is formulated under the assumption that [[ ]] The objective of the PBLE01 is to produce [[ ]] that best explain the measurements given the vessel acoustic environment. [[

]]

Appendix B shows comparison plots for the predicted versus measured pressures at the PT sensor locations for the GGNS PLTP conditions. These predicted values were based on [[ ]] as the input to the PBLE01 methodology. In general, the comparison plots in Appendix B demonstrate that the PBLE01 methodology is capable of adequately capturing the frequency content across the dryer face.

During the power ascension testing, [[

]]

The comparison plots in Appendix C demonstrate that the PBLE01 methodology is capable of adequately capturing the frequency content across the dryer face at EPU conditions. [[

]]

Overall the PBLE01 from [[ ]] emerges as a viable tool for developing dryer load definitions. The frequency content and the spatial distribution are well matched, the amplitude predictions are generally conservative and pressures away from the MSL nozzles are consistent with plant test data from other dryers.

Table 4 (Table Deleted)

Figure 15. (Figure Deleted)

Figure 16. (Figure Deleted)

Figure 17. (Figure Deleted)

4.0 APPLICATION METHODOLOGY

4.1 Scope of Application and Licensing Requirements

4.1.1 Scope of Application

The scope of the application for the Plant Based Load Evaluation Engineering Report is to provide a methodology for determining the fluctuating pressure loads that the ESBWR steam dryer will experience during normal operation. This fluctuating load definition can then be applied to a finite element model of the ESBWR steam dryer in order to determine the structural qualification of the dryer.

4.1.2 Specific Licensing Requirements

Plant components, such as the steam dryer in a BWR nuclear power plant, perform no safety function but must retain their structural integrity to avoid the generation of loose parts that might adversely impact the capability of other plant equipment to perform their safety function. Potential adverse flow effects must be evaluated for the steam dryer to meet the requirements of GDC 1 and 4 in Appendix A of 10 CFR Part 50.

Standard Review Plan [12], Section 3 requires that the dynamic responses of structural components with the reactor vessel caused by steady-state and operational flow transient conditions should be analyzed for prototype (first of a design) reactors. The analytical assessment of the vibration behavior of the steam dryer includes the definition of the input-forcing function including bias errors and uncertainty. References [12] and [13] contain specific acceptance criteria related to formulating forcing functions for vibration prediction. Reference 1 provides guidance on acceptable methods for formulating the forcing functions for vibration prediction.

4.2 Proposed Application Methodology

The PBLE01 method for formulating the forcing function for vibration prediction for the ESBWR steam dryer is in conformance with the guidance contained in Regulatory Guide 1.20 Revision 3.

4.2.1 Conformance with Regulatory Guide 1.20 Rev 3

The following table provides the conformance of the PBLE01 to the requirements contained in Section 2.1 of Regulatory Guide 1.20 Revision 3 [1].

RG 1.20 Section	Criteria	PBLE01 Conformance
2.1.(1)(a)	Determine the pressure fluctuations and vibration in the applicable plant systems under flow conditions up to and including the full operating power level. Such pressure fluctuations and vibration can result from hydrodynamic effects and acoustic resonances under the plant system fluid flow conditions.	Acceptable -The PBLE01 method is applicable up to the full power level of the plant. Since the PBLE01 approach in this Engineering Report uses [[ ]], all pressure fluctuation, either hydrodynamic or acoustic are captured.
2.1.(1)(b)	Justify the method for determining pressure fluctuations, vibration, and resultant cyclic stress in plant systems. Based on past experience, computational fluid dynamics (CFD) analyses might not provide sufficient quantitative information regarding high-frequency pressure loading without supplemental analyses. Scale testing can be applied for the high-frequency acoustic pressure loading and for verifying the pressure loading results from CFD analyses and the supplemental analyses, where the bias error and random uncertainties are properly addressed.	The justification of the PBLE01 method is acceptable based on the end to end benchmarking shown in Section 4.4.4 of this report. CFD modeling is not applicable to the PBLE01
2.1.(1)(c)	Address significant acoustic resonances that have the potential to damage plant piping and components including steam dryers, and perform modifications to reduce those acoustic resonances, as necessary, based on the analysis.	Acceptable – the PBLE01 is capable of determining acoustic resonances that may be detrimental to the steam dryer. Modifications for reducing acoustic resonances is beyond the scope of this Engineering Report
2.1.(1)	Scale Model Testing	Not applicable - Scale model Testing is not used in the PBLE01 for determination of the steam dryer loads
2.1.(1)	Computational Fluid Dynamic (CFD) modeling	Not applicable - CFD modeling is not used in the PBLE01 for determination of the steam dryer loads

RG 1.20 Section	Criteria	PBLE01 Conformance
2.1.(2)	Describe the structural and hydraulic system natural frequencies and associated mode shapes that may be excited during steady-state and anticipated transient operation, for reactor internals that, based on past experience, are not adversely affected by the flow-excited acoustic resonances and flow-induced vibrations. Additional analyses should be performed on those systems and components, such as steam dryers and main steam system components in BWRs and steam generator internals in PWRs, that may potentially be adversely affected by the flow-excited acoustic resonances and flow-induced vibrations. These additional analyses are summarized below.	Acceptable - The PBLE01 is capable of determining the acoustic mode shapes within the reactor steam dome. It will simulate the acoustic response of the steam dome from the significant excitation sources.
2.1.(2)	Determine the damping of the excited mode shapes, and the frequency response functions (FRFs, i.e., vibration induced by unit loads or pressures, and stresses induced by unit loads or pressures), including all bias errors and uncertainties.	Acceptable – FRF are determined by the PBLE01. Bias errors and uncertainties have been addressed.
2.1.(3)	Describe the estimated random and deterministic forcing functions, including any very-low-frequency components, for steady-state and anticipated transient operation for reactor internals that, based on past experience, are not adversely affected by the flow-excited acoustic resonances and flow-induced vibrations. Additional analyses should be performed on those systems and components, such as steam dryers and main steam system components in BWRs and steam generator internals in PWRs, that may potentially be adversely affected by the flow-excited acoustic resonances and flow-induced vibrations. These additional analyses are summarized below.	Acceptable – the PBLE01 is capable of determining the forcing functions in the frequency range important to BWR dryers.
2.1.(3)	Evaluate any forcing functions that may be amplified by lock-in with an acoustic and/or structural resonance (sometimes called self-excitation mechanisms). A lock-in of a forcing function with a resonance strengthens the resonance amplitude. The resulting amplitudes of the forcing function and resonance response can therefore be significantly higher than the amplitudes associated with non-lock-in conditions.	Lock in assessment is not required for PBLE01 loads [[ ]]

RG 1.20 Section	Criteria	PBLE01 Conformance
2.1.(3)	The applicant/licensee should determine the design load definition for all reactor internals, including the steam dryer in BWRs up to the full licensed power level, and should validate the method used to determine the load definitions based on scale model or plant data. BWR applicants should include instrumentation on the steam dryer to measure pressure loading, strain, and acceleration to confirm the scale model testing and analysis results. BWR licensees should obtain plant data at current licensed power conditions for use in confirming the results of the scale model testing and analysis for the steam dryer load definition prior to submitting a power uprate request.	Acceptable – The PBLE01 uses in plant data for the determination of the steam dryer load definition.
2.1.(3)	In recent BWR EPU requests, some licensees have employed a model to compute fluctuating pressures within the RPV and on BWR steam dryers that are inferred from measurements of fluctuating pressures within the MSLs connected to the RPV. Applicants should clearly define all uncertainties and bias errors associated with the MSL pressure measurements and modeling parameters. The bases for the uncertainties and bias errors, such as any experimental evaluation of modeling software, should be clearly presented. There are many approaches for measuring MSL pressures and computing fluctuating pressures within the RPV and the MSLs. Although some approaches reduce bias and uncertainty, they still have a finite bias and uncertainty, which should be reported. Based on historical experience, the following guidance is offered regarding approaches that minimize uncertainty and bias error:	Acceptable – the PBLE01 methodology in this report uses [[ ]] for determination of the load definition. The PBLE01 methodology in this report demonstrates the methodology to determine end to end bias errors and uncertainties associated with the PBLE01 methodology [[ ]].
2.1.(3)(a)	At least two measurement locations should be employed on each MSL in a BWR. However, using three measurement locations on each MSL improves input data to the model, particularly if the locations are spaced logarithmically. This will reduce the uncertainty in describing the waves coming out of and going into the RPV. Regardless of whether two or three measurement locations are used, no acoustic sources should exist between any of the measurement locations, unless justified.	Not applicable – the PBLE01 methodology in this report [[ ]].

RG 1.20 Section	Criteria	PBLE01 Conformance
2.1.(3)(b)	Strain gauges (at least four gauges, circumferentially spaced and oriented) may be used to relate the hoop strain in the MSL to the internal pressure. Strain gauges should be calibrated according to the MSL dimensions (diameter, thickness, and static pressure). Alternatively, pressure measurements made with transducers flush-mounted against the MSL internal surface may be used. The effects of flow turbulence on any direct pressure measurements should be accounted for in a bias error and uncertainty estimate.	Not applicable – the PBLE01 uses [[ ]] The effects of flow turbulence on the pressure measurement is included in the PBLE01 uncertainty assessment.
2.1.(3)(c)	The speed of sound used in any acoustic models should not be changed from plant to plant, but rather should be a function of temperature and steam quality.	Acceptable – the speed of sound in the PBLE01 is a function of the steam fluid conditions within the RPV.
2.1.(3)(d)	Reflection coefficients at any boundary between steam and water should be based on rigorous modeling or direct measurement. The uncertainty of the reflection coefficients should be clearly defined. Note that simply assuming 100-percent reflection coefficient is not necessarily conservative.	Acceptable – the conditions of the steam water interface and the associated uncertainty is developed for the PBLE01 method.
2.1.(3)(e)	Any sound attenuation coefficients should be a function of steam quality (variable between the steam dryer and reactor dome), rather than constant throughout a steam volume (such as the volume within the RPV).	Acceptable – the PBLE01 formulation uses the steam quality in the reactor steam dome and dryer for the sound attenuation coefficients.
2.1.(3)(f)	Once validated, the same speed of sound, attenuation coefficient, and reflection coefficient should be used in other plants. However, different flow conditions (temperature, pressure, quality factor) may dictate adjustments of these parameters.	Acceptable – the speed of sound is based on the thermodynamic properties of steam in the RPV
Other	Model Benchmarking	PBLE01 is benchmarked against previously instrumented dryer data
Other	Determination of Biases and Uncertainty	Biases and Uncertainty have been calculated

Note that other sections of Reference 1 refer to structural analysis of the steam dryer or preoperational/startup testing that is outside of the scope of this Engineering Report.

4.3 Range of Application

The PBLE01 method described in this report is capable of determining the vibratory forcing function for the entire operating range of the ESBWR steam dryer.

4.4 Plant-Specific Application Methodology

4.4.1 [[ ]] Model Inputs

The vessel [[

]]

Acoustic Finite Element Model Mesh

A FE model of the [[

]]

[[

]]

Figure 18. [[ ]]

[[

]]

Table 5 Parameters in the [[ ]]

Phenomena	Parameter
[[	
	]]

4.4.2 Plant Input Measurements

Sensor Type and Location

For the PBLE01 [[

]]

Error in Measured Dryer Pressures

This error, [[

]]

In addition, for the ESBWR on-dryer instrumentation, the strain gauge manufacturer will be involved to ensure proper installation and calibration of the strain gauges used in the ESBWR measurement program during plant startup testing, including a "pipe and beam" calibration effort, as applicable. If instrumentation is similar to strain gauges used in the past, [[

]] Uncertainties will be evaluated for the specific strain gauges and will be accounted for in the final assessment.

The installation and data acquisition procedures for the ESBWR on-dryer instrumentation will follow the procedures used at GGNS, to the extent applicable to the specific gauges, and will incorporate operating experience from those measurement sessions. To the extent applicable to the type and model of strain gauges used in the ESBWR measurements, [[

]] The installation procedure, data acquisition procedure, instrumentation acceptance criteria, and instrumentation startup report from the previous work will be updated as part of the implementation of the RG 1.20 comprehensive vibration assessment program.

4.4.3 Plant-Specific Load Definition

The following steps are involved in the calculation of dryer loads with the PBLE01:

[[

]]

Figure 19. (Figure Deleted)

4.5 Example Implementation of Methodology

Section C.III.4.3, "Combined License Information Items that Cannot be Resolved Before the Issuance of a License," in Regulatory Guide 1.206 states that for each Combined License (COL) action that cannot be resolved before license issuance, the COL applicant should provide sufficient information to support the NRC licensing decision, and propose a method for ensuring the final closure of the item following COL issuance. One of the methods for final closure of a COL Information Item specified in Regulatory Guide 1.206 is development of a new Inspections, Tests, Analyses, and Acceptance Criteria (ITAAC).

For ESBWR COL applicants that do not perform a fatigue analysis prior to COL issuance, the COL applicant will need to follow the guidance of Regulatory Guide 1.206 to provide sufficient information to support the NRC licensing decision and then rely on an ITAAC to complete the resolution of the COL Information Item. To support this effort, the ESBWR steam dryer methodology using PBLE Method I has been applied to the GGNS replacement steam dryer at EPU conditions as an example of the successful implementation of the methodology to allow the COL applicant to incorporate by reference this information in its FSAR to satisfy Regulatory Guide 1.20. This example implementation includes the fatigue analysis to develop the end-to-end defined bias and uncertainties as well as consideration of lessons learned from issues identified during the analysis of the steam dryer data.

At a high level, the steam dryer fatigue analysis consists of four steps: (1) input signal processing, where a time segment or sample of [[ ]] data is selected for input into the acoustic model; (2) an acoustic "load definition," where fluctuating pressures are determined from an acoustic FEM of the reactor steam dome containing the dryer (Section 3.3); (3) a dynamic structural evaluation of the dryer, driven from the acoustic loads (i.e., the "global model" analysis using a large ANSYS model, comprised of mostly shell type elements); and (4) post-processing of stress, strain or acceleration results. In the post-processing step, [[

]] These results are referred to as the projected data at each dryer location (e.g., location of peak stress or location of on-dryer sensor).

The following sections discuss the details of the fatigue evaluations for the GGNS replacement steam dryer at EPU conditions as an example implementation of the ESBWR steam dryer methodology and in particular, the determination and application of the methodology's end-to-end bias and uncertainties.

4.5.1 Structural Model

The GGNS replacement steam dryer structural model was developed in accordance with the guidelines defined in Reference [14]. Modifications to the structural model that was used for the pre-EPU analysis were made [[

]]

4.5.2 FIV Analysis

The ANSYS FE code was used to obtain the structural responses of the steam dryer to the FIV loads at the plant conditions where measured data was obtained. The dynamic analysis was performed [[ ]] The maximum stress intensity [[

]]

For determination of peak stress conditions, [[ ]] submodels were used in the development of stress reduction factors (SRFs) used in the analysis. These are the [[ ]] The FEM for the [[ ]] submodel is shown in Figure 20 and provides a detailed representation of the [[ ]] The SRF is based on [[

]]

The [[ ]] submodel is shown in Figure 21 and the boundaries encompass [[

]] The section paths investigated are shown in Figure 22. The resulting SRFs are [[ ]]

The [[ ]] submodel is constructed of the [[ ]] shown in Figure 23. The displacements at the cut boundary are [[

]] The section paths investigated are shown in Figure 24 and represent the most controlling sections. The resulting SRF is [[ ]]

[[

]]

Figure 20. [[ ]] Submodel

[[

]]

Figure 21. [[ ]] Submodel

[[

]]

Figure 22. Section Paths Selected for the [[ ]] Submodel

[[

]]

Figure 23. [[ ]] Submodel

[[

]]

Figure 24. Section Paths Selected for the [[ ]] Submodel

4.5.3 End-to-End Bias and Uncertainties

The final test condition performed during the GGNS EPU power ascension is defined as test condition [[ ]] As discussed above, pressure loads were generated for this test condition using the PBLE01 Method I based on [[ ]] data at that test condition. These loads were then used to drive the ANSYS FE model to produce the structural response of the steam dryer and the projected strain or acceleration at each on-dryer sensor location.

To monitor the dryer dynamic response [[ ]] accelerometers and [[ ]] strain gauges were installed. The accelerometer and strain gauge locations were selected to monitor the global response of [[[redacted]]] high stress regions. The strain and acceleration instruments are well distributed over different dryer regions. Where possible, locations were selected where the sensor would see [[ ]] The regional layout of the GGNS accelerometers and strain gauge sensors is summarized in Appendix A. The installed locations were selected to provide good correlation with dryer high stress areas and redundancy such that multiple instruments will have good correlation with the high stress regions. For the same time segment selected for the generation of the steam dryer loads (steps one and two above) data was obtained for the on-dryer strain gauges and accelerometers (measured data).

The end-to-end bias values are based on the comparison of the measured PSD data over the projected PSD data at each of the on-dryer sensor locations. For each instrument, [[ ]] seconds of measured PSD data [[ ]] are compared with the ANSYS-predicted strain and acceleration PSD results based on [[ ]] analysis [[

]]

Figures 25 and 26 show plots of the mean bias and uncertainty [[ ]] GGNS [[ ]] test condition. PSD comparisons of the ANSYS predictions from the GGNS [[ ]] test condition and the measured data for the analysis time interval are included in Appendix E for each sensor. Tabular values of the [[ ]] end-to-end bias and uncertainty are provided in Appendix F as a function of frequency. The ESBWR stress adjustment calculations [[

]]

[[

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Figure 25. [[ ]]

[[

]]

Figure 26. [[ ]].

4.5.4 Application of the End-to-End Bias and Uncertainties

To demonstrate the application of the end-to-end bias and uncertainty methodology, the end-to-end biases and uncertainties described in Section 4.5.3 are applied to the projected data from the ANSYS structural model to develop adjusted data for each on-dryer sensor location. The end-to-end biases and uncertainties are applied using the [[ ]] method in accordance with Reference [14].

Plots of the simulated strain and acceleration peak amplitudes and spectra for each of the GGNS replacement steam dryer sensors are provided in Appendix G. The projected strain and acceleration amplitudes and spectra have been determined by [[ ]]. This has been performed for the [[ ]] representing the [[ ]]. An upper bound envelope was generated for the spectra based on the results of the nine frequency shift load cases including the bias errors and uncertainties. Figure G-1 is an example of the construction of the upper bound envelope from the nine frequency shift load cases.

Also plotted on the figures in Appendix G are the measured sensor responses over the analysis time period. The measured amplitude response curves (plotted in black) show the peak amplitude in each [[ ]] time segments over the [[ ]] time period used in the demonstration benchmark analyses. The adjusted amplitude curves (plotted in red) are shown [[ ]] The spectral plots (covering the LF and HF regions) in Figures G-2 through G-13 compare the upper bound envelope of the adjusted strains and accelerations (plotted in red) to the measured signal spectra for the time segments that had the maximum amplitudes for the measured signals (plotted in black). For example, in Figure G-2 (sensor A1), the maximum amplitude occurs in time segment [[ ]] the spectrum shows the frequency content for time segment [[ ]]

The peak amplitude plots show that the adjusted strains and accelerations bound the measured data for [[ ]] The spectral plots for the sensors all show [[ ]] however, since fatigue is dependent on the alternating stress intensity, the adjusted peak amplitude comparison is the proper metric for determining whether the measured response is bounded by the analysis. There are a few sensors where the measured amplitude [[ ]] the ESBWR licensing basis applies a minimum alternating stress ratio (MASR) acceptance criterion of 2.0 for the ESBWR steam dryer design fatigue analyses. The MASR is defined as the ratio of the steam dryer design fatigue limit 93.7 MPa (13,600 psi) to the peak adjusted stress. This is also consistent with replacement steam dryer analyses where a MASR of 2.0 is applied to address uncertainties in steam dryer fatigue analyses.

In addition, the ESBWR stress adjustment calculations will not take credit for [[

]]. These increases in the prescribed margin in the methodology are sufficient to ensure that the upper bound of the adjusted strains and accelerations in the fatigue analysis will bound measured strains and accelerations.

4.5.5 FIV Peak Stress Results

To determine the peak stress results for the GGNS replacement steam dryer, the projected data from the ANSYS structural model is scoped to identify peak stress in each major structural component of the steam dryer. The global dryer FEM is divided into [[ ]] major structural components. Three components (baseplate, inner bank end-plates, and inner hoods) are segregated into subgroups to further refine the location of peak stress. In addition, the [ ]] are split into two subgroups each [[ ]] The sum total of the primary scoping groups is [[ ]] Weld lines associated with segregated components are correspondingly divided into weld subgroups resulting in [[ ]] weld scoping groups. In total, [[ ]] scoping groups are defined for the stress post-processing.

For each component and subgroup, the results of the ANSYS FIV analysis are scoped to determine the peak stresses. Where applicable, factors are applied to the ANSYS FIV results to account for stresses in the weld geometry that is not explicitly modeled in the global FEM. Also, submodels are applied at several locations and the resultant SRFs applied to the ANSYS FIV results. The end-to-end biases and uncertainties are then applied using the [[ ]] method in accordance with Reference [14] to develop the adjusted stress projections for the dryer components.

The results of the adjusted stress projections for the GGNS [[ ]] test condition are shown in Table 6 for the seven highest component/subcomponents. The peak adjusted stress reflects the application of [[ ]] For these seven high stress components, [[ ]] The stress contours and maximum stress locations for three of the limiting components are shown in Figures 27 through 29. Figures 30 and 31 show the dryer sensor locations (in yellow dots) and the seven highest [[ ]] stress locations and the [[ ]] stress location for the tie bar pad (in gray dots).

The installed sensor locations were selected to provide good correlation with dryer high stress areas and redundancy such that multiple instruments will have good correlation with the high stress regions. The same approach has been applied to describe how the maximum stress locations at the [[ ]] test conditions are associated with the strain gauges and accelerometers.

To select the strain gauge and accelerometer locations, the [[

]]

The results [[ ]] are presented in Figures H-1 through H-7 for the seven high stress locations depicted in Figures 30 and 31. The [[ ]] figures demonstrate that for the seven high stress locations, [[

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The sensors were located to measure the global dryer response [[

]] The [[ ]] charts presented in Appendix H and summarized in Table 7 illustrate that multiple sensors [[ ]] and support using [[ ]]

Table 6 Summary of Adjusted Stress Projections at GGNS [[ ]] Test Condition

Component/Subgroup Name	Load Case	Maximum Stress (psi)	LF Stress Contribution (psi)	HF Stress Contribution (psi)
[[				

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Table 7 Seven Highest Stress Locations and Well Correlated Dryer Instruments

	Lower Dryer					Upper Dryer						
Maximum Stress Location	[[											

												]]

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Figure 27. Stress Contour and Maximum Stress Location for [[ ]]

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Figure 28. Maximum Stress Location for [[ ]]

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Figure 29. Stress Contour and Maximum Stress Location for [[ ]]

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Figure 30. [[ ]]

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Figure 31. [[ ]]

4.5.6 Projection of Stress Results to Full EPU Conditions

The final test condition for the GGNS EPU startup was at [[ ]] of the previous licensed thermal power (full EPU defined as [[ ]] and did not represent full EPU conditions. During the power ascension testing, it was also noted that [[ ]] To address these differences in conditions, the peak adjusted stresses were further modified to develop a final set of peak adjusted stresses at full EPU conditions [[ ]]

To project the results to the full EPU conditions, [[ ]] Figure 32 is an example of the waterfall plot for strain gauge S1. For frequency bands outside the SRV resonance range, [[ ]] For frequency bands within the SRV resonance range, [[ ]]

In addition to the projection to full EPU conditions, adjustments were also made [[ ]] Data from 40 FIV test conditions were evaluated to determine the sensitivity of the measured on-dryer sensor response [[ ]] From the evaluation of the measured response, [[ ]]

The [[ ]] dryer factors that are a function of [[ ]] are used to adjust the [[ ]] The maximum stress [[ ]] is evaluated [[ ]] The results of the adjusted stress projections are shown in Table 9. The results are for the [[ ]] Table 9 shows the stress results for the seven highest component/subcomponents. These seven highest stress locations [[ ]] The results shown in Table 9 demonstrate that for the high stress locations, [[ ]] with a maximum stress projection of [[ ]]

The FIV results are also screened for the maximum membrane stress for each of the [[ ]] primary scoping components for all load cases. The resultant membrane stress is then adjusted with the [[ ]] to determine the adjusted FIV membrane stress for use in the ASME load combinations. Similar to the peak stress, for the components with segregated subcomponents, the membrane stress used in ASME analysis is the maximum of adjusted peak membrane stresses from all subcomponents.

4.5.7 ASME Code Load Case Stress Results

The GGNS replacement steam dryer was analyzed for the ASME Code load combinations for each component with FIV peak stresses (bending plus membrane) and FIV membrane stresses from the limiting condition defined in Table 8 (Condition 2). The results of these analyses are used to assess dryer component primary stresses versus ASME design criteria as described in Appendix I for a total of twelve load combinations also described in Appendix I under normal, upset, emergency and faulted operation conditions at EPU power level. The summary of the results is presented in Table 10. The acceptance criteria used for these evaluations are the same as those used for safety-related components. The results indicate that the stresses for all structural components are below the ASME Code allowable limits at EPU operating conditions.

[[

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Figure 32. [[ ]]

Table 8 Extrapolation Conditions for Full EPU Power [[ ]]

#	Full EPU Extrapolated Condition	Core Thermal Power, (MWth)	% PLTP (3898 MWth)	[[				
1								
2								
3								
4								
5								]]

Table 9 Summary of Adjusted Stress Projections at EPU [[

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Component/Subgroup Name	Method	Load Case	Time Interval	Maximum Stress (psi)	LF Stress Contribution (psi)	HF Stress Contribution (psi)
Maximum Adjusted Stress for Five Conditions of Full EPU Projection						
[[						
						]]

Table 10 ASME Results for Normal, Upset, Emergency and Faulted Conditions

	Normal		Upset										Emergency		Faulted									
Component	A1		B1		B2		B3		B4		B5		C1		D1		D2		D3		D4		D5	
	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b
[[																								

	Normal		Upset										Emergency		Faulted									
Component	A1		B1		B2		B3		B4		B5		C1		D1		D2		D3		D4		D5	
	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b

	Normal		Upset										Emergency		Faulted									
Component	A1		B1		B2		B3		B4		B5		C1		D1		D2		D3		D4		D5	
	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b	Pm	Pm+b
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5.0 CONCLUSIONS

The Plant Based Load Evaluation methodology [[ ]] is available to predict dryer pressure loads and their associated uncertainty.

A built-in [[ ]]

The PBLE01 technique is validated by the Grand Gulf Nuclear Station application cases. From comparison between measurements and projections, the PBLE01 predicts good frequency content and spatial distribution. The SRV valve resonances are well captured. The methodology has been benchmarked by applying the PBLE01 generated loads to an ANSYS finite element model and comparing the predicted strains and accelerations to measured values for on-dryer strain gauges and accelerometers.

The PBLE01 addresses a wide range of load cases:

- MSL valve resonance (SRV/branch line) or broadband excitations (venturi)
- Sources in the vicinity of nozzles
- Hydrodynamic loading (pseudo-pressures)

The effects from the last two types of sources can be advantageously modeled by [[ ]]; for this reason the PBLE01 from [[ ]] is adequate to predict fluctuating dryer loads at any ESBWR plant.

The ESBWR steam dryer methodology using PBLE01 has been applied to the GGNS replacement steam dryer at EPU conditions as an example of the successful implementation of the methodology to allow COL applicants to incorporate by reference this information in its FSAR to satisfy Regulatory Guide 1.20. This example implementation includes the fatigue analysis to develop the end-to-end bias and uncertainties as well as consideration of lessons learned from issues identified during the analysis of the steam dryer data.

6.0 REFERENCES

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APPENDIX A
GGNS DRYER INSTRUMENTATION LOCATIONS

Table A-1 Instrument/Sensor Locations

Sensor ID	Location
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Figure A-1. [[ ]]

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Figure A-2. [[ ]]

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Figure A-3. [[ ]]

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Figure A-4. [[ ]]

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Figure A-5. [[ ]]

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Figure A-6. [[ ]]

APPENDIX B
GGNS PBLE01 VALIDATION AT PLTP

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Figure B-1. [[ ]]

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Figure B-2. [[ ]]

Figure B-3. (Figure Deleted)

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Figure B-4. [[ ]]

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Figure B-5. [[ ]]

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Figure B-6. [[ ]]

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Figure B-7. [[ ]]

Figure B-8. (Figure Deleted)

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Figure B-9. [[ ]]

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Figure B-10. [[ ]]

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Figure B-11. [[ ]]

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Figure B-12. [[ ]]

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Figure B-13. [[ ]]

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Figure B-14. [[ ]]

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Figure B-15. [[ ]]

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Figure B-16. [[ ]]

APPENDIX C
GGNS PBLE01 VALIDATION AT EPU

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Figure C-1. [[ ]]

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Figure C-2. [[ ]]

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Figure C-3. [[ ]]

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Figure C-4. [[ ]]

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Figure C-5. [[ ]]

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Figure C-6. [[ ]]

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Figure C-7. [[ ]]

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Figure C-8. [[ ]]

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Figure C-9. [[ ]]

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Figure C-10. [[ ]]

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Figure C-11. [[ ]]

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Figure C-12. [[ ]]

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Figure C-13. [[ ]]

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Figure C-14. [[ ]]

APPENDIX D
ACOUSTIC FINITE ELEMENT PROGRAM REQUIREMENTS FOR PBLE01

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APPENDIX E
Comparison of Projected versus Measured PSD Accelerations (A) and Strain (S) at GGNS EPU Conditions

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Figure E-1. [[ ]]

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Figure E-2. [[ ]]

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Figure E-3. [[ ]]

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Figure E-4. [[ ]]

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Figure E-5. [[ ]]

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Figure E-6. [[ ]]

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Figure E-7. [[ ]]

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Figure E-8. [[ ]]

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Figure E-9. [[ ]]

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Figure E-10. [[ ]]

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Figure E-11. [[ ]]

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Figure E-12. [[ ]]

APPENDIX F

[[ ]]

Table F-1 [[ ]]

Note: The ESBWR stress adjustment calculations [[

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APPENDIX G
COMPARISON OF ADJUSTED VERSUS MEASURED PSD ACCELERATIONS (A) AND STRAIN (S) AT GGNS EPU CONDITIONS

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Figure G-1. Upper Bound Envelope – Sensor [[ ]]

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Figure G-2. Predicted vs. Measured Sensor Response – [[ ]]

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Figure G-3. Predicted vs. Measured Sensor Response – [[ ]]

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Figure G-4. Predicted vs. Measured Sensor Response – [[ ]]

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Figure G-5. Predicted vs. Measured Sensor Response – [[ ]]

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Figure G-6. Predicted vs. Measured Sensor Response – [[ ]]

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Figure G-7. Predicted vs. Measured Sensor Response – [[ ]]

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Figure G-8. Predicted vs. Measured Sensor Response – [[ ]]

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Figure G-9. Predicted vs. Measured Sensor Response – [[ ]]

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Figure G-10. Predicted vs. Measured Sensor Response – [[ ]]

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Figure G-11. Predicted vs. Measured Sensor Response – [[ ]]

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Figure G-12. Predicted vs. Measured Sensor Response – [[ ]]

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Figure G-13. Predicted vs. Measured Sensor Response – [[ ]]

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Figure G-14. Predicted vs. Measured Sensor LF Response – [[ ]]

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Figure G-15. Predicted vs. Measured Sensor LF Response – [[ ]]

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Figure G-16. Predicted vs. Measured Sensor LF Response – [[ ]]

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Figure G-17. Predicted vs. Measured Sensor LF Response – [[ ]]

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Figure G-18. Predicted vs. Measured Sensor LF Response – [[ ]]

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Figure G-19. Predicted vs. Measured Sensor LF Response – [[ ]]

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Figure G-20. Predicted vs. Measured Sensor LF Response – [[ ]]

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Figure G-21. Predicted vs. Measured Sensor LF Response – [[ ]]

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Figure G-22. Predicted vs. Measured Sensor LF Response – [[ ]]

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Figure G-23. Predicted vs. Measured Sensor LF Response – [[ ]]

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Figure G-24. Predicted vs. Measured Sensor LF Response – [[ ]]

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Figure G-25. Predicted vs. Measured Sensor LF Response – [[ ]]

APPENDIX H
CORRELATION OF MAXIMUM STRESS LOCATIONS WITH ON-DRYER SENSORS

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Figure H-1. [[ ]] High Stress Location and [[ ]] Dryer Instruments

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Figure H-2. [[ ]] High Stress Location and [[ ]] Dryer Instruments

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Figure H-3. [[ ]] High Stress Location and [[ ]] Dryer Instruments

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Figure H-4. [[ ]] High Stress Location and [[ ]] Dryer Instruments

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Figure H-5. [[ ]] High Stress Location and [[ ]] Dryer Instruments

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Figure H-6. [[ ]] High Stress Location and [[ ]] Dryer Instruments

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Figure H-7. [[ ]] High Stress nts

APPENDIX I
ASME LIMITS AND LOAD COMBINATIONS FOR DEMONSTRATION ANALYSIS

Table I-1 Demonstration Analysis ASME Code Stress Limits

			Stress Value (ksi) at Temperature	
Service Level	Stress Category	Stress Limit	[[	
Design	P_m	S_m		
	P_m+P_b	$1.5S_m$		
Service Levels A & B	P_m	S_m		
	P_m+P_b	$1.5S_m$		
Service Level C	P_m	$1.5\ S_m$		
	P_m+P_b	$2.25\ S_m$		
Service Level D	P_m	Min ($0.7S_u$ or $2.4S_m$)		
	P_m or $P_L + P_b$	Min 1.5 ($0.7S_u$ or $2.4S_m$)		]]

Note: Upset condition service level B limits are increased by 10% above the limits shown in this table per NG-3223(a).

Legend

P_m: General primary membrane stress intensity
P_l: Local primary membrance stress intensity
P_b: Primary bending stress intensity
S_m. Design Stress Intensity
S_u: Ultimate tensile strength

Table I-2 Demonstration Analysis Load Combinations

Comb. No	Level	Combination
A-1	Normal	[[
B-1	Upset	
B-2	Upset	
B-3	Upset	
B-4	Upset	
B-5	Upset	
C-1	Emergency	
D-1	Faulted	
D-2	Faulted	
D-3	Faulted	
D-4	Faulted	
D-5	Faulted	]]

Notes:

1 For the D-2 case, the load combination used in the analysis is [[ ]] which is conservative compared to the definition in the load combination as shown in this table.

2 In ASME code evaluation the stress intensity values obtained from different load cases, such as FIV and ΔP_N, are combined directly, which produces more conservative results.

Definition of Load Acronyms:

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APPENDIX J
PBLE01 Load Bias and Uncertainty Based on GGNS

The ESBWR stress adjustment calculations [[

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Table J-1 PBLE01 Bias and Uncertainty based on the GGNS Demonstration Case

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Figure J-1. [[

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Figure J-2. [[

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