Appendix B

ESBWR Steam Dryer - Plant Based Load Evaluation Methodology (NED-33408)

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GE Hitachi Nuclear Energy

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Licensing Topical Report

ESBWR STEAM DRYER - PLANT BASED LOAD EVALUATION METHODOLOGY

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IMPORTANT NOTICE REGARDING THE CONTENTS OF THIS REPORT

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Acronyms and Abbreviations

BWR	Boiling Water Reactor
CAD	Computer-Aided Design
CLTP	Current Licensed Thermal Power
CFD	Computational Fluid Dynamics
CFR	Code of Federal Regulations
DOE	Design Of Experiments
EPU	Extended Power Uprate
ESBWR	Economic Simplified Boiling Water Reactor
FE / FEM	Finite Elements / Finite Element Method / Finite Element Model
FRF	Frequency Response Function
GDC	General Design Criteria
GEH	GE Hitachi Nuclear Energy
Hz	Hertz
LTR	Licensing Topical Report
MSL	Main Steam Line
OLTP	Original Licensed Thermal Power
NRC	Nuclear Regulatory Commission
PBLE	Plant Based Load Evaluation
PSD	Power Spectral Density
PT	Pressure Transducer
PWR	Pressurized Water Reactor
QC2	Quad Cities 2
RG	Regulatory Guide
RPV	Reactor Pressure Vessel
SF	Singularity Factor
SRSS	Square Root of the Sum of the Squares

SRV	Safety / Relief Valve
3D	Three Dimensional

Abstract

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

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 load in a structural analysis to qualify the steam dryer design

(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 the PBLE method that will be applied for determining the fluctuating loads on the ESBWR steam dryer, describes the PBLE analytical model, determines the biases and uncertainties of the PBLE formulation and describes the application of the PBLE method to the evaluation of the ESBWR steam dryer.

2.0 MODEL DESCRIPTION

2.1 Overview

[[ ]]

Figure 1. PBLE Process Flow

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

The PBLE 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 PBLE 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 PBLE 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.

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:

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

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. Vessel response (left) [[
]]

[[
]]

[[ ]]

Figure 4. First typical [[

]]

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. [[ ]]

[[

]]

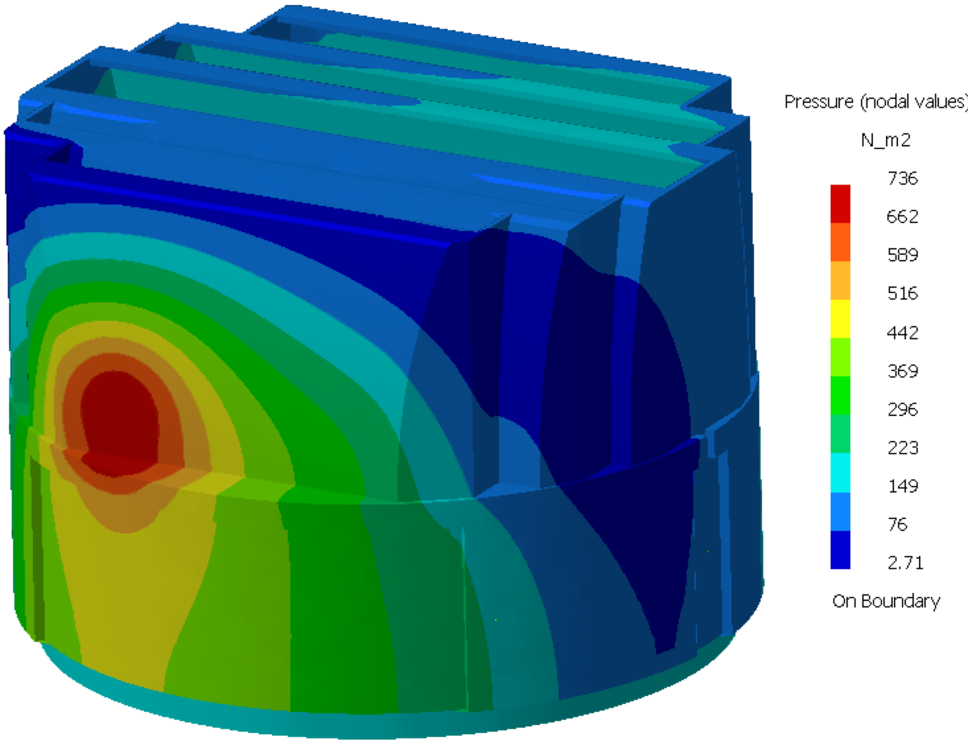

Figure 7. Pressure amplitudes on dryer at 15 Hz (Forced Response)
View of CD side

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 PBLE from [[ ]]

2.3.1 Solution Formulation

The pressure at any dryer point P [[

]] as shown in the benchmark assessments in Sections 3.2 and 3.3 of this report.

[[

]]

These considerations make the PBLE 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 PBLE. It is calculated as: [[

]]

[[ ]]

Figure 9. [[ ]]

2.4 Steam and Water Acoustic Properties

This section describes all steam and water characteristic properties used in PBLE 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

[[				
				]]

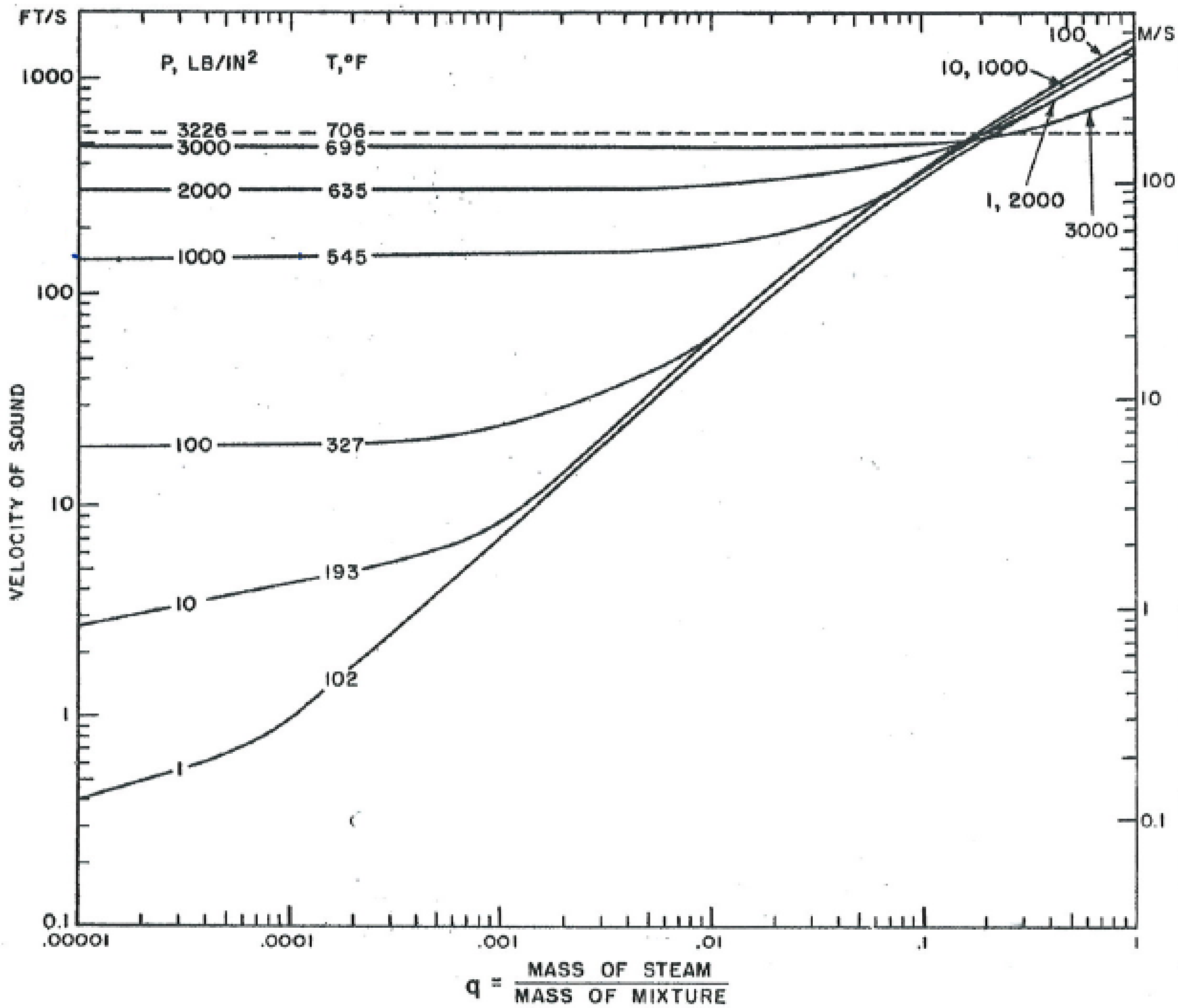

Figure 12. Speed of sound in [[ ]] **(Fig. 5 in Karplus [8])**

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

]]

3.0 MODEL QUALIFICATION: BWR PLANT VALIDATION

The Quad Cities Unit 2 (QC2) replacement steam dryer, installed in 2005, was the first GEH BWR unit instrumented with a significant number of on-dryer pressure sensors. This section presents the steam dryer fluctuating load definitions obtained with the PBLE at QC2 for two power levels, one at the QC2 Original Licensed Thermal Power (OLTP) level and at Extended Power Uprate (EPU) conditions.

3.1.1 Procedure for QC2 benchmarks

The QC2 dryer instrumentation comprised 27 PT sensors, labeled P:1 through P:27 [9]. Pressure sensor P:26, which was installed on the stream dryer temporary instrumentation mast, is not considered in this benchmark since the main interest is in pressure on the dryer surface. [[

]]

[[ ]]

Figure 13. Sensor Positions for Dryer Data Benchmark

[[

]]

Table 4 QC2 Frequency Bands for Main Acoustic Peaks

OLTP		EPU	
Begin Frequency (Hz)	End Frequency (Hz)	Begin Frequency (Hz)	End Frequency (Hz)
8	10	8	10
13	16	13	16
22	26	22	26
29	31	28	34
32	35	38	46
44	48	48	58
61	69	132	145
130	136	146	153
137	142	154	158
147	149	159	168
150	153	146	158
154	158		
150	158		

[[

]] The last segment PSDs at all sensors locations are plotted in Appendix A and Appendix B.

3.2 QC2 Benchmark at OLTP

3.2.1 From [[ ]]

[[ ]]

Figure 14. [[ ]]
(Numbers in parenthesis refer to the equation numbers)

3.2.2 From [[ ]]

[[ ]]

Figure 15. [[ ]]

3.3 QC2 Benchmark at EPU

3.3.1 From [[ ]]

[[ ]]

Figure 16. QC2 EPU Benchmark from [[ ]]

3.3.2 From [[ ]]

[[ ]]

Figure 17. QC2 EPU Benchmark from [[ ]]

3.4 QC2 Benchmark Conclusions

The PBLE predictions using [[ ]] are highly accurate: the low frequency content below [[ ]] These good results validate the main assumption that [[ ]] to reproduce measured dryer pressures, including at low frequencies.

Using [[ ]] is on the conservative side. [[ ]] This demonstrates the [[ ]].

The main limitations in these dryer data benchmark lie within the FE model. [[ ]] at both power levels.

The modeling of the region inside the dryer is also challenged; [[ ]] are generally less accurate.

Overall the PBLE 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.

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 Licensing Topical 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 PBLE 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 PBLE to the requirements contained in Section 2.1 of Regulatory Guide 1.20 Revision 3 [1].

RG 1.20 Section	Criteria	PBLE 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 PBLE method is applicable up to the full power level of the plant. Since the PBLE approach in this LTR 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 PBLE method is acceptable based on the benchmarking shown in Section 4.5 of this report. Stress analysis is not applicable to the scope of this LTR. CFD modeling is not applicable to the PBLE
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 PBLE 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 LTR
2.1.(1)	Scale Model Testing	Not applicable - Scale model Testing is not used in the PBLE for determination of the steam dryer loads
2.1.(1)	Computational Fluid Dynamic (CFD) modeling	Not applicable - CFD modeling is not used in the PBLE for determination of the steam dryer loads

RG 1.20 Section	Criteria	PBLE 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 PBLE 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 PBLE. 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 PBLE 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 PBLE loads [[ ]]

RG 1.20 Section	Criteria	PBLE 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 PBLE 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 PBLE methodology in this report uses [[ ]] for determination of the load definition. The PBLE methodology in this report demonstrates the methodology to determine bias errors and uncertainties associated with the PBLE 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 PBLE methodology in this report [[ ]].

RG 1.20 Section	Criteria	PBLE Conformance
2.1.(3)(b)	Strain gages (at least four gages, circumferentially spaced and oriented) may be used to relate the hoop strain in the MSL to the internal pressure. Strain gages 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 PBLE uses [[ ]] The effects of flow turbulence on the pressure measurement is included in the PBLE 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 PBLE 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 PBLE 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 PBLE 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	PBLE 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 Licensing Topical Report.

4.3 Range of Application

The PBLE 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. [[ ]]

[[

]]

4.4.2 Plant Input Measurements

Sensor Type and Location

For the PBLE [[

]]

Error in Measured Dryer Pressures

This error, [[

]]

4.4.3 Plant-Specific Load Definition

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

]]

4.4.4 Application Uncertainties and Biases

This section describes the processes for how to calculate the PBLE uncertainties for a plant-specific application.

The methodology presented here provides an uncertainty due to errors in the PBLE inputs: [[

]]

4.4.4.1 Method Presentation

This section describes constituting elements of the uncertainty analysis: the varying input parameters, the statistical methods in use, the nominal case and how deviations from the nominal case are calculated.

Parameters in the Uncertainty Analysis

The code parameters and variables that have an influence in the load definition are listed in Table 5. All influence [[ ]]

Table 5 Parameters in the [[ ]]

Phenomena	**Parameter**
[[	
	]]

Analysis Techniques

The techniques used in the evaluation of the uncertainty are briefly introduced in the following paragraphs.

Design of Experiments

A Design of Experiment (DOE) is a structured, organized method for determining the relationship between parameters affecting a process and the output of that process. Forced changes are made methodically to the input parameters as directed by mathematically systematic tables and the impact on the results is assessed. It is suitable for the present study since it allows maximizing information with a limited number of well-chosen parameter variations. The effect of input variables can be judged when acting alone, or in combination with others.

For each input parameter, a number of possible values are defined, representing the known variation range for each variable. [[

]]

Monte Carlo Analysis

The Monte Carlo method is a way to statistically evaluate a system using random samples. The larger the number of random samples is, the more accurate the results. From the mathematical point of view it consists of choosing a large number of parameter values at random from within a variation interval. It is useful to assess uncertainty when the ranges of the input parameters can not be given in a deterministic way (upper and lower bounds), but their probability density functions are known.

Deviations from Nominal Case

The nominal case corresponds to the PBLE results with all parameters at their best known values. These results are obtained by following the guidelines outlined in Section 4.4. [[

]]

4.4.4.2 Step 1 – Sensitivity of [[ ]]

Aside from parameters related to numerical accuracy, a range of values is known for each parameter in Table 5. [[

]]

Based on the results of these DOEs, [[

]]

[[ ]]

Figure 19. [[ ]]

Numerical Accuracy

The uncertainty due to [[

]]

4.4.4.3 Step 2 - Uncertainty in [[ ]]

Once [[ ]] that take into account the influence of the sensitive parameters in Table 5 have been pre-computed, the overall uncertainty in the PBLE loads can be evaluated.

[[

]]

4.4.4.4 Combination of Uncertainties and Biases

Individual uncertainties (due to different parameters or groups of parameters) are combined into a single one by taking the square root of the sum of the squares (SRSS):

(22) $U = \sqrt{\sum u_i^2}$ where:

U = Total uncertainty

u_i = Individual uncertainties

If the parameters or groups of parameters are not independent from each other, the combined uncertainty is conservative.

A benchmark against measured dryer pressures would produce a bias and an uncertainty in each frequency band. Then the total bias of the PBLE loads is the benchmark bias and the total uncertainty is a SRSS in which the benchmark uncertainty is a term of the sum.

4.5 Demonstration Analysis

This section details how uncertainties are combined in the example of Section 3.3.2: QC2 at EPU condition, [[ ]] The QC2 at OLTP had a different set of acoustic frequencies and benchmark results, but the bias and uncertainties would be calculated and assessed in the same manner.

The deviation from measured data (bias and uncertainty) is covered in the benchmark section (Section 3.3.2). The bias [Equation (17)] indicates any [[

]]

For QC2 at EPU, the biases and uncertainties from the comparison between nominal projections and measured pressures are in Figure 17. The uncertainties due to the model parameters is calculated in detail in Appendix C.

For the PBLE from in-vessel pressures, the contributors are: [[

]]

The consolidated results are shown in Table 6 and Figure 20. In Figure 20 the predicted summed PSDs are also corrected with the biases from the benchmark against test data.

[[ ]]

Figure 20. PBLE [[ ]] **- Range of Predictions Versus Measurements**

Table 6 Total Bias and Uncertainty for PBLE from [[ ]] for QC2 at EPU

Frequency Band (Hz)	8 -10	13 - 16	22 - 28	28 - 34	38 - 46	48 - 58	132 - 145	146 - 153	154 - 158	159 - 168	146 - 158
BIAS (%)											
[[ ]]	**-8.36**	**-6.43**	**8.49**	**6.28**	**5.47**	**-12.04**	**-14.20**	**20.99**	**-4.70**	**-4.70**	**9.60**
UNCERTAINTY (%)											
[[	8.74	4.79	2.98	2.06	1.44	2.67	2.89	0.76	0.97	3.00	1.08
	0.86	0.82	0.95	0.66	0.76	6.07	3.85	10.64	2.18	4.62	6.30
	2.89	3.57	3.99	3.83	3.11	2.96	3.07	4.03	3.69	2.69	3.87
	0.38	0.49	0.36	0.24	0.62	0.66	2.69	2.46	1.31	1.88	1.99
]]	0.91	1.12	1.24	0.95	0.64	0.76	3.08	4.63	1.56	3.41	3.40
Total uncertainty (SRSS)	**9.30**	**6.15**	**5.23**	**4.51**	**3.62**	**7.33**	**7.02**	**12.55**	**4.84**	**7.26**	**8.45**

5.0 CONCLUSIONS

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

A built-in [[

]]

The PBLE technique is validated by the Quad Cities 2 application case. From comparison between measurements and projections, the PBLE predicts good frequency content and spatial distribution. The SRV valve resonances are well captured. The PBLE predictions are highly accurate: the low frequency content below [[

]] These good results validate the main assumption that [[ ]] to reproduce measured dryer pressures, including low frequencies.

The PBLE 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 PBLE from [[ ]] is adequate to predict fluctuating dryer loads at any BWR plant.

6.0 REFERENCES

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[12] U.S. Nuclear Regulatory Commission, NUREG-0800, Revision 3, March 2007, Section 3.9.2, "Dynamic Testing and Analysis of Systems, Structures and Components."

[13] U.S. Nuclear Regulatory Commission, NUREG-0800, Revision 3, March 2007, Section 3.9.5, "Reactor Pressure Vessel Internals."

APPENDIX A QC2 OLTP BENCHMARKS PSDS

[[ ]]

Measured –Red
[[ ]] - Green
[[ ]] - Blue

[[ ]]

Measured - Red
[[ ]] - Green
[[ ]] - Blue

[[ ]]

Measured - Red
[[ ]] - Green
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Measured - Red
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APPENDIX B QC2 EPU BENCHMARK PSDS

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Measured - Red
[[ ]] - Green
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Measured - Red
[[ ]] - Green
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Measured - Red
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[[ ]]

Measured - Red
[[ ]] - Green
[[ ]] - Blue

[[ ]]

Measured - Red
[[ ]] - Green
[[ ]] - Blue

[[ ]]

Measured - Red
[[ ]] - Green
[[ ]] - Blue

[[ ]]

Measured - Red
[[ ]] - Green
[[ ]] - Blue

[[ ]]

Measured - Red
[[ ]] - Green
[[ ]] - Blue

APPENDIX C QC2 EPU UNCERTAINTY ASSESSMENT

C.1. VARIATIONS IN PBLE INPUT PARAMETERS

Table 7 Nominal, Upper and Lower Bound Parameter Values for QC2

	Units	**Nominal**	**Lower**	**Upper**
[[				
				]]

Table 7 gives the nominal values and the upper and lower limits for all the input parameters. The [[ ]] is described in Section 2.2.2. In addition to the content of Table 7, [[

]]

C.2. STEP 1 – SENSITIVITY OF FRFS

The goal of this step is to determine which variables in the vessel have an influence in [[

]]

Mesh Independent Parameters

Figure 21 shows results, for high and low frequency respectively, for the DOE [[
]]

The curves for all experiments lay on top of each other. No variability is observed due to these parameters in their variation range.

Figure 22 shows results [[ ]] For this group of variables some differences are observed. By observing the [[

]]

[[ ]]

Figure 21. DOE on [[ ]]

[[ ]]

Figure 22. DOE on [[ ]]
Black Thick Line is the Nominal Experiment

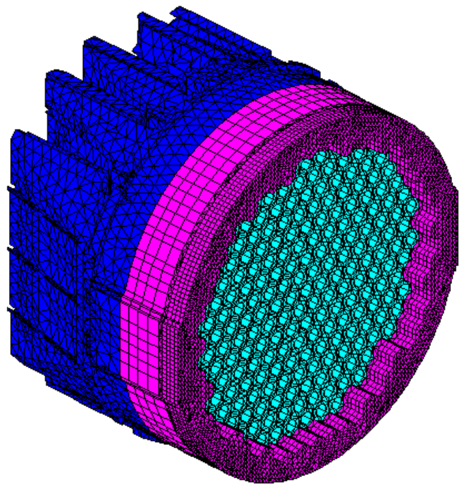

Figure 23. FEM Mesh Upstream the Dryer Showing the Regions With [[
]]

[[

]]

Table 8 Changes in [[ ]]

	[[	
Mesh 1		
Mesh 2		
Mesh 3		]]

Table 9 Acoustic Modes (Hz) of the Nominal and Modified Meshes

Modes	Nominal	Mesh 1	Mesh 2	Mesh 3
1	[[			
2				
3				
4				
5				
6				
7				
8				
9				
10				]]

[[ ]]

Figure 24. FRFs for Different FE Meshes With [[ ]]

[[ ]]

In view of [[

]]

Table 10 [[ ]]

	[[	
		]]

[[

]] In any case, the curves reproduce each other reasonably well.

[[ ]]

Figure 25. FRFs With Finer FE Mesh

Figure 26 [[

]]

[[ ]]

Figure 26. [[ ]]

C.3. STEP 2 – UNCERTAINTY IN DRYER LOADS

From the previous section, it is clear that [[

]]

[[ ]]

Figure 27. [[ ]]

Table 11 [[

]]

[[						
						]]

Table 12 [[

]]

[[					
					]]

Uncertainty due to Errors in the Measurement Loop

It has been shown in a previous report [11] that this measurement loop, [[

]] The results are shown in Figure 28 and quantified in Table 13 and Table 14.

Table 13 PBLE predictions – Measurement Loop Deviations from Nominal at Low Frequencies

Frequency band (Hz)	8 – 10	13 – 16	22 – 28	28 – 34	38 – 46	48 – 58
Upper deviation (%)	[[					
Lower deviation (%)						]]

Table 14 PBLE predictions – Measurement Loop Deviations from Nominal at High Frequencies

Frequency band (Hz)	132 – 145	146 – 153	154 – 158	159 – 168	146 – 158
Upper deviation (%)	[[				
Lower deviation (%)					]]

[[ ]]

Figure 28. PBLE Predictions – Uncertainty Due to the Measurement Loop

Uncertainty due to [[ ]]

The uncertainty [[

]]

Table 15 [[

]]

[[						
Deviation (%)						
Deviation (%)						]]

Table 16 [[

]]

[[					
Deviation (%)					
Deviation (%)					]]

C.4. CONSOLIDATED UNCERTAINTY

The results are shown in Figure 29, Table 17 and Table 18. The largest contribution to uncertainty [[

]]

The overall uncertainty remains below 10%, except for the 146 – 153 Hz bands, where it peaks at a value of 12.55%.

Table 17 Consolidated Uncertainty – [[ ]]

Frequency Bands (Hz)	8 -10	13 - 16	22 - 28	28 - 34	38 - 46	48 - 58
[[						
						]]

Table 18 Consolidated Uncertainty – [[ ]]

Frequency Bands (Hz)	132 - 145	146 - 153	154 - 158	159 - 168	146 - 158
[[					
					]]

In Figure 29, the PBLE uncertainties are quite small but some bias compared to the measured PSDs remains; this is reconciled by the benchmark against measured pressures in Section 3.3.2.

[[ ]]

Figure 29. PBLE from [[ ]]

Appendix C

ESBWR Steam Dryer - Plant Based Load Evaluation Methodology, Supplement 1 (NED-33408, Supplement 1)

Revision 1 of this report was submitted to the NRC by GEH in MFN Letter 09-579, dated August 31, 2009. GEH did not submit a nonproprietary version of the report in accordance with NRC Information Notice 2009-07, Requirements for Submittals, (2): "In instances in which a nonproprietary version would be of no value to the public because of the extent of the proprietary information, the agency does not expect a nonproprietary version to be submitted." The same exclusion is being taken here, and a non-proprietary version of Appendix C is not provided.

Appendix D

GEH BWR Steam Dryer - Plant Based Load Evaluation (NED-33436)

This appendix contains Revision 0 of NEDO-33436, which was submitted to the NRC by GEH in MFN Letter 08-876, Supplement 1, dated October 14, 2009.

GE Hitachi Nuclear Energy

Non-proprietary Version

NEDO-33436
Revision 0
Class I
DRF 0000-0087-3726
November 2008

Licensing Topical Report

GEH Boiling Water Reactor Steam Dryer - Plant Based Load Evaluation

IMPORTANT NOTICE REGARDING THE

CONTENTS OF THIS REPORT

Please Read Carefully

INFORMATION NOTICE

This is a non-proprietary version of NEDC-33436P, which has the proprietary information removed. Portions of the document that have been removed are indicated by an open and closed bracket as shown here [[ ]].

IMPORTANT NOTICE REGARDING THE CONTENTS OF THIS REPORT

Please Read Carefully

The information contained in this document is furnished for the purpose of obtaining NRC approval for the use of the Plant Based Load Evaluation Methodology for GEH Boiling Water Reactor Steam Dryers. The only undertakings of GE Hitachi Nuclear Energy respecting information in this document are contained in the contracts between GE Hitachi Nuclear Energy and the participating utilities in effect at the time this report is issued, and nothing contained in this document shall be construed as changing those contracts. The use of information by anyone other than that for which it is intended is not authorized; and with respect to any unauthorized use, GE Hitachi Nuclear Energy makes no representation or warranty, and assumes to liability as to the completeness, accuracy, or usefulness of the information contained in this document.

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ACRONYMS AND ABBREVIATIONS

Acronym / Abbreviation	Description
ABWR	Advanced Boiling Water Reactor
BWR	Boiling Water Reactor
ESBWR	Economic Simplified Boiling Water Reactor
ft/s	Feet per second
GEH	General Electric Hitachi Nuclear Energy
Hz	Hertz
MSL	Main Steam Line
NRC	U.S. Nuclear Regulatory Commission
PBLE	Plant Based Load Evaluation
RPV	Reactor Pressure Vessel
SRV	Safety Relief Valve

EXECUTIVE SUMMARY

Plant Based Load Evaluation (PBLE) refers to the methodology for defining the fluctuating pressure loads that are imposed upon the steam dryer used in the GEH-designed Boiling Water Reactors (BWRs). The PBLE 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 PBLE is applicable to BWRs with parallel bank design steam dryers, including the BWR/2 through BWR/6, ABWR (Advanced Boiling Water Reactor), and ESBWR (Economic Simplified Boiling Water Reactor) product lines. The PBLE modeling and application methodology for the ESBWR (References 2 and 3) were submitted to the NRC for review and approval.

The NRC review of References 2 and 3 includes the PBLE methodology itself. Therefore, the discussion herein is limited to the application of the PBLE methodology to BWR/2 through BWR/6, and ABWR product lines.

As discussed herein, the PBLE methodology is applicable and acceptable for the BWR/2 through BWR/6 and ABWR product lines due to the evolutionary design of the BWR plant and similar operating conditions.

1. INTRODUCTION

The NRC has issued revised guidance, Regulatory Guide 1.20 Rev. 3, to address a comprehensive vibration assessment program acceptable for use in verifying the structural integrity of reactor internals, including steam dryers (Reference 1). The NRC guidance presents individual analytical, measurement, and inspection programs. GEH has developed the PBLE for parallel bank steam dryers contained in GEH-designed BWRs to address the analytical program of the revised NRC guidance.

PBLE refers to the methodology for defining the fluctuating pressure loads that are imposed upon the steam dryer used in the GEH-designed Boiling Water Reactors. The PBLE load definition will be applied to a structural finite element model of the steam dryer in order to determine the steam dryer alternating stresses.

The PBLE was submitted for NRC review and approval in References 2 and 3. These references provide the theoretical basis and benchmarking of the PBLE method that will be applied for determining the fluctuating pressure loads on the ESBWR steam dryer, describes the PBLE analytical model, determines the biases and uncertainties of the PBLE formulation and describes the application of the PBLE method to the development of the fluctuating pressure load definition for steam dryer structural analyses.

The PBLE is a three dimensional acoustic model of the steam dome and dryer region inside the reactor vessel. [[

]] Therefore, the PBLE is applicable to BWRs with parallel bank design steam dryers, including the BWR/2 through BWR/6, ABWR, and ESBWR product lines. The acceptability of the PBLE methodology to the BWR/2 through BWR/6 and ABWR is presented herein.

The NRC review of References 2 and 3 includes the PBLE methodology itself. The details of the methodology are not changed herein. Therefore, the discussion herein is limited to the application of the PBLE methodology to BWR/2 through BWR/6, and ABWR product lines.

2. APPLICABILITY

2.1 PBLE APPLICABILITY TO OPERATING PLANTS

The PBLE is applicable to BWRs with parallel bank design steam dryers. This includes the BWR/2 through BWR/6, ABWR, and ESBWR product lines. The evolutionary design of the

BWR plant has resulted in similar reactor vessel, steam dryer, and main steamline geometrical configurations, as well as similar plant operating conditions. As a result, the range of plant-to-plant variations that the PBLE must accommodate is small. These plant-to-plant variations in geometry and operating conditions would be addressed in the plant-specific application of the PLBE. In addition, the PBLE predictions have been benchmarked against [[ ]] taken in operating plants. Therefore, the ESBWR PBLE modeling and application methodology described in References 2 and 3 are also directly applicable to operating plants in the BWR/2 through BWR/6 and ABWR product lines.

2.2 GEOMETRICAL CONSIDERATIONS

2.2.1 Overall Reactor Configuration

The overall reactor assembly is shown in Figure 1. The steam dryer is located in the top of the vessel. The steam separator assembly, located directly below the steam dryer, forms part of the lower boundary of the PBLE. The steam flow path through the dryer is shown in Figure 2. Steam is generated in the reactor core and enters the upper plenum and steam separators as a two-phase mixture. The steam separators remove most of the water, sending moist steam up into the dryer. The chevron flow paths through the dryer vanes remove almost all the remaining moisture from the steam prior to the steam leaving the vessel through the main steam nozzles. The steam separator and dryer configuration is common to the BWR/2 through BWR/6, ABWR, and ESBWR product lines.

PBLE Application

[[

]]

2.2.2 Steam Dryer Configuration

Figure 3 shows the basic configuration and components for a typical BWR steam dryer. The same basic GEH BWR steam dryer design has been used in BWR/2 through BWR/6, ABWR, and ESBWR plants. This basic design consists of four to six parallel banks supported by a circumferential ring at about mid height of the dryer. The banks consist of hood panels that direct the steam flow through the dryer vane assemblies. The skirt is suspended from the support ring and extends down below the reactor water level and outside the steam separator assembly. The skirt forms a water seal and directs the steam leaving the separators up through the vanes. Water removed from the steam is collected in troughs below the vane assemblies and returned to the RPV water through the drain channels.

The dryer hoods run parallel to the 0-180° vessel line with the steamlines symmetric about the 90-270° vessel line as shown in Figure 5. The cavity between the outer hood bank and the vessel wall forms an exit plenum for the steam flow leaving the steam dome. The steam flow velocities are low where the flow exits the dryer banks and in the steam dome. The flow accelerates in the outer hood region as the flows collect in exit plenum and accelerate into the steamlines. Most of the pressure loading acting on the dryer occurs on the outer hoods as the steam flows accelerate through this exit plenum region.

Four basic dryer hood shapes have been used in the operating plant steam dryers. These hood shapes are shown in Figure 4.

- BWR/2s and BWR/3s use square hood dryers. The BWR/2 steam dryer is similar to a square hood dryer; the difference between the two designs is that the vane assemblies are tilted approximately 20° off vertical in the BWR/2 design. However, the BWR/2 exterior hood shape is the same as the square hood dryer.
- Most BWR/4s use the slant hood design.
- Some of the later BWR/4 plants and later reactor designs used the curved hood dryer design.
- The Quad Cities replacement dryer used a flat plate slant hood design, while the Susquehanna replacement dryer replicated the original curved hood shape.

PBLE Application

In the PBLE modeling, the vessel acoustic region is defined by [[

]] This process allows the PBLE application methodology to accommodate different vessel sizes, RPV head shapes, and dryer designs. This process also ensures that the load definition generated by the PBLE acoustic model will accurately match the dryer structural model.

2.2.3 Main Steamline Configuration

The main steamline configuration for the BWR/2 through BWR/6, ABWR, and ESBWR product lines is similar across the plant product lines, particularly within the containment drywell where the limited space dictated a standardized pipe routing. Figures 6 and 7 show a typical BWR steamline layout from the RPV to the turbine for a plant with a Mark I containment. The main steam lines (MSLs) exit the vessel symmetrically offset about 18-20° from the 90-270° vessel line, then collect and exit the drywell along the 0-180° vessel line towards the turbine. Outside the drywell, the MSL configuration varies from plant to plant, [[

]]

The different containment types introduce only a minor difference in the main steamline configuration within the drywell. In the Mark I and Mark II containments, the steamlines drop down and exit the drywell at an elevation near the bottom of the RPV. For the Mark III, ABWR, and ESBWR containments, the steam lines do not drop as far and exit the drywell at roughly mid-height of the RPV. [[

]]

A few plants have a stagnant branch line, or deadleg, on some of the main steamlines. This steamline configuration is shown in Figure 8. These deadlegs serve as a mounting location for safety relief valves (SRVs). Acoustically, the deadleg provides a resonating chamber that may amplify the low frequency pressure content of the fluctuating pressure loads acting on the dryer. The PBLE modeling and qualification basis presented in Reference 3 includes a benchmark comparison of the PBLE prediction against [[ ]] for a plant with deadlegs. Therefore, the PBLE is qualified for application to plants with deadlegs.

BWR/2 plants differ from the typical steam line arrangement in that these plants have only two steamlines instead of four. The steamlines for these plants exit the vessel at 90-270° then follow the same routing as the other Mark I plants. [[

]]

The SRV standpipes could generate acoustic resonances that can acoustically couple with the RPV and produce a pressure load on the dryer. Whether a standpipe will generate a resonance and, if so, whether that resonance couples with the RPV is highly plant-specific and depends on several geometric and flow dependent parameters. [[

]]

PBLE Application

[[

]]

2.3 OPERATING CONDITIONS

The evolutionary nature of the BWR design has dictated that the reactor operating conditions (e.g. pressures, temperatures, flow velocities) remain within a fairly narrow range in order to ensure that the plant operation are within the experience base and supporting licensing bases (e.g., fuel thermal/hydraulic performance tests, transient and accident analysis codes). Plant power output was initially accommodated in the original plant designs by scaling the size of the reactor and components, which keep the operating conditions within the experience base. [[

]] References 2 and 3 describe how these parameters and properties are addressed for a plant-specific application.

2.4 PLANT OBSERVATIONS

Steam dryers on several plants have been instrumented. [[

]] Figures 9 through 12 show the frequency content of the pressure load acting on the dryer. Table 1 provides a comparison of the plant characteristics for the four plants from which the measurements in Figures 9 through 12 were taken. [[

]] The high quality SRV resonance peaks occur above 100 Hz. The frequency is dependent on the SRV branch line cavity depth; whether or not the SRV acoustic resonance actually produces a pressure load that acts on the dryer depends on whether or not the SRV acoustically couples with the vessel through the steamline. [[

]] These observations reinforce the conclusion that the PBLE is applicable across the GE BWR product lines. [[

]]

2.5 PBLE QUALIFICATION BASIS

The PBLE methodology has been benchmarked against [[ ]] taken on instrumented replacement dryers in operating plants. In Reference 2, the PBLE was benchmarked against the data taken at Quad Cities Unit 2. [[

]] In Reference 3, the PBLE was benchmarked against the data taken at Susquehanna Unit 1. [[

]] These two benchmarks provide confidence that the PBLE will provide accurate predictions over the full frequency range of interest for any plant application.

3. CONCLUSIONS

The PBLE modeling and application methodology described in References 2 and 3 are applicable to BWRs with parallel bank design steam dryers. This includes the BWR/2 through BWR/6, ABWR, and ESBWR product lines. The evolutionary design of the BWR plant has resulted in similar reactor vessel, steam dryer, and main steamline geometrical configurations, as well as similar plant operating conditions. [[

]] These plant-to-plant variations in geometry and operating conditions are addressed in the plant-specific application of the PLBE. [[

]] This approach allows the PBLE to be applied to a wide variety of configurations. In addition, the PBLE predictions have been benchmarked against [[ ]] taken in operating plants and provide confidence that the PBLE will provide accurate predictions over the full frequency range of interest for any plant application. Therefore, the ESBWR PBLE modeling and application methodology described in References 2 and 3 are also directly applicable to operating plants in the BWR/2 through BWR/6 and ABWR product lines.

4. REFERENCES

1. Regulatory Guide 1.20 Rev. 3, "Comprehensive Vibration Assessment Program for Reactor Internals During Preoperational and Initial Startup Testing," March 2007.

2. NEDC-33408P, "ESBWR Steam Dryer – Plant Based Load Evaluation Methodology," February 2008.

3. NEDC-33408P Supplement 1, "ESBWR Steam Dryer – Plant Based Load Evaluation Methodology," October 2008.

Table 1
Comparison of Plant Characteristics

Product Line	RPV Diameter (inch)	Average MSL Velocity (ft/s)	Dryer Hood Design	Containment Type	Figure
BWR/3	188	149	Square	Mark I	9
BWR/3 (Quad Cities 2)*	251	200	Slanted	Mark I	10
BWR/4 (Susquehanna 1)*	251	129	Curved	Mark II	11
ABWR	280	139	Curved	ABWR	12

* Plants used for PBLE benchmarking.

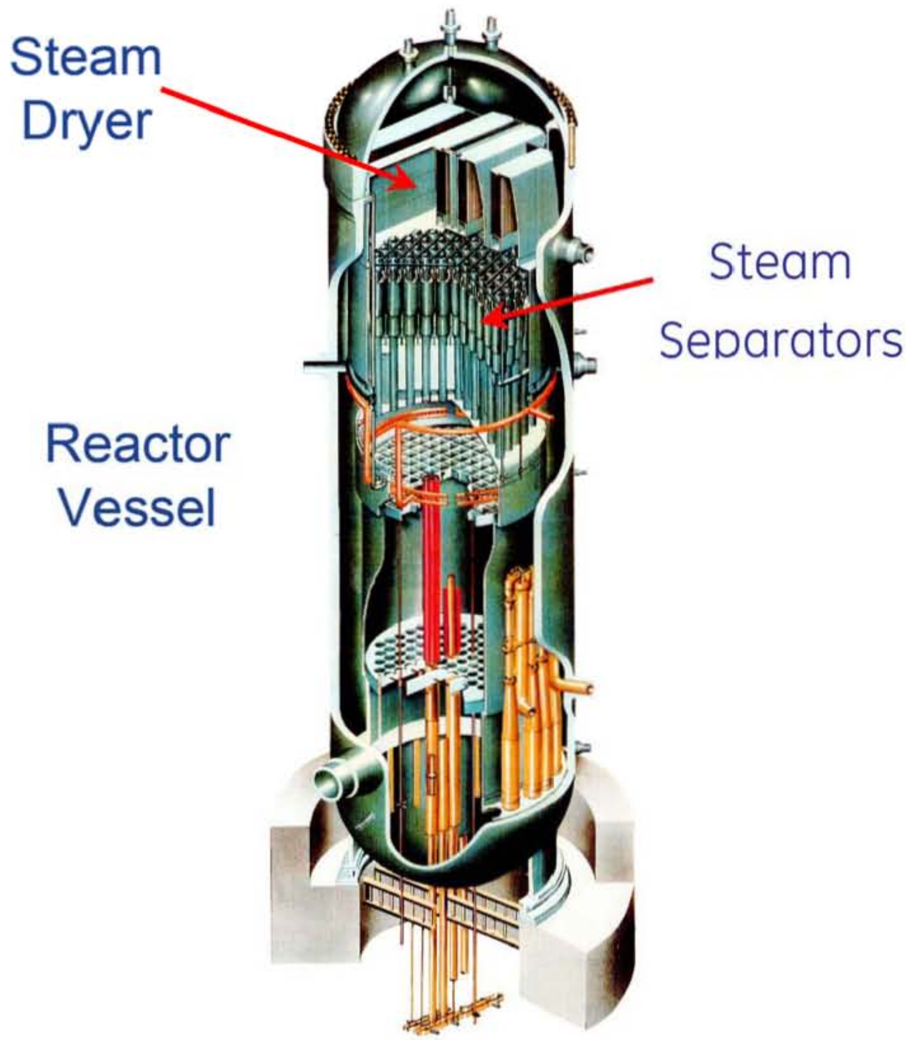

Figure 1: Reactor Vessel Configuration

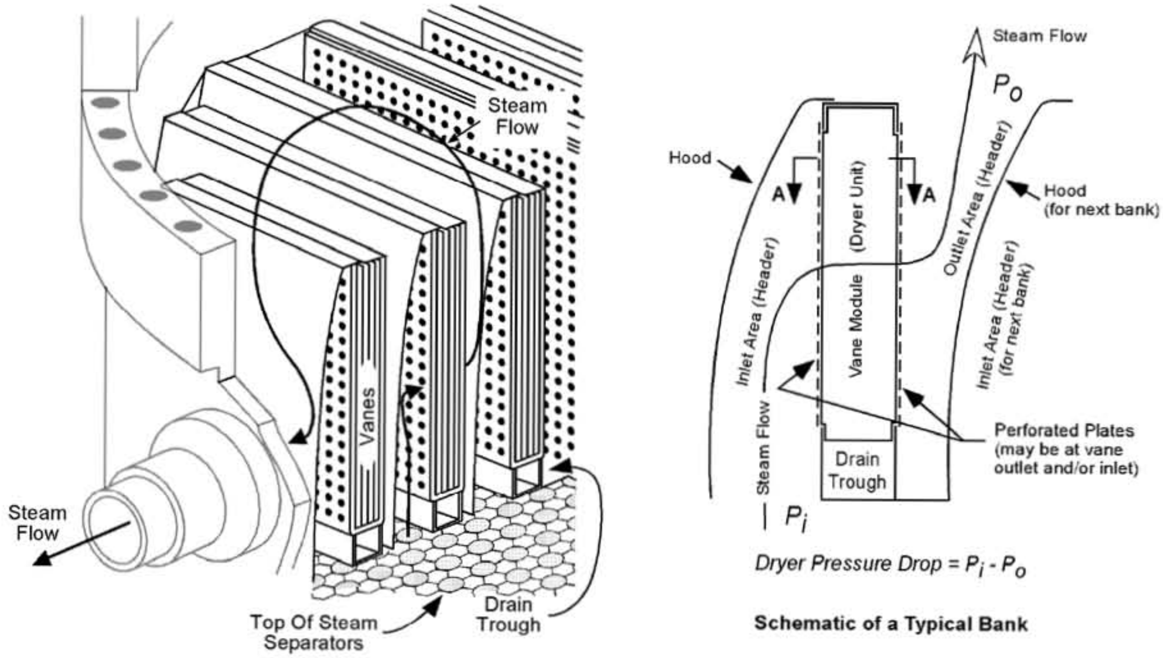

Figure 2: Steam Flow Path Through Dryer

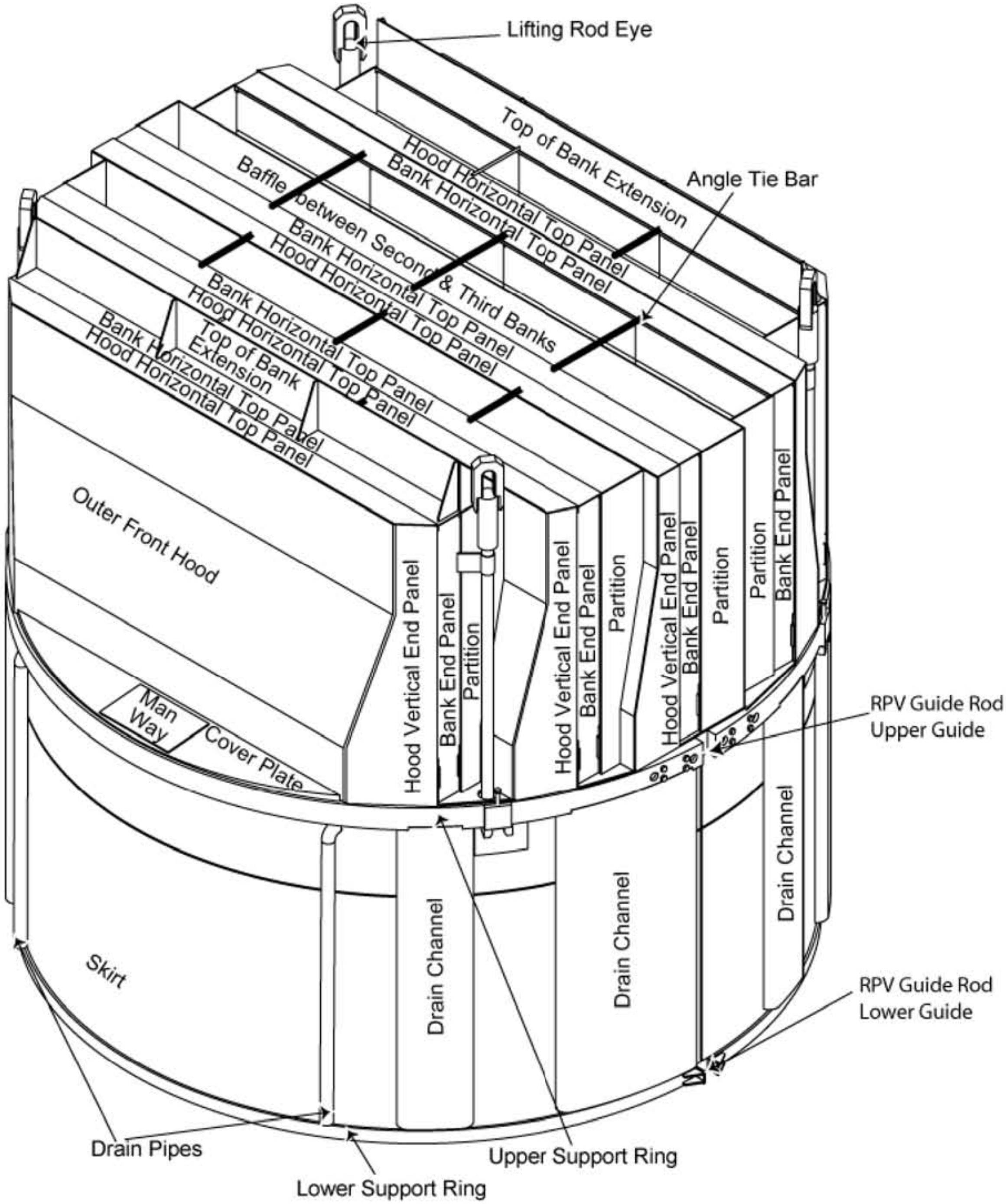

Figure 3: Typical Steam Dryer (BWR/4 Slant Hood Design Shown)

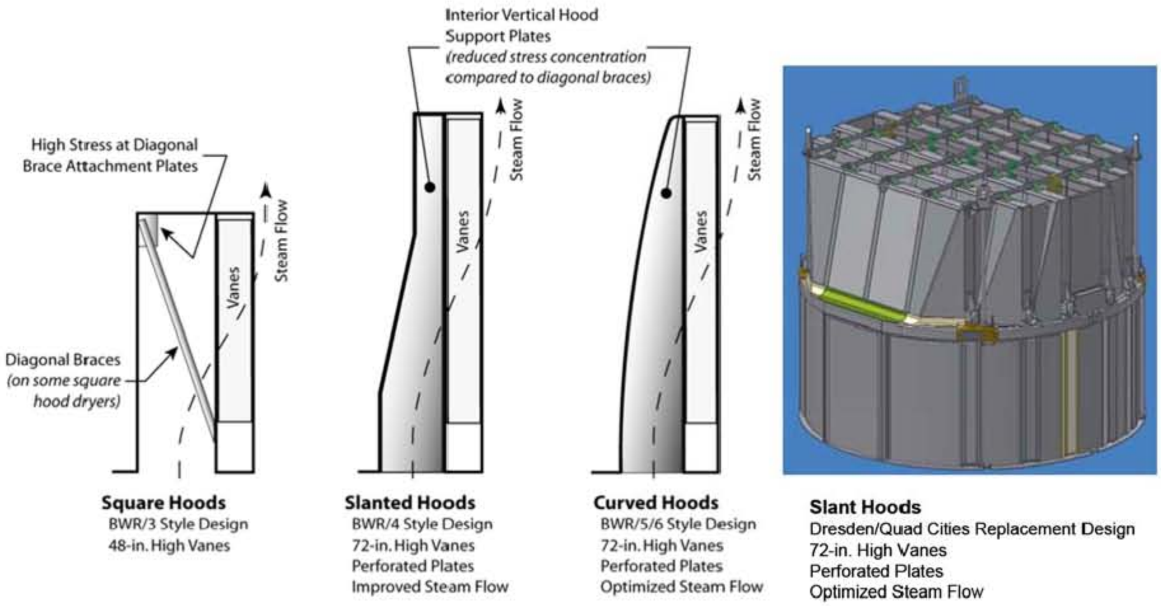

Figure 4: BWR Dryer Hood Designs

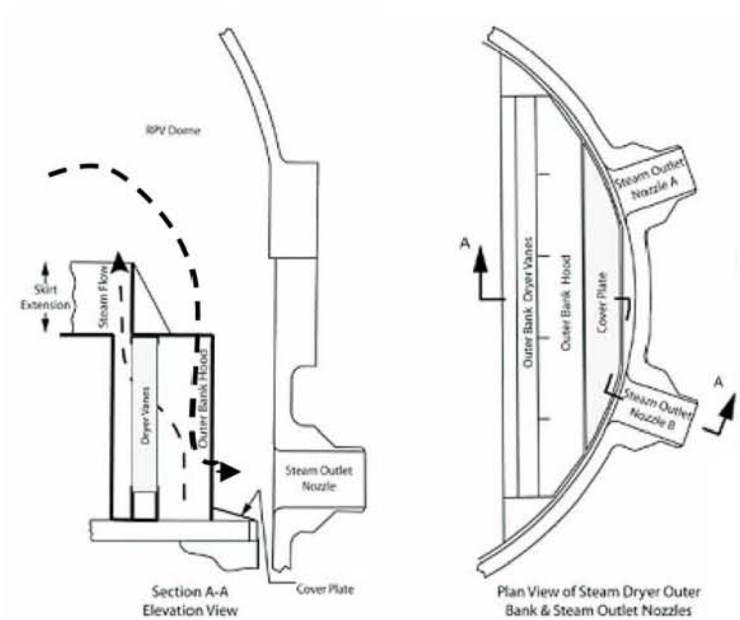

Figure 5: Orientation of Main Steam Nozzles to Steam Dryer

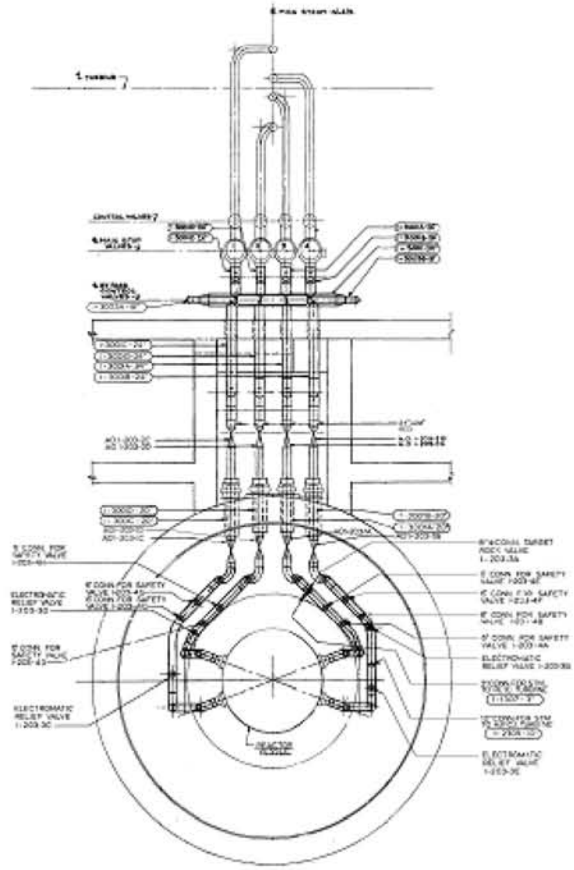

Figure 6: Typical Main Steam Line Layout Between RPV and Turbine (plan view)

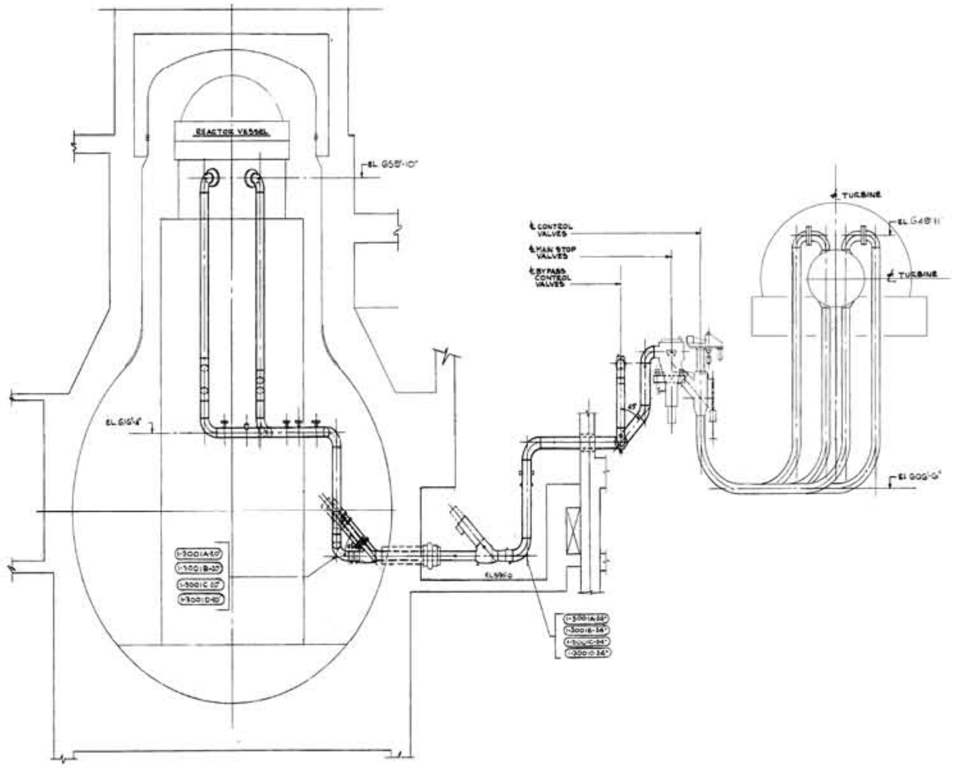

Figure 7: Typical Main Steam Line Layout Between RPV and Turbine (elevation view)

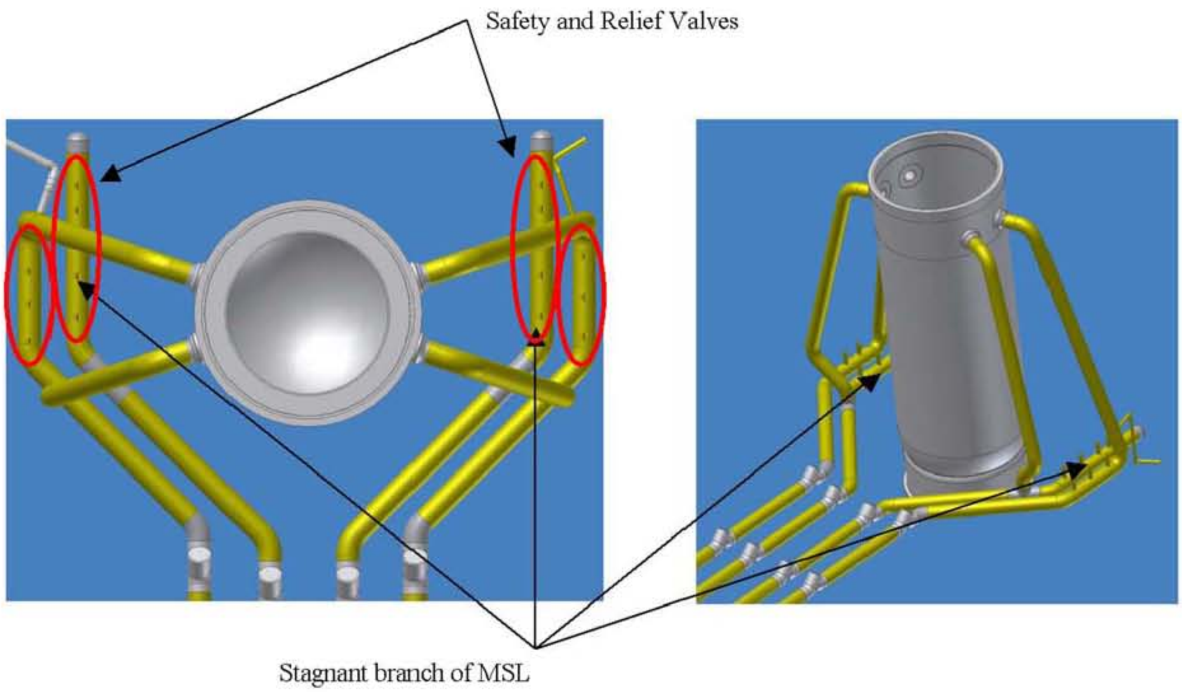

Figure 8: MSL Layout Showing S/RVs Located on Stagnant Branch Lines

[[

]]

Figure 9: Pressure on Skirt Below Cover Plate (188" BWR/3, Square Hood Dryer)

[[

]]

Figure 10: Pressure on Skirt Below Cover Plate (251" BWR/3, Slant Hood Dryer)

Note: Both figures show the same data. The scale has been changed on the lower figure to better show the frequency content outside the 150-160 Hz range.

[[

]]

Figure 11: Pressure on Cover Plate (251" BWR/4, Curved Hood Dryer)

[[

]]

Figure 12: Pressure on Skirt Below Cover Plate (280" ABWR, Curved Hood Dryer)

[[

]]

Figure 13: PBLE Acoustic Regions and Boundaries

[[

]]

Figure 14: Comparison of Steam Flow over Outer Hood, BWR/2 and Later Plants